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CH-47D Rotating System Fault Sensing for Condition Based Maintenance

THESIS

Stephen M. Dickerson, Major, USMC

AFIT/GAE/ENY/11-M08

DEPARTMENT OF THE AIR FORCE
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AFIT/GAE/ENY/11-M08

CH-47D Rotating System Fault Sensing for Condition Based Maintenance

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

Stephen M. Dickerson, B.S.

Major, USMC

March 2011

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CH-47D Rotating System Fault Sensing for Condition Based Maintenance

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Abstract

The Department of Defense (DoD) has mandated the use of maintenance practices based on component condition rather than component time in service or age. This practice is known as Condition Based Maintenance, and it relies on accurate detection and identification of material deficiencies in system components. Rotor system components in rotary-wing aircraft can be difficult to monitor due to the rotational environment experienced by the sensors and the difficulty of signal transmission. Current methods are able to detect the existence of a fault in the rotor system but cannot link the vibrations experienced in the airframe to a specific material defect. This results in inefficient maintenance practices associated with identifying the faulty components for repair or replacement. This research seeks to create an analytical model in the Rotorcraft Comprehensive Analysis System which will enable the identification of component deficiencies in the rotating system from vibration characteristics experienced in the fuselage, in order to increase maintenance efficiencies leading to cost savings and increased operational readiness for in-service CH-47D aircraft. This research successfully modeled additional mass to rotor blades and changes in pitch link length. However, only limited success was achieved when modeling changes to trim tab angle and incorporation of elastic fuselage representations.

Acknowledgements

The research and writing of this thesis has been a time-consuming and, at times, frustrating endeavor which required assistance from many people to complete. I owe a heart-felt acknowledgement and appreciation to the incredible support I have received through these months of work.

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Stephen M. Dickerson

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CH-47D Rotating System Fault Sensing for Condition Based Maintenance

I. Introduction

There is a constant desire to improve the safety and reliability of rotary wing aircraft. The high number of complex moving parts in the rotorcraft drivetrain introduce numerous locations for faults to occur and degrade the ability of the drivetrain to perform its function, sometimes with catastrophic results. Rotorcraft manufacturers, operators, and maintainers have historically relied upon time-based metrics to perform preventative maintenance actions on these complex aircraft. Unfortunately, the data necessary to formulate these time-based metrics was often acquired through mechanical failure which resulted in extensive harm to man and machine.

1.1 Condition Based Maintenance (CBM) and Health and Usage Monitoring Systems(HUMS)

To prevent such harm, manufacturers, maintainers, and operators determined time intervals for inspection and replacement of aircraft components based on historical data. While effective in improving the safety and reliability of rotary wing aircraft, this preventive process necessitates greater amounts of maintenance be performed which increases operating costs. To combat these ever growing costs, the United States Department of Defense (DoD) mandated [1] that the armed services transition to a Condition Based Maintenance (CBM) process. The premise of this program is that maintenance actions will be performed based on the actual need of the components rather than on statistical averages. The CBM program will reduce operating costs to rotary wing fleets while increasing readiness [2] for operational tasking. Governments and civilian operators which utilize CBM will also benefit from improved fleet readiness and enhanced safety [3] as the maintenance process will be more directly tied to the physical condition of the aircraft.

In order to realize these gains through CBM, methods of monitoring the aircraft material state were developed and incorporated by various manufacturers under the industry term of Health and Usage Monitoring Systems (HUMS). Where time-based preventive maintenance uses historical statical averages and qualitative inspections by trained personnel to determine the lifespan of a component, HUMS sensors allow real-time monitoring [2] of mechanical and energy states of specific components, as well as data collection on specific components for numerical analysis between flights. Statistical averages used for time-based maintenance do not adequately account for the varying maximum stresses placed on aircraft flying different mission profiles. Using HUMS, components of individual aircraft can be monitored for indicators of the condition and health of specified components and using the principles of CBM those components can be replaced or repaired upon presenting indications of malfunction. Thus an aircraft which may meet the time-based requirements for maintenance but which has conducted relatively benign flight operations may not present indications of required maintenance, allowing maintenance personnel to focus efforts on other aircraft. At the other extreme, an aircraft which has flown repeatedly near operating limits may require maintenance earlier than the scheduled time-based maintenance. Only through HUMS and CBM can these aircraft receive the most accurate and timely maintenance while maximizing parts availability and supply requirements.

1.2 Applying HUMS and CBM

Monitoring the mechanical state of the aircraft is only the beginning; the resulting data must be converted to a useful form which aircrew and maintenance personnel can use to determine future performance of components. Through this prognostication, maintenance and operations personnel can determine whether components should be replaced or receive servicing prior to completion of the next assigned mission. Accurate prognostics will enable more efficient scheduling and logistics utilization [4]. However, prognostics have proven to be more complicated than even monitoring of the existing aircraft state. A difficult balance must be reached between

false-alarms and replacing parts which continue to have significant useful life, which is similar to the current time-based maintenance criteria.

Compounding the difficulty in reaching this balance is the need to minimize the weight and complexity added to an aircraft by health and usage monitoring systems. Accelerometers and temperature gauges are the predominant sensors in current monitoring systems. The shear number and primacy of rotating components in a rotorcraft introduce vast opportunities for harmonic oscillations, or vibrations, to be experienced by the aircraft. Thus accelerometers measuring normalized movements placed at key locations in the airframe can provide detailed information on the health of the aircraft systems. These accelerometers are typically mounted near gearboxes, driveshaft hanger bearings, and engines. Additional sensors mounted on rotating components downstream of the rotating swashplate could provide more detailed information of vibrations on individual blades and rotor bearings, however transmission of the information from sensor to data system becomes problematic. Slip rings are an obvious solution but are susceptible to the degrading effects of environmental conditions, in addition to the complexity of the slip ring itself which is added to the maintenance burden. Wireless sensors have been developed and tested as a solution [5], but these have their own inherent difficulties such as powering the sensors and transmission interference, or even existence of the transmissions in a combat environment. For these reasons the vibration data determined through sensors mounted prior to the rotating swashplate, such as those mounted on or near a main gear box, currently provide the vibration data which must be analyzed for characteristics that allow accurate determination of the current health of rotor head components and possible prognostics.

1.3 Vibration Analysis

For nearly a decade, several programs have worked to identify and correlate vibration data to known maintenance faults. One such program is the Vibration Monitoring Enhancement Program (VMEP). This program has successfully shown

the promise of HUMS [6] and CBM through installation on a limited number of US Army aircraft. Last year the Army announced that such systems would now be installed on all rotorcraft in the service [7]. In order to maximize the capability of HUMS and realize the full potential of CBM, the ability to relate vibration data to aircraft faults must continue to be refined.

This thesis seeks to create models to assist in addressing the interpretation of vibration data from the CH-47D rotor system in order to determine which components require servicing or replacement. Using the Rotorcraft Comprehensive Analysis System (RCAS) software, faults will be introduced to these models in order to observe and analyze resulting vibration characteristics. These resulting vibrations can be compared to limited vibration data obtained from aircraft which have experienced identical or nearly identical faults in order to validate the models in this thesis. Due to time and computational limitations, this research did not reach a stage where this comparison could be undertaken. In the future, if vibration models can accurately model these faults, then the models can be incorporated into the diagnostic and prognostic systems in order to enhance the efficiency of maintenance operations, safety of flight, and operational readiness.

II. Background

This chapter presents the need for an understanding of vibrations in rotary wing aircraft and the relevance of this paper to that understanding. Several programs have been enacted in recent years to address the maintenance and operational impacts of rotorcraft vibrations.

2.1 The CH-47D Chinook

This research specifically targets the CH-47D Chinook helicopter built by Boeing Aircraft Industries, such as seen in Figure 2.1. The aircraft is a twin-turbine engine, tandem rotor helicopter designed to transport cargo, troops, and weapons during day or night in visual or instrument conditions [8]. The engines drive two three-bladed rotors which rotate in opposite rotational directions (counterrotating). The sections of fuselage above the cabin and cockpit which contain gearboxes and swashplates are known as the forward and aft pylons. Variations of the aircraft have been in service with the United States Army for decades. The basic aircraft is also in service with civilian agencies and companies as well as numerous foreign governments and militaries.

2.2 Vibrations

Vibrations result in mechanical systems with rotating components when mass or aerodynamic imbalances are excited in an oscillatory manner [9]. The numerous rotational components of a helicopter rotor system can experience these imbalances from a variety of sources throughout the drivetrain, beginning with the engines and continuing through the dynamic components to the rotor blades. Fixed wing aircraft generate lift and control forces through relatively static components of the airframe, such as wings, flaps, and stabilizers. Rotary wing aircraft must generate these forces through the constant rotation of large components about the fuselage. This necessary rotation creates the conditions for introduction of numerous points of system interaction with causes of vibrations. At each of these points an imbalance in mass or

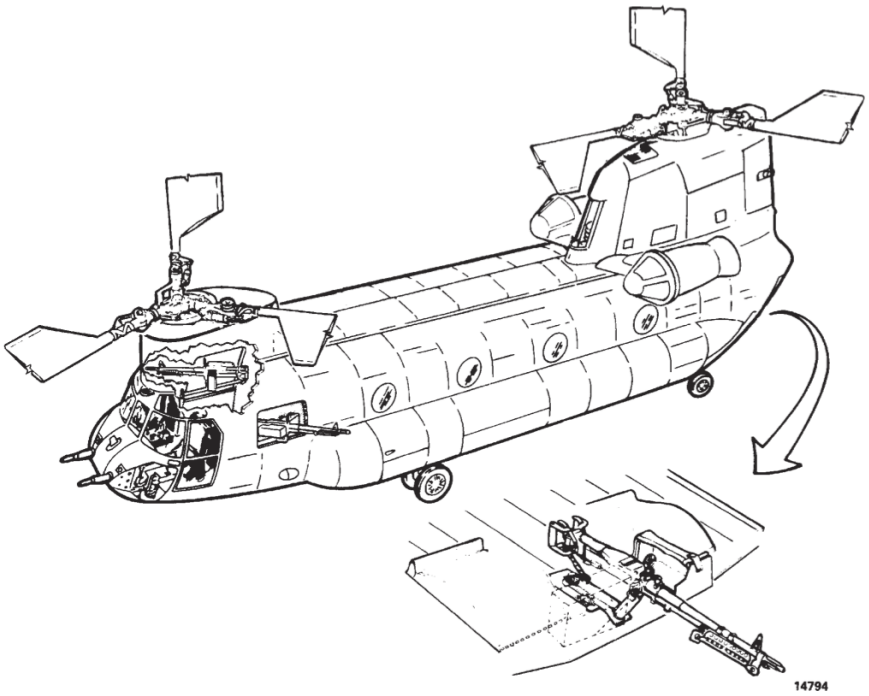

Figure 2.1: CH-47D Chinook [8]

aerodynamic forces will subsequently be experienced by the airframe and aircrew as a periodic oscillation, better known as a vibration.

One of the most basic equations for vibratory motion relates the mass M, stiff - ness K, damping C, and external forces F of a system; where M, K, and C are matrices of values for the appropriate elements representing the system. The force F is a matrix of the forces applied to the system. The equation [9] is expressed as:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = [F] \tag{2.1}$$

The value $\{x\}$ in Equation 2.1 is the dependent variable for displacement. To maintain equilibrium in the equation, the reader can see that any change to one variable will result in changes to the dependent variable. For example, a change in force $[F]$ will necessitate changes to the values of $\{x\}$, assuming $[M]$, $[C]$, and $[K]$ to be constant. Those new displacements are at the heart of the vibrations experienced by the aircraft. In the same manner, if the forces stay constant but a change in displacement is indicated then there must be a change to one of the matrices on the left side of Equation 2.1. These changes in mass and/or stiffness are detected by the health and usage monitoring systems discussed in this thesis.

2.2.1 Aerodynamic Imbalance. Vertical vibrations, as experienced relative to aircrew and fuselage, can be encountered due to aerodynamic imbalance. In a multi-blade rotor system a single blade generating lift significantly different from the other blades in the rotor system will generate a vertical force difference of a harmonic nature as the blade rotates about the rotor shaft. The change in lift generated could be due to several factors, such as blade pitch or airfoil shape. Blade pitch is usually set relative to the rotating swashplate through an adjustable pitch link (PL), shown in Figure 2.2. A misadjusted PL would create a greater or lesser pitch angle on a single blade resulting in a higher or lower angle of attack and resultant aerodynamic forces. Rotor blades with differing aerodynamic twists would also result in vertical

vibrations as sections of the blade in question produce aerodynamic forces out of sync with the other blades. Finally, many rotor blades utilize trim tabs on the trailing edge of a portion of the blade; see Figure 2.3. These trim tabs are used to make very small airfoil shape changes to a blade to alter the resultant aerodynamic forces. A trim tab bent to an inappropriate position would result in aerodynamic forces being created on that particular blade which would not be harmonious with the forces created by the other rotor blades.

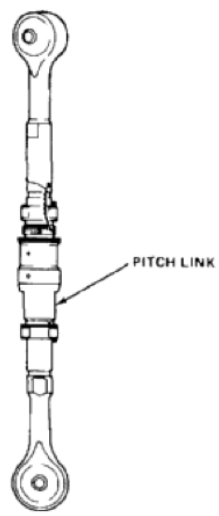

Figure 2.2: CH-47D Pitch Link [10]

The rotating airfoils of a rotor system experience aerodynamic imbalances in non-hovering flight. Rotor blades transitioning into the direction of flight path (advancing) will experience higher aerodynamic velocities than blades progressing away from the direction of aircraft movement (retreating). This difference between advancing and retreating blades creates one example of an aerodynamic imbalance. Recalling basic aerodynamic principles of lift and drag, we can visualize that as the advancing blade experiences higher relative airflow and lift, an increase in drag will also be experienced. Conversely, the retreating blade will experience less drag. In an articulated rotor system the difference in drag between these opposing blades creates conditions in which the blades attempt to shift relative position within the rotor disc. A basic representation of this imbalance can be seen in Figure 2.4.

As the blades attempt to shift, the sum of the mass of the blades will progress to an imbalanced state relative to the rotational disc area. Such an imbalance results in a vibration experienced by the airframe which is often referred to as a lateral vibration as it is typically felt in the lateral direction relative to the long axis of the aircraft.

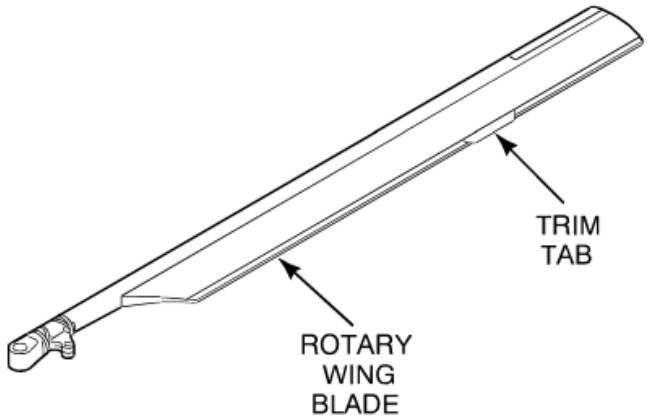

Figure 2.3: CH-47D Rotor Trim Tab [10]

Several methods are utilized to prevent this imbalance. Mechanical dampers filled with a viscous and pressurized fluid, commonly referred to as lag dampers, link the rotor blades to the rotor hub and attempt to minimize this out-of-balance condition. Blades are also allowed to rotate in the vertical plane at varying amounts due to the differential lift. This rotating action is known as flapping and requires the use of a flap bearing. This flap bearing and the lag damper are both potential sources of vibration if they are not performing to required specifications.

These same aerodynamic conditions can apply to hovering flight in high relative wind conditions. Blades advancing into the wind will experience the same conditions as if the helicopter were moving in that direction, just as blades retreating relative to that wind will experience the reduction in lift and drag.

2.2.2 Mass Imbalance. This same out-of-balance condition can be experienced for nearly identical reasons though with a different underlying cause; a mechanical cause could also create an out of balance condition within the plane of the rotor disk. Using the first example as an illustration, it can be seen that aircraft

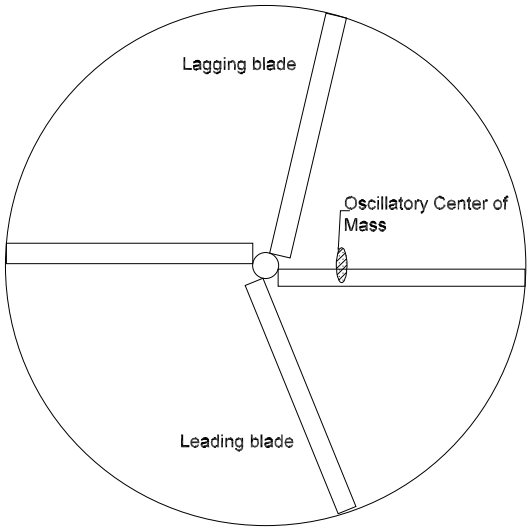

Figure 2.4: Rotor Mass Imbalance

manufacturers and operators seek to utilize rotor blades of nearly identical mass for the rotor system of an aircraft. During normal operations these blades can be affected by dust, debris, or other external sources of damage which alter the mass of one or more blades resulting once again in mass imbalance in the rotor system. The mass imbalance creates a lateral vibration very similar to that experienced by the aircrew when a damper is faulty in an articulated rotor system.

2.2.3 Vibration Corrections. Making a definitive determination of the cause of these vibrations for corrective maintenance action can be tricky due to the multiple components which are potential generators of these vibrations. The corrective actions become time consuming and often result in the replacement of numerous components in the search for a cure. In the case of a misadjusted PL, one potential corrective action is to adjust all the PLs. In such a case the underlying cause of the vibration was not found, but rather a process was enacted which compensated for the source of vibration. In all cases, the aircraft operators have experienced reduced aircraft

readiness rates and aircraft maintainers have potentially replaced many components which did not need replacement. Such instances are fiscally inefficient and in the case of emergency services or armed forces aircraft the results can directly impact lives.

Concurrent with these actions to directly address faults in the rotor system are time-based actions which indirectly address rotor system faults. Utilizing inspections and historical averages of component failure determined during development, testing, and operational usage, aircraft components are given lifetime limitations based on in-service time. This in-service time is usually identified by either calendar periods or periods based on flight time of the airframe and its components. Due to the critical nature of the components in a rotary wing aircraft, the safety margins for component replacement must be sufficiently large to ensure a minimum possibility of component failure during operational use. Large safety margins necessitate that nearly all components are replaced well before failure, hence while still possessing the capability for useful service. This early replacement introduces additional inefficiencies to the process of aircraft maintenance and scheduling.

2.3 Condition Based Maintenance

Recognizing this fiscal inefficiency and reduction in readiness, the Department of Defense directed in 2003 [1] that efforts based on the principles of Condition Based Maintenance (CBM) be instituted. CBM is a proactive form of maintenance which relies on forecasted maintenance action requirements. In order to forecast maintenance actions, the current condition of components must be monitored in a real-time or near real-time manner using embedded sensors and other component monitoring devices [2]. As Butcher notes, CBM can be defined as maintenance performed only when objective need is validated, while also ensuring equipment reliability, safety, and reduction of total ownership costs [2].

One notable philosophical difference between traditional time-based maintenance practices and CBM is the realization that not all flight sorties stress an aircraft in a similar manner. A ferry flight between two points at a cruising altitude will place

much less stress on aircraft components than an aircraft flying in the terrain flight environment utilizing rapid and significant power changes and maneuvers eliciting a greater dynamic range of response from the rotor system. Thus flight time is not necessarily an accurate gage of component health, as the actual conditions of usage are far more important. Condition Based Maintenance relies on the physical properties of components to indicate signs of wear rather than relying on only the amount of flight time in which a component has been in flight. A component which has less severe usage than predicted in its design should experience a longer service life [11] and require maintenance less frequently than would be scheduled using traditional methods.

Monitoring the condition of components through CBM is also being linked to the supply management system to allow greater efficiency in parts availability and purchasing [12]. Through this monitoring of the components, maintenance actions can be scheduled [2] and aircraft availability can be planned in advance. Without monitoring of component condition, maintenance actions would be performed only once components reach a pre-determined lifespan or once components fail. In order to conduct unplanned maintenance, a large inventory of parts must be maintained which drives up costs of ownership [2]. More maintenance personnel are also needed to conduct unplanned maintenance as personnel must be available and prepared to conduct a wide range of maintenance actions over a broader period of time. For military applications, this also means larger transportation requirements to distant areas of operation which increases the maintenance requirements on the vehicles transporting all these parts. The larger parts inventory on hand and greater numbers of personnel in turn demand larger ships and bases to store these quantities of parts and house these personnel. Larger forward operating bases require more personnel to secure and operate them, again feeding into this growing requirement. When viewed in this manner, the higher order savings from CBM begin to be understood.

As has been stated, in order for CBM to work there must be a means of monitoring the actual condition of the aircraft components. The systems designed to ac-

complish this goal are referred to as Health and Usage Monitoring Systems (HUMS). Monitoring of the components is accomplished through the use of various temperature sensors and accelerometers mounted throughout the aircraft. Data from these sensors are measured and recorded by computer systems installed aboard the aircraft or ground monitoring station as part of the HUMS package. Using a variety of computational methods, the results of the data are used for later analysis and for real-time fault indication to the aircrew. Many HUMS installations are now streaming live data to maintenance personnel on the ground.

The benefits of CBM are becoming apparent to planners and leaders operating rotorcraft fleets. For the US Army, HUMS and CBM have been credited with a 30 percent reduction in mission aborts, a 5 to 10 percent reduction of scheduled maintenance, and a 20 percent reduction of maintenance test flights [7]. With these results in mind, the Army recently determined to install HUMS [7] in all the service's rotary-wing aircraft. Eurocopter has also noted benefits of HUMS [13], including a 60 percent reduction in maintenance test flights and a 20 percent reduction in unscheduled maintenance actions.

The Goodrich Integrated Mechanical Diagnostics Health and Usage Management Systems (IMD-HUMS) has been installed in a number of aircraft to include H-47 (Chinook), H-53, and H-60 aircraft in both Army and Naval aviation. In the Goodrich IMD-HUMS systems, analysis of the vibration data results in Condition Indicators (CI) which are used in sets to form a broader Health Indicator (HI) used by aircrew and maintenance personnel. These condition and health indicators are used for both in-flight health monitoring, such as for swashplate bearings, as well as for use by maintenance personnel between flights. Data obtained through flight measurements is compared to known faults for updates to thresholds of health indicator limits [11].

Also providing a HUMS system to the US Army is Intelligent Automation Corporation (IAC). Together with the US Army, IAC developed the Vibration Manage-

ment Enhancement Program (VMEP) which has been installed on aircraft such as the H-47, H-60, and H-58 to monitor drive train dynamic components [11]. Like the Goodrich system, the IAC system consists of an on-board computer which collects and evaluates in-flight vibration information as well as ground-based software to display information to maintenance personnel. The IAC system also contains web-based infrastructure tools [11] which allow data storage and analysis at off-site locations. Data from the VMEP continues to be collected and compared to known faults.

In the United Kingdom, Smiths Aerospace has developed the Generic HUMS (GenHUMS) which has been installed on UK Chinook aircraft [11]. The GenHUMS includes powertrain and gearbox diagnostics [11]. The UK Civil Aviation Authority (CAA) has a long history leading the CBM field and lends support to Smiths Aerospace in researching the behavior of aircraft components to determine normal versus abnormal patterns of component characteristics.

Honeywell also builds health usage systems for aircraft such as the Sikorsky S-76 [13]. Like other HUMS, the Honeywell VXP HUMS uses on-board sensors and processors to monitor and evaluate vibration data for aircrew and maintenance personnel use. Honeywell is working to integrate HUMS with cockpit voice and flight data recorders and transmit the total data package to ground monitoring stations. Such an application clearly has significant safety implications.

2.4 Research

Clearly the key to successful CBM lies in the determination of the condition indicators. When determining condition indicators, a balance must be struck which limits the rate of false alarm indications while maximizing successful determinations of faulty components. Since the CIs are determined across a fleet of similar aircraft and not for individual aircraft, some variance must also be allowed for specific differences between airframes and environmental conditions.

Research to utilize vibration data to create useful information has progressed far in the last decade. A first step in analyzing vibrations is to understand the underlying mathematical governing equations and be able to simulate the conditions necessary. Fries conducted such work in the early 1990s by considering aerodynamic forces and moments using blade element theory [14]. Using basic theory previously determined by other researchers [14], the aerodynamic forcing functions were separated into individual harmonics in order to link frequency filtering from individual blades into the fuselage and to determine physical parameter contributions to the aerodynamic forcing functions. The harmonic forcing functions derived by Fries were used to calculate the aircraft's dynamic response and the vibrations experienced in the cockpit, in this case the cockpit of a UH-60 Blackhawk. Fries computer code also modeled the fuselage as a rigid frame structure. To simulate damaged rotors, blade sections were reduced from the tip creating an unbalanced rotor. In this work, the computer models calculated short term effects after the simulated damage was introduced to the system. While limited in scope, this research was useful to demonstrate the valuable data which can be modeled and determined using modern computing methods.

As the concept of Health and Usage Monitoring Systems advanced, the US Army and South Carolina National Guard developed the Vibration Management Enhancement Program (VMEP) in conjunction with Intelligent Automation Corporation. This program developed an automated vibration monitoring and set of diagnostic tools [6]. Basic vibration related HUMS functions [6] were integrated into VMEP with the primary purpose of improving the rotor smoothing process. VMEP also provides for drive train diagnostics through accelerometer measurements provided by measurements on transmission, high speed inputs, auxiliary drives, tail-rotor drive shaft hanger bearings, and intermediate and tail-rotor gearboxes [6]. Grabill notes that classical machinery monitoring algorithms are used to isolate the specific drive train faults. General vibration surveys can also be taken to help diagnose unexpected vibrations sometimes encountered. The VMEP system uses two types of accelerometers: a larger cylindrical sensor often referred to as the "spark plug type" and a

bracket type which can mount to flanged surfaces. Additionally, an optical sensor is used for rotor blade tracking allowing measurements from the accelerometers to be correlated to specific blades. Standard main and tail rotor tachometer inputs are also utilized. Rotor smoothing is accomplished by the VMEP ground based station using a neural network based algorithm [6]. Users are able to interact with the software to view and edit the predicted vibration response during rotor smoothing. By using instrumented hammer impact testing and ground run data, resonances for sensor locations could be observed and filtered or amplified as necessary to highlight possible vibrations emanating from gears or bearings. At the time of Grabill's paper, only the initial Blackhawk and AH-64 Apache installations had been completed, but with further installations on the horizon the researchers were confident that higher fidelity condition indicators could be determined as additional VMEP data was acquired.

Research continued on these instrumented aircraft with further work published by A. I. Cuc in 2002. With vibration data available for analysis, experimentation with methods of analysis could be conducted. Traditional Fourier transform are still used, however Cuc used two other methods [15] to analyze cracked components: Short Time Fourier Transform (STFT) and Wigner-Ville Distribution (WVD). The results of these methods were both successful in accurately predicting faults. The STFT method provided better indication of higher harmonics of the main frequency due to crack growth [15] while the WVD method provides stronger sensitivity to crack presence. Cuc found the WVD method to predict crack growth more accurately than STFT.

Research into threshold indicators also continued during this time period to improve false detection rates while continuing to provide reliable fault detection [16]. Statistical methods which modeled variance and sampling theory were used to improve the robustness of condition indicators. The researchers assumed a Gaussian distribution of faults and a sampling of known good aircraft to set thresholds for fault detection. To reduce false detections, several CI are calculated per component and brought together to create a health indicator [16]. Such statistical methods provide

another useful tool to HUMS which can lead to greater responsiveness and accuracy in condition based maintenance.

Statistical methods were also explored by Cox [17] using the VMEP data acquired. Using neural networks and classification trees methods to analyze and compare vibration data to maintenance data [17], Cox looked for time series data which rapidly diverged from expected norms. Cox found that the classification trees method did not provide useful results however neural networks did show promise in predicting failures for a flight [17]. The research did not result in an ability to predict individual component failures from vibration data but could be used toward improving maintenance cycles. Cox recommended that additional research be conducted and applied to predicting failures of individual components.

However in 2006, Willard and Klesch [18] also conducted classification trees and logistic regression HUMS research using UH-60 generators for comparison. Using the condition and health indicator history, predictions of impending generator failure could be accurately made. This research was important to validating the threshold limits of CI and HI, but did not relate directly to determining those CI and HI from the vibration data.

In 2005 B. Wu et al published vibration monitoring research specific to gearbox components. While the work of this paper will focus on components of the rotor system, the methods of analyzing gear faults could be beneficial to a wider range of components. To reduce computational time, Wu et al used Harmonic Index in the frequency domain and Intra-Revolution Energy Variance in the wavelet domain to differentiate planetary gears with and without faults rather than traditional time synchronous averaging methods [19]. Using feature extraction from these techniques, the researchers determined that these methods can predict planetary gear failure with the same accuracy as time synchronous averaging techniques.

When determining rotor smoothing adjustments, linear mapping algorithms have been applies to the process. The assumed linear nature of the adjustment pro-

cess was questioned and researched by N. Miller in 2006. Applying neural networks to determine if non-linear mapping could provide a more accurate set of blade adjustments during rotor smoothing [20], Miller determined that traditional linear mapping solutions are a correct assumption and that non-linear mapping coefficients do not provide an improvement over these linear techniques. The validation of this linear assumption allows the research of this paper to utilize the linear methods incorporated into RCAS knowing that the methods will not adversely or inaccurately bias the results which model the aircraft behavior.

Specifically investigating tail rotor drive shaft and engine input shaft vibrations, Avila et al determined that prognostication of vibrations could be accomplished using discriminant analysis techniques [21]. This method of analysis used the difference between measurements from a real system to outputs of a mathematical model to make predictions. Discriminant analysis was found to have very good false positive rates of less than 10% , indicating very good ability to predict no increase in vibration when no increase actually exists. A higher rate of false negative (no prediction of increased vibrations when such an increase did occur) was found using this method, though Avila et al note that more research will be needed to improve the false negative rate.

Again using data from helicopter transmissions, Dempsey et al [11] continued to refine the process of determining CI and HI thresholds. With current time-based and limited condition-based maintenance, component failures on operating helicopters are necessarily limited. In order to accurately set CI and HI thresholds, models used in determining these thresholds must provide a high degree of correlation to the limited data available from real world component malfunctions. Dempsey et al were able to show that the method of Receiver Operating Characteristic curves can be used to assess HUMS condition indicators [11]. For the analysis, the research utilized data from UH-60 oil cooler fan bearings, tail gearbox output gear and main gearbox bevel gear as well as AH-64 hangar bearing and nose gearbox bearings.

Hasty et al published work in 2008 which built upon the knowledge of VMEP and several other HUMS installations to improve coefficients currently in use by the U.S. Army's Aviation Vibration Analyzer (AVA) [22]. The AVA system has been in use by the Army since the early 1990s and has been the predominant system used to perform track and balance adjustments to the CH-47 aircraft. Sensitivity coefficients inherent to AVA provide suggested maintenance actions to reduce vibrations in the rotor system and aircraft. The coefficients are based on a limited sampling of aircraft [22], which may play a role in the relative difficulty in balancing the CH-47 rotor system. Hasty et al used the large amount of data available to current researchers to refine the AVA sensitivity coefficients in order to provide a more efficient means of balancing the CH-47 rotor system. If the simulation models being constructed in this paper are successfully built, their performance will be compared to the updated AVA coefficients determined by Hasty et al for accuracy of the models.

Building upon the work of these previous authors, the methods used to determine accurate models and comparing those models to vibration data gathered from operating aircraft can be used to research a greater variety of faults found in rotorcraft. Several authors have conducted research into drive train bearings and gearbox faults; research has also been conducted to determine the accuracy of models which determine vibrations in the rotor system. More recently, research has determined a means to accurately relate model predictions to limited field data. Knowing that the linear model for rotor smoothing is indeed accurate, and that the Receiver Operating Characteristic curves can correlate limited vibration data from field tests [23], we can expand our models and predictions to other common vibration problems encountered in rotorcraft to predict impending faults from vibration data gathered through HUMS. The research of this paper seeks to create computational models which accurately portray the vibrations in the CH-47D resulting from additional mass added to a rotor blade or combination of blades, the vibrations resulting from pitch links not set to an optimal length, and vibrations resulting from rotor trim tabs which are out of proper alignment.

III. Methodology

3.1 Overview

Introducing faults into a full-scale flying aircraft for investigative purposes is expensive, laborious, and can be dangerous. For this reason computational models are an effective and safe way to explore variations in aircraft design and response. The models may differ in detail, but ultimately these details will determine how effectively the models represent the actual behavior of the aircraft.

3.2 Rotorcraft Comprehensive Analysis System

The Rotorcraft Comprehensive Analysis System (RCAS) was developed jointly by the U.S. Army Aeroflightdynamics Directorate (AFDD) and Advanced Rotorcraft Technology, Inc. (ART) [24]. The system is exactly as it sounds; a computational analysis tool available to Government and Government-approved industry and academia to research a wide range of topics such as vehicle performance, aerodynamics and rotor loads, vehicle vibration, flight control analysis, aeroelastic stability, flight dynamics, and flight simulation. RCAS grew out of the Second Generation Comprehensive Helicopter Analysis System (2GCHAS) and provides improved computational efficiency, improved user interface, the capability to compute large motion maneuvers, and an interactive development environment [24].

RCAS is a hierarchical system where the user brings modeling elements together to build complex models. The elements consists of items such as nodes, hinges, rigid bars, non-linear beams, airfoil representations, and analysis commands. The model is arranged into two distinct categories: physical data and analysis data. Physical data are entries which describe the structure of the model, the structural and aerodynamic properties of the model, the control system, and drivetrain data. Analysis data provides parameters for the interaction and iterative calculations of the physical and aerodynamic data. Structurally, the model is composed of subsystems which are composed of primitive structures, which are in turn composed of primitive elements. This relationship can be seen in Figure 3.1.

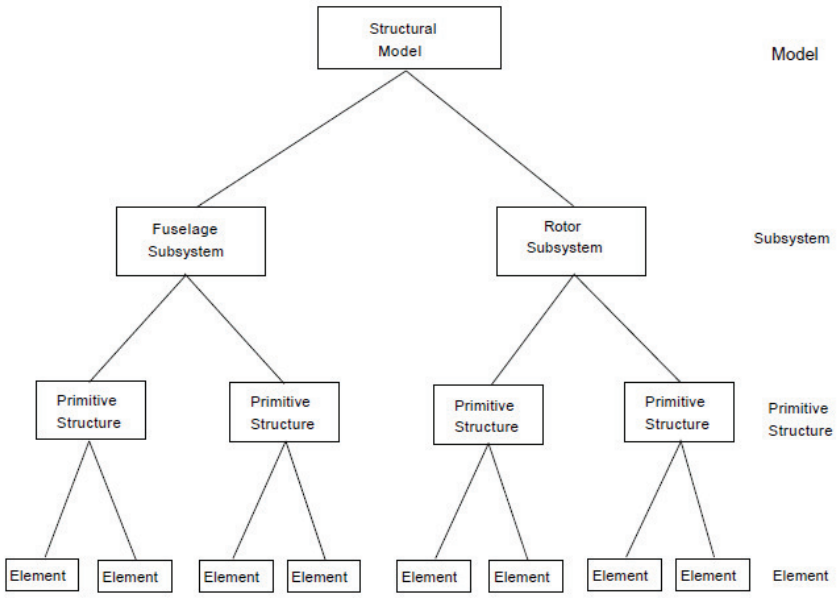

Figure 3.1: RCAS Physical Model Hierarchy [24]

Aerodynamically, the model is defined in a similar manner. Aerodynamic subsystems of the model are called supercomponents. The supercomponents are composed of aerodynamic components which are linked to primitive structures defined in the structural model. The aerodynamic components are defined by aerodynamic segments; see Figure 3.2. The aerodynamic model addresses the aerodynamic surfaces, the structure of the supercomponents, the connections to the structural model, and offers choices for representing the airloads, induced flow fields and wakes, and aerobodies, as well as interference between components [24]. Aerodynamic model data also defines the manner in which the aerodynamic model is connected to the structural model. For control system analysis and engine/drivetrain analysis, models defined by data related to that analysis would also be defined. For this research, neither control system nor engine and drivetrain analysis were conducted. Options for type of aerodynamic inflow calculations are also provided in the analysis section.

The researcher may determine to model inflow as no inflow, uniform inflow, or varying inflow models up to free wake conditions.

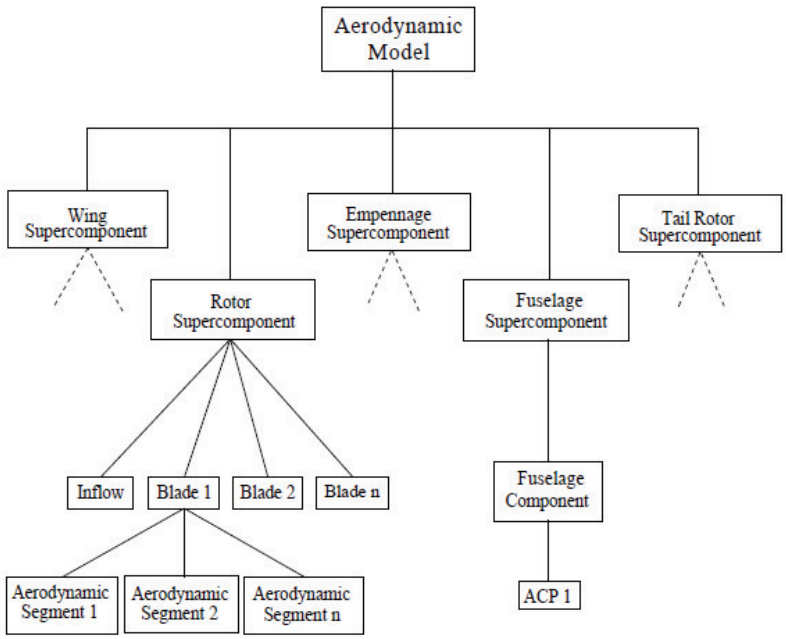

Figure 3.2: RCAS Aerodynamic Model Hierarchy [24]

Analysis data of the RCAS model refers to the type of analysis, such as trim or maneuver, as well as how that analysis is to be performed through numerical methods. Another option in the analysis data is the ability to run multiple cases of a model by varying defined parameters. Solutions in RCAS are derived largely through iteration, therefore iterative tolerances for the solution are also defined in the analysis section.

Forces are transmitted within structures via nodes and elements, such as rigid bars, springs, dampers, hinges, or slides. Slides are a structure which allow movement in one coordinate direction only. Assembling the elements together is geometrically exact and all elements are geometrically exact with the exception of nonlinear beam elements.

The RCAS model is defined through menu navigation and entry to screens. In the models found in Appendix A and B, these screens are delineated by the letter 'S' prior to the screen name. For example, the line S CONTROLMIXER notes that the menu screen for control inputs and relationships is to follow. The RCAS user can navigate through the user interface menu structure and screens to build a model, or may build a model using a text editor to create a script file. Due to the large number of entries made to create a working model, the script file method is the most common and is used in this paper, as seen in Appendix A and Appendix B.

In order to fully understand the code found in the appendices, the reader should be aware of some elements of RCAS syntax. For the following RCAS commands which are utilized in the appendices and throughout this paper, only the first letter of the RCAS command is necessary for the RCAS software to recognize the necessary command; RCAS is not sensitive to letter case.

SCREEN As noted above, defines a data entry screen command where the argument after the 'S' or SCREEN denotes which data entry screen to apply the subsequent commands and data.

NEXT The next data entry screen of a multi-screen entry is presented for entry.

! Instructs RCAS to ignore input beyond this character for the data entry stream. This is the most common way of providing comments within the code. This is also the preferred means of deactivating a line of code in this work. For the remainder of this paper, the terms 'active/activate' and 'inactive/deactivate' refer to use of this character within the script files of code.

ADD This command enters or replaces entries into a data entry screen.

CHANGE This command allows changes to be made to data entry screens. This can be very useful for changing partial entries in the model script file while retaining different experimental values or approaches to problem solving.

3.3 The Baseline CH-47D Model

A baseline model of a CH-47D rigid body fuselage and fore/aft rotor systems analyzed in a prescribed wake condition was obtained from the sponsors of this research at the U.S. Army Aviation and Missile Research Development and Engineering Center (AMRDEC) . The physical shape of the rotor hubs and their relation to the pylons and fuselage are seen in Figure 3.3. Each is represented by a finite element model where nodes are identified relative to a reference coordinate system and connected by various elements. In this model, blade weights are invariant as are pitch link lengths and trim tab angles. The model was built in a script file following the pre-defined screens and pathways of RCAS. The model is oriented to a global coordinate system in the screen GFRAMEORIG where the model reference node is attached to the global reference system and active degrees of freedom are entered into the model parameters. The CH-47D model in this research is attached to the global frame at the center of gravity and is free to translate in the X, Y, and Z direction and rotate about all three axes. Origins for each subsystem are defined relative to the reference node which is the center of gravity of the aircraft. A computer aided design (CAD) drawing of the structural model which was created in AutoCAD can be seen in Figure 3.4.

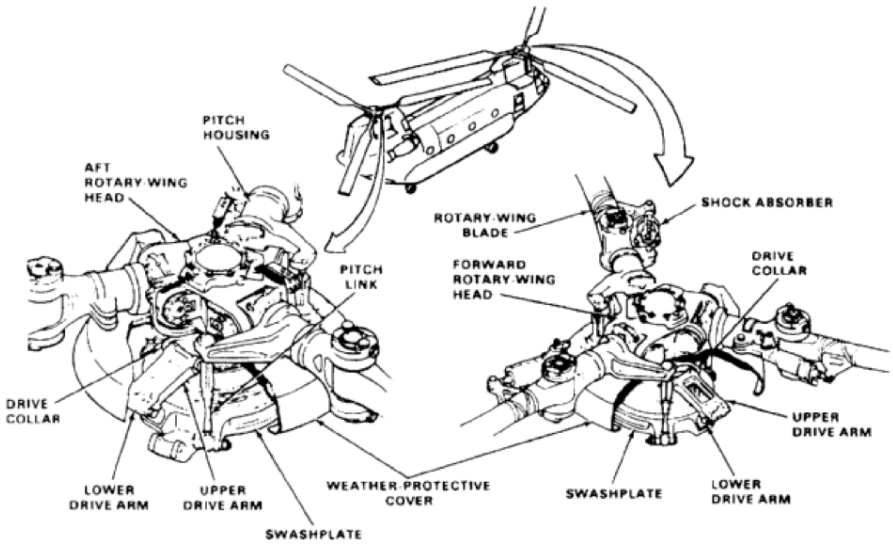

Figure 3.3: CH-47D Rotor System [8]

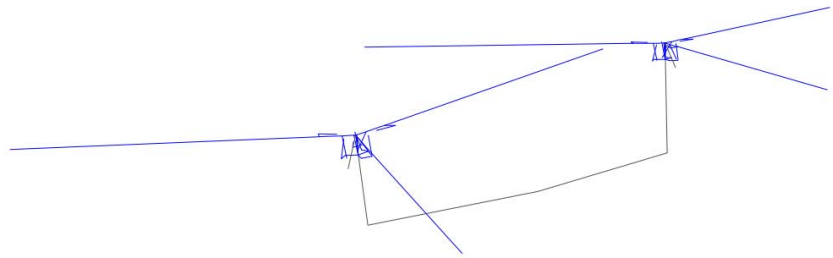

Figure 3.4: CAD Representation of the CH-47D Structural Model

Control inputs to the rotor systems were next defined in the CONTROLMIXER screen. Coefficients representing collective and cyclic position relative to the the rotor system are entered as well as inputs to the collective, lateral cyclic, and longitudinal cyclic position for the flight condition to be modeled. In the screen CONTROLMIXER of Appendix A and Appendix B the six inputs to the forward and aft rotors are seen in control IDs one through six. The additions to the control inputs will be explained in the next section. Rotating and non-rotating subsystems are connected in the ROTNONCONST screen. In the models it can be seen that the forward rotor center node 30 is connected to the fuselage node 3, while aft rotor node 30 is connected to fuselage node 5.

```
S CONTROLMIXER
! Input pilot stick movement to swashplate pitch
! Control Value at zero   ------ Coefficients for Pilot Control -------
!  ID     pilot control    Coll.     Lat.     Long.      Pedal    Throt
a   1         0            .389       0       -0.119      0        0
a   2         0             0       -.400       0       -.666      0
a   3         0             0         0         0         0        0
a   4         0            .389       0       -0.119      0        0
a   5         0             0       -.400       0       -.666      0
a   6         0             0         0         0         0        0

S ROTNONCONST
!              Non-rotating                      Rotating
! Cnstr.  Subsystem Primitive  Node      Subsystem Primitive  Node
!  ID       Name      Name      ID         Name      Name      ID
```

```
a  1       fusrigd     fuseps    3        rotorf   blade1f     30
a  2       fusrigd     fuseps    5        rotora   blade1a     30
```

3.3.1 Structure Model. The fuselage subsystem is now defined in greater detail. The primitive structures which constitute the fuselage subsystem are defined, their origin defined and orientation to the global frame defined. The fuselage model is very simple, containing rigid bars originating from the aircraft center of gravity. The primitive structure is created by first defining the nodes in screen FENODE, then linking to properties at that node in screen RBMELE, and finally connecting the nodes in screen RIGIDBAR. The property ID noted in RBMELE will be defined later in the model. An example of these sections of code:

```
S FENODE
!  node ID,   X,       Y,       Z
A      1      0.0      0       0.0
A      2     19.879    0       0.0
A      3     21.013    0    -7.1598
A      4    -18.7046   0    -1.2333
A      5    -17.8775   0   -11.8275

S RBMELE
! Generate rigid body mass element for fuselage mass & hub mass
! ELID,  node ID, prop ID
A    1      1       1
! Hub masses added at enode
A    6      3       2
A    7      5       3

S RIGIDBAR
!!  Element  Node1  Node2        Center of gravity offset
!!    ID      ID     ID        X            Y            Z
a     2       1      2         0            0            0
a     3       2      3         0            0            0
a     4       1      4         0            0            0
a     5       4      5         0            0            0
```

Each rotor system was based around a single defined blade using the SINGLE-BLADE screen which uses the resulting analysis of a single blade to represent the three bladed rotor. The original CH-47D baseline model utilizes this single blade analysis option to reduce computational time. As with other primitive structures, the frame origin and orientation of each primitive structure must be defined and connectivities of the primitive structures to the subsystem must also be defined. These relationships are found in screens PSORIGIN, PSORIENT, and CONNCONST, respectively. The rotational speed of the rotor subsystem will also be defined in this section. Data sets containing properties of the primitive structure are defined by the screen ELDATASETID associated to the particular primitive structure. Multiple primitive structures may reference the same property data set if those structures are intended to have identical properties in the model.

The layout of the primitive structure is defined in a similar manner as the subsystems such as the fuselage, by defining nodes which reference the coordinate system of the subsystem in screen FENODE and then the elements which connect those nodes. The connecting elements can be a variety of connections, such as springs, dampers, hinges, rigid bars, elastic bars, or elements known as slides. The latter is an element which allows motion in one degree of freedom; the motion can be controlled or represented by spring or damper coefficients. Non-linear beam behavior may be modeled at this point for the blades using screen NLBEAMDEF. Finally, in screen CONTROLCONNECT the inputs defined by the screen CONTROLMIXER will be related to specific elements of the subsystem. In the baseline CH-47D model, the control connections can be seen between the swashplate and the collective input, swashplate lateral cyclic input, and swashplate longitudinal cyclic input.

```
S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                 53
a    2       SPLATR         0.0           HIN                 53
a    3       SPLONG         0.0           HIN                 53
```

From a central rotor hub node, rigid bars were used to model the lower swashplate nodes for pitch link attachment. Additional nodes represent the attachment points for the lag dampers. Spring and damper elements allow the model to mimic the behavior of lag dampers. The reader may note that the pitch links are modeled as a spring element with a very high stiffness; this spring element at this location aids in accurately modeling the inherent flexibility of the materials and bearings which comprise the actual rotor system. Vertical and horizontal hinge elements represent the vertical and horizontal hinge pins of the rotor. The blade is then defined as a series of nodes connected by nonlinear beam elements which refer to proprietary Boeing data tables.

The next major section of the model defines properties for subsystems. Mass, non-linear beam properties, material properties and mode shapes are defined or a reference to a data table is provided. The element properties are repeated because the individual components may be assigned unique element properties in the modified experimental code.

3.3.2 Aerodynamic Model. The aerodynamic model begins by listing the supercomponents which will comprise the aerodynamic model using the screen AEROMODCOMP. The origins of the supercomponents in relation to the global frame are defined for each supercomponent and the orientation of the supercomponent is defined.

```
S AEROMODCOMP
! List of Supercomponent of the system
a   fusead
a   adrotorf
a   adrotora

S SCORIGIN
!  Supercomponent          Origin Coordinates
!       Name          x            y            z
a   fusead           0            0            0
a   adrotorf         21.013       0          -7.1598
a   adrotora        -17.8775      0          -11.8275
```

```
S SCORIENT
! Supercomponent   rotation 1        rotation 2        rotation 3
!       Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   fusead          2       0         0       0         0       0
a   adrotorf        2     171         0       0         0       0
a   adrotora        2     176         0       0         0       0
```

Airfoil look-up tables are also defined in this section. Remaining at the higher level of model definition, the aerodynamic interference options are selected in screen INTERFERENCE. Aerodynamic interactions can be selected between the two rotors and the fuselage, such as forward rotor to aft rotor interference, forward rotor to fuselage interference, and fuselage to forward rotor interference. In all, six interference options were activated for this research. The individual aerodynamic supercomponents are then defined in more detail for the model. The structural subsystem to which the aerodynamic supercomponent is associated is defined in screen SUPCMPTOSS, if necessary such as the case of the fuselage. Additional details such as supercomponent type, origin, and orientation defined in the subsequent screens of SUPCMPTYP, COMPID, CPORIGIN, and CPORIENT. The type of aerodynamic inflow is defined as well as dynamic stall options, if applicable. Wake properties for the supercomponent, such as the forward rotor, are defined before proceeding to define the aerodynamic segments of the supercomponent in more detail.

Aerodynamically, the blade is represented by aerodynamic segments which define chord, width, twist, and aerodynamic properties proprietary to the manufacturer. The aerodynamic nodes are defined in the screen AERONODE, followed by the aerodynamic segments which will connect between these nodes in screen AEROSEG. The segments define chord length as well as a reference to a data lookup table for airfoil properties of that section, as well as the amount of rotor blade twist which that segment experiences. The code looks similar to the following:

```
S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
```

```
a     1          6.00000      0.0          0.0
a    11         20.00000      0.0          0.0
a    12         20.00000     -0.026042   -0.000341
a    15         22.50000     -0.026042   -0.000115
a    16         24.00000      0.0          0.0


S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2      2.2704     VR7TM4P5    0     X.XXXX
a  2       2        3      2.6667     VR7TM4P5    0     X.XXXX
```

The baseline CH-47D model obtained from AMRDEC included additional model data in the form of fuselage airloads which were referenced immediately prior to the Analysis Data section. This additional model data was included through the RSCOPE model 'WORLD_MODEL_FUSRIGD_ FUSEPS_FALOADS1_ALCOORD'.

3.3.3 Analysis Data. The analysis section begins with the screen SEL-ANALYSIS where the type of trim analysis must be defined. A trimmed flight condition for a fixed set of control inputs results when using the 'Trim' option selection. If using a periodic solution, the control inputs will also vary to meet required tolerances defined in the analysis section. Multiple cases may be run within a single run of a model; these cases are identified in the subsequent screens which define the case title, the screen and data entry to be altered for a particular case, and the new values of the data entry. Initial conditions are defined for control inputs and for position and velocity of the model frame to the inertial frame. If a wind effect on the model is to be experienced, such as in forward flight, this will be noted in the screen CONSTWIND. The manner in which iterations are performed and to what tolerances are defined in the screens which follow CONSTWIND. Finally, output analysis file types and names are defined. Much of the work of this thesis was conducted in the analysis section of the script file and will therefore be explained in greater detail in the following section.

3.4 Modifications to Baseline CH-47D Model

Work began by first making changes to the supplied model which would be common and required for all cases of modeling. To implement a fault in a single rotor of the six-bladed aircraft, the forward or aft rotor would need to be defined for analysis purposes as three distinct blades rather than single blades copied to represent the remaining blades. This was a relatively simple modification to the baseline model since much of the necessary definitions was supplied but inactive. Removing the comment syntax activated these multiple distinct blades in the rotor subsystem; however, the data tables and structural definition of each primitive structure needed to be created by copying the definitions of the existing blade to create, and relabeling the copied definitions as a new primitive structure with a distinct label. To do this, the screens for PRIMITIVEID, ELDATASET, PSMODALDAMP, FENODE, SPRELE, DMPELE, HINGE, RIGIDBAR, NLBEAMDEF, GCBEAMDEF, and CONTROLCONNECT were reproduced under the new primitive for the newly created individual blades. During most of the model testing, only the forward rotor system was modeled in this manner in order to reduce computation times. The final rigid fuselage and elastic fuselage models use distinct rotors for both the fore and aft rotor system in order to provide the ability to input corrections to the system on any individual blade.

The critical data input screens of the CH-47D baseline code which were modified were the following:

```
S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a       blade1f
a       blade2f
a       blade3f

S SINGLEBLADE
!!     Identical Blade      Number of
!!     Analysis Option      Blades
!!         (Y/N)             (2:9)
a           N                  3
```

With these changes the basic Rigid Fuselage Model was created. From this model additional changes to the analysis requirements were made and the means of entering one or more of the three types of faults were added to the script file.

The most time consuming portion of this research was compiling and running a model to determine response. The versions of RCAS available for this research were incapable of parallel processing. Additionally, the software license is linked to a specific workstation, therefore computer clusters at AFIT were not able to be used. In order to decrease the time required for each run of the model, several additional simplifications were made to the model parameters during initial testing of model changes. As already mentioned, the first of these involved reducing the number of blades for which behavior was calculated by utilizing single-blade analysis for only the aft rotor. The next step in model simplification involved numerous changes to aerodynamic conditions and analysis options. The original model supplied by AMRDEC used a prescribed wake condition with parameters previously determined to model inflow through the rotor systems and fuselage environment. This was changed to a condition of uniform inflow through the rotors which would reduce iterative calculations determining blade nodal response. This primarily involved a change to the supercomponent screen INFLOW for each rotor supercomponent.

```
S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a        1
```

With the inflow type changed to option 1, uniform momentum inflow, the supercomponent screens for PRESWAKE needed to be deactivated in order to not be included in calculations. Dynamic stall continued to be modeled with the Leishman methods using separation and vortex shedding. As will be discussed in Chapter 4, it was necessary to later change the dynamic stall condition for some model options.

Additional compilation time reductions were made by changing parameters found in the analysis section of the model code. Since iterations are made to reach a solution which meets the convergence tolerances noted in the model analysis section, these tolerances were relaxed in the screen CONVERGETOL, seen below, for cases where only the functioning of the model was being examined and not the resulting nodal responses. The maximum number of trim iterations were reduced from 40 to 30, and in some cases as low as 20. Displacement translation tolerances were relaxed from 0.002 feet to 0.005 feet, occasionally as much as 0.02 feet. Rotation tolerances were also relaxed from 0.001 radians to 0.01 radians. The intent of these relaxations in convergence tolerance was to reach a solution in less time, while providing solutions of sufficient accuracy to determine nodal behavior and whether changes to the model code were accurately producing expected results.

```
S CONVERGETOL
!# of  # of  # of  -Displacement Tolerance-   -Velocity Tolerance-  Min.
!Trim  PSol  Time   translation  rotation    translation rotation  # of
!Iter  Iter  Step    (ft)         (rad)       (ft/sec)  (rad/sec) PS Rev
a 30    40    72     0.02          0.01          5.0       2.0       5
c 40    30    72     0.002         0.001         0.18      0.09      5
```

With the model simplified to realize shorter run calculation times, changes could now be made to the rigid fuselage baseline script file which would provide the ability to model specific system faults. In order to approximate the HUMS accelerometers in the fore and aft pylons of the CH-47D, an additional node was connected to the fuselage structure near the forward rotor hub and another node near the aft rotor hub. These nodes were connected to the fuselage model using rigid bars connected to the fuselage rotor hub nodes. It should be noted that these positions are not exact representations of accelerometer position, but are approximations made for this research after consulting aircraft drawings and photographs.

```
S FENODE
!  node ID,   X,       Y,       Z
! Nodes added to represent accelerometers of HUMS
A      80    21.813    0    -4.6598
```

```
A       81   -19.7046   0    -9.3275
```

The basic rigid fuselage model was now ready to be tested to ensure that blade and accelerometer nodal displacements remained consistent with the baseline CH-47D model. The foundation was in place for additional modifications to the rigid fuselage model. Three variable parameters were sought to be introduced to the system:

1. Introduction of additional weight to a single rotor blade;
2. Introduction of a change in length of a single pitch link;
3. The introduction of a single trim tab angle deflection;

Each was introduced to the basic rigid fuselage model and tested individually. Once the necessary definition changes to the model were validated, the variable parameters could be combined to produce a single model with the ability to introduce any combination of the three types of faults to any combination of blades.

3.4.1 Rigid Body Mass Fault. Introducing a small mass to a rotor blade appeared to be the simplest condition and was tackled first. This small mass would represent blade repair materials used by maintenance personnel. The first step was to add lines to an individual blade primitive structure for the screen RBMELE, or rigid body mass element.

```
S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance
```

In the RBMELE screen, a unique element ID value within the primitive structure must be assigned for each additional mass which will be attached to the blade. Each of those masses must also note the location in the screen FENODE where the mass will be attached to the primitive structure, as well as the properties for that mass. As can be seen above and in the appendices, two rigid body masses were identified as

elements 780 and 781 for each blade. The former is an element for providing a fault to the blade and the latter as a placeholder to note blade weights which would be attached to the blades during maintenance in order to alleviate vibrations caused by the introduced fault. These weights would be compared with weights determined by the AVA coefficients to determine model accuracy.

With the location of the seed fault mass added to the primitive structure, the properties of that mass needed to be defined in the element property data sets. Using the hierarchical process, for each element identified by the screen Element Property ID (ELEPROPID) the properties of rigid bodies in that element were identified in screen RBMPRP, or Rigid Body Mass Properties. This screen assigns a property ID which is referenced by masses in RBMELE. The properties of that mass are identified by entries for that property ID such as mass, the offset of the mass from its center of gravity, and moments and products of inertia for the mass. A thin layer of excessive resin or epoxy would provide additional mass. Proper location of the screen RBMPRP in the model text file proved to be important to proper functioning of the model. The entry would appear as follows:

```
S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix
```

3.4.2 Pitch Link Faults. Changes to pitch link length are introduced during required maintenance actions. Whether replacing a link and setting the new link to the same length as the old, or making changes to pitch link length during rotor track and balance operations, the possibility exists that a pitch link will not be the length required to eliminate vibrations. In order to model this altered pitch link length from the optimal condition, a method of introducing the resulting pitch change to the blade must be developed. Several methods could be used to model this change in length. One method would be to redefine the node locations such that the end nodes of the

pitch link are further apart. Changing the top node would change the location of the pitch horn end, which would then require a corresponding input to the pitch bearing HINGE entry. This would not be an elegant solution, and it would be time consuming to recalculate and redefine these nodes and screen entries for every case.

Another solution which was previously used by the sponsor of this research was to add an additional hinge element at the location of the pitch bearing. This hinge element would receive an input from a unique control input in the screen CONTROLMIXER. This method requires that the angular change to the pitch bearing be calculated and applied for changes in pitch link length. While accurate and simple, this method does not mimic the physical conditions which actually cause the pitch change. This method would also be difficult to directly compare to the AVA coefficients due to the units of the AVA pitch link coefficients.

A third method was employed for this research. A slide element in RCAS allows movement in a single axis direction. The slide will be defined by a starting and ending node, with the movement between the nodes either controlled or free with given values of stiffness or damping that restrict the node movement. For this research the slide used a controlled, fixed movement which modeled an end node displacement as seen in Figure 3.5. The element on the left represents the unaltered pitch link while the element on the right is a schematic representation of the pitch link with a negative slide element displacement.

In this manner, the top node of the pitch link which connected to the pitch horn could be moved and subsequent connections would cause a rotation of the blade pitch bearing. In the screen CONTROLMIXER an additional entry was made for the slide element of each blade. The value at zero pilot control entry location would determine how much displacement the slide would exhibit. No entries to pilot control coefficients were needed.

```
S SLIDE
!Elem  Node1  Node2  Slide   Free or    Spring      Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
```

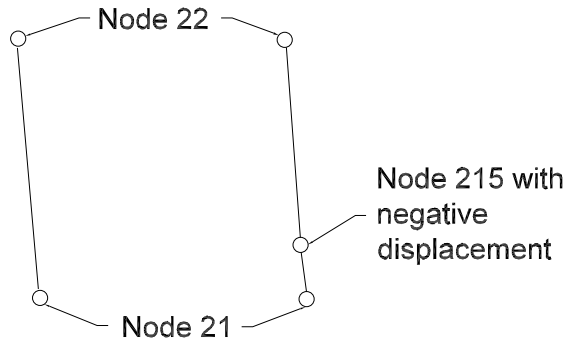

Figure 3.5: SLIDE Representation for Pitch Link Modeling.

```
a 211    21      215      Z         1          0              0
```

Several changes were made to the primitive structure of each blade, beginning with the addition of a new node location which was referred to as node 215. Node 21 is the swashplate node where the lower pitch link connection is made. Node 22 is the pitch horn node where the upper pitch link connection is made. Node 215 is the intermediate node which will displace through movement of the slide. For RCAS purposes, node 215 must initially be co-located with the fixed node of the slide. Once the program begins to run, the CONTROLMIXER entry determines the behavior of the sliding node. As previously mentioned, the pitch link is modeled as a spring element for structural behavior modeling of the rotor system; this modeling technique will not change. However, instead of the SPRELE entry connecting nodes 21 to 22, the element was changed to connect nodes 215 and 22. The screen SLIDE was added to each blade to connect node 21 to node 215 using slide element 211. The slide element ID must be unique for the primitive structure. As can be seen in

the SLIDE entries, movement was allowed along the Z axis in a controlled manner. Finally, an additional control connection was made for each blade primitive structure in the screen CONTROLCONNECT where the direct connection was made from the appropriate control ID found in the CONTROLMIXER screen to the element ID of the SLIDE. A critical point to realize is that the element type must be annotated as 'SLD' representing the slide connection. Neither the RCAS Users Manual nor HELP screens within RCAS make any mention that 'SLD' is an available option for entry to this location in the CONTROLCONNECT screen.

```
S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                 53
a    2       SPLATR         0.0           HIN                 53
a    3       SPLONG         0.0           HIN                 53
a    8       DIRECT         0.0           SLD                 211
```

3.4.3 Trim Tab Faults. The baseline CH-47D model contained detailed blade descriptions which indicated the location and change in airfoil chord for the blade sections where the trim tabs exist. Use of the RCAS elevon elements was suggested by the research sponsor as a simple and efficient means of modeling trim tab adjustments. The structure of the blade primitive elements does not change from that which is modeled in the baseline model. Therefore, no changes are made in the screens which define structural shape of the blades. Instead, changes which model the trim tab angles are implemented in the aerodynamic components which represent the blades. The bendable trim tab is modeled as an elevon for which appropriate control behavior entries are defined.

In the aerodynamic component screens for each blade, the screen ELEVONSEG is utilized to define the portion of the blade which will be treated as an elevon. The elevon segment definition requires that the ratio of the movable elevon chord to the chord of the entire airfoil be defined. From the finite element structural mode

the difference in chord between the trim tab segments and non-tabbed segments of the blade was found and divided by the total chord of the tabbed airfoil section to determine the chord ratio of the trim tab for input to the ELEVONSEG screen. Deficiency factors and Theodorsen wake factors were taken from a sample model used for other work which AMRDEC made available.

```
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          13
a  12  .0375939  .667    .60          1          0          13
```

The input to the trim tabs could be either a periodic input or a non-periodic input received from the CONTROLMIXER screen. This research modeled a fixed trim tab deflection. Therefore, a non-periodic input was applied in the form of an additional entry to the CONTROLMIXER screen for each blade. That entry ID number was then provided in the screen ELEVONSEG to link the elevon angle change, in radians, to the desired deflection noted in radians in the screen CONTROLMIXER. The value of deflection is entered as the second data screen entry per trim tab CONTROLMIXER entry as seen in Appendix A and Appendix B.

Finally, the dynamic stall modeling was altered for trim tab experimentation. Chapter 4 Results will discuss this in more detail; however, the reader should be made aware that for trim tab entries to the model behavior, results indicate dynamic stall cannot be modeled and only simple static stall of the airfoil can be computed by RCAS. In the AEROPTION screen the last change entry was activated in the following manner when modeling trim tab deflections:

```
S AEROPTION
! Dyn Stall opt
!      0 => static stall
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                            separation
!      3 => Leishmann model - w/ separation
```

```
!                                          + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                        separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                       shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           5                0
c     0           0        0           3                0
!*********************************************************************
! Deactivate the following line for dynamic stall modeling
c     0           0        0           0                0
```

3.4.4 Elastic Fuselage Modeling. The next step of the model design was to incorporate the elasticity of the fuselage into the model. Up to this point the model had been defined as a rigid fuselage with fixed movement between the fore and aft rotor hubs. A matrix of eigenvectors representing the nodal behavior of the fore and aft rotor hub nodes and center node of the fuselage was provided by AMRDEC. Additional changes were needed to incorporate this matrix into the model. These changes began with the simple change in nomenclature of the fuselage in the model script. Since this was no longer the model with a rigid fuselage, the fuselage nomenclature was changed from 'fusrigd' to 'fusCH47D'. To assist RCAS in calculating fuselage effects on air flow as well as interference between the fuselage and rotor components, an additional fuselage structure was created for the fuselage body, referenced as 'bodycp' which was given a mass of zero. All aircraft mass continued to be represented by the same structural nodes as before.

Movement of the elastic fuselage causes nodal displacement at the rotor hubs which affects the aerodynamics and vibratory response of nodes in the two rotor

supercomponents. For this reason, additional nodes were created in the structure and co-located with the rotor hub attachment nodes of the original fuselage in screen FENODE of the fuselage primitive structure. These new nodes were labeled as nodes 13 and 15, coincident with nodes 3 and 5 respectively. At these forward and aft nodes, elastic joints were implemented with the addition of entries to screen EJOINT where the elastic joint elements derive their behavior from the matrix of eigenvectors.

```
S EJOINT
! Model - Elastic fuselage behavior at left & right rotor
!   Elem.  Bnode  Enode   Eigenvector
!    ID     ID     ID     Seqence ID
a    20     3      13          1
a    21     5      15          2
```

The most significant change to the rigid fuselage model involved a coordinate transformation to account for the structure of the eigenvector elastic matrix. Again using an elastic fuselage model supplied by AMRDEC, it was determined that the elastic fuselage matrix provides eigenvectors for a structure rotated 180 degrees about the Y-axis from the coordinate system of the CH-47D modeled for this research. In order to align all nodes properly, several additional changes needed to be made to the fuselage subsystem. The first was to change entries in the primitive structure orientation screen, PSORIENT. The fuselage would need to undergo a 180 degree rotation about the 2-axis, or Y-axis. Additionally, the massless body primitive structure must also be defined with finite element nodes and a rigid body mass element.

```
S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
! fuselage rotated by 180 for elastic model only (elastic matrix)
a    fuseps       2    180         0       0         0       0
a    bodyps       0      0         0       0         0       0
```

With the fuselage primitive structure rotated by 180 degrees, the structural nodes defining the fuselage relative to the global frame coordinate system needed to change. Fore and aft displacements, X-axis, changed signs as did the vertical

displacements, Z-axis. Additional coordinate transformations were not necessary. The additional RSCOPE model with rigid fuselage information was deleted for the elastic model since rigid fuselage information was no longer relevant. Note the change in sign values for the elastic fuselage model as compared to the earlier rigid fuselage model:

```
S FENODE
! The data is based on 7 inch aft cg
!  node ID,   X,       Y,       Z
A      1      0.0      0       0.0
A      2    -19.879    0       0.0
A      3    -21.013    0     7.1598
A      4     18.7046   0     1.2333
A      5     17.8775   0    11.8275
A     11      0.0      0       0.0
A     13    -21.013    0     7.1598
A     15     17.8775   0     11.8275
! Nodes added to represent accelerometers of HUMS
A      80   -21.813    0     4.6598
A      81   -19.7046   0     9.3275
```

The last modification to the rigid fuselage model needed to create the elastic fuselage model was to append the elastic fuselage eigenvalue matrix to the RCAS file. When RCAS initially compiles the script file to be run, this and the other matrices will be extracted as stand-alone files to be referenced during computation.

3.4.5 Combined Rigid Fuselage Model. The changes to the baseline CH-47D seem simple in writing, however determining the proper syntax to make each method work proved to be more difficult than expected. The pitch link and trim tab model both required the use of a combination of elements and screens which are not clearly explained, if at all, in the RCAS Users Manual. Only through significant trial and error and consultation with experienced RCAS users could the working methods be determined. Once the necessary model changes were determined, the three methods were combined into a rigid fuselage model where individual rotors were specified for both the forward and aft rotors.

The AVA coefficients of Ref. [22] are noted for the hover, 100 knot, and 130 knot flight regimes. In order to determine accuracy of the model created in this research, the model would need to mimic those flight conditions as closely as possible. At those flight conditions several entries to the model would depend on airspeed and flight condition. Cyclic and collective will be at different locations for each airspeed. These positions are noted in the CONTROLMIXER screen for zero pilot input, found in Appendix A. In the analysis section of the model, the initial pilot control positions are also noted for the different airspeeds in the first screen of initial conditions, INITCOND. In the different flight regimes the aircraft attitude will vary as well; this is noted by the varying inputs to the second screen of INITCOND.

```
S INITCOND
! Initial Pilot Controls , ft
!  collective, lateral, longitudinal, pedal, throttle
a     0.0       0.0          0.0          0.0        0.0  ! ground
!a     0.13133   0.0         0.0           0.0        0.0  ! hover
!a     0.216     0.0049      0.0042       -0.007      0.0  ! 89 kts
!a     0.393     0.004      -0.049        -0.008      0.0  ! 136kts
N
! G position Frame wrt I
!  X  Y    Z    Roll   Pitch   Yaw
a  0  0    0     0.0     0.0      0.0  ! ground/hover
!a  0  0    0    -.004    0.027    0.0  ! 89kts
!a  0  0    0    -.0075  -0.052    0.0  ! 136kts
```

Finally, the constant wind experienced by horizontal movement (assuming a level flight condition) is provided to the model in the screen CONSTWIND. These variables were added to the rigid fuselage model. It became apparent through several weeks of computer simulation that insufficient time would be available to conduct analysis for all three flight regimes. The 90 knot condition was selected as the primary focus of effort for computational analysis and comparison. This flight regime was chosen because the aircraft would not be flying at the limits of its performance at this speed. In the 152 knot case, the CH-47D is flying near maximum airspeed and therefore the ability to reach a trimmed and convergent solution is more difficult.

With the complete rigid fuselage model created, computations could begin in earnest. A control model was created with zero inputs to each of the three test behaviors. This control model used uniform inflow, individual blade analysis for all six blades, and static stall blade behavior. Recall that for uniform inflow conditions the screens for prescribed wake, PRESWAKE, and free wake conditions, FREEWAKE, must be inactive. This model was then compiled and run, checking for errors and observing the output for expected results. Next, a single test condition was changed. The model remained a rigid fuselage with single blade analysis and uniform inflow, but the blade stall characteristics were changed to model a dynamic stall response. The modified model was also compiled and run, checking for errors. It is important to note that any time the model was changed to include dynamic stall conditions, the trim tab ELEVONSEG screens must be made inactive. The third rigid fuselage model to be created was one which modeled prescribed wake flow conditions but continued to use a static stall blade response. The fourth test condition changed the blade stall characteristics to dynamic stall blade response while maintaining the prescribed wake condition. Finally, a fifth rigid fuselage baseline model was created which included free wake conditions and dynamic blade stall conditions. Summarizing, the models for the rigid fuselage are:

1. Uniform inflow, static stall blade behavior.
2. Uniform inflow, dynamic stall blade behavior (no trim tab coding).
3. Prescribed wake, static stall blade behavior
4. Prescribed wake, dynamic stall blade behavior (no trim tab coding).
5. Free wake, dynamic stall blade behavior (no trim tab coding).

With models for a rigid fuselage created, test computations could begin for each type of fault. WIth five rigid fuselage models and three types of faults, 15 batches of calculations would result. For each batch calculation, the RCAS ability to run multiple cases in one computational run could be utilized. In the analysis section of the model, the first SELANALYSIS screen provides the ability to list multiple cases

to be calculated. The second screen provides the formatting to label each separate case. The third screen of SELANALYSIS defines the variables which will be changed, while the fourth SELANALYSIS screen links the subject variable to the specific case. The structure of multi-case analysis for a script file is exemplified here:

```
S SELANALYSIS
!  Trim analysis
!  Trim Options: 1 - Trim; 2 - Periodic Solution; 3 - Static Analysis
! Case_id Trim, Maneuver, Stability, Init_condn, Scope Script_Filename
a     1     1       0          0         D               NO
a     2     1       0          0         D               NO
a     3     1       0          0         D               NO
N
! Case_id    Case_Title
a   1         ground_0n
a   2         ground_5n
a   3         ground_1slug
N
!N
!Multiscreen: 3  of 4    Type: Iterative      Screen: SELANALYSIS
!                       DEFINE CASE VARIABLES
! Case_Var   --Screen Name--  Data_Group_id   Screen  Field   Row
!    _ID                       ("--" if none)   Nbr    Nbr    Nbr
!a    1       CONTROLMIXER        --             1      2      7
!a    2       RBMELE            blade1f          1      2      1
!N
!Multiscreen: 4  of 4    Type: Iterative        Screen: SELANALYSIS
!                  SPECIFY VALUES FOR THE CASE VARIABLE
!Note: The values specified in this screen for the defined variables
!      will supersede the information given in the respective screen.
!Row ID    Case_Var_ID     Case ID                Value
!                                            (Numeric or Character)
a  1            1             1                      0
a  2            1             2                      0.0019841271
a  3            2             7                      1.00
```

The intent for building working rigid fuselage and elastic fuselage models was to specify a range of values for the particular test variable (rigid body mass, pitch links, trim tabs) and conduct the simulation for this range of cases in the analysis section.

For example, in the pitch link models a single pitch link was tested over a range of lengths from zero change in length to one inch change in length.

The rigid body mass tests could explore a range of values for both the additional mass as well as the placement of that mass. In the research, the variability of the range of mass was purposefully limited and the model was tested for a range of mass values all close to the tip of the blade. The trim tab model was also run for a range of trim tab angular changes.

As will be described in more detail in Chapter IV, the first step to analysis of the output was comparison of the nodal displacement of the blade tips for the three blades of the rotor which included a blade fault. If no difference to the fourth decimal place of blade displacements (in feet) between blades was observed then it was clear that the model was not accurately modeling a fault and further work was necessary in the code. If however a displacement was observed then the analysis could continue.

RCAS contains a set of modules which are collectively known as the Technology Output Processor (TOP). TOP processes resulting data from RCAS and can output this data in tabular or graphic form. Through a series of menu screens and options, the user can select nodal behavior output to be presented by displacements, velocities, or accelerations. Vibration harmonics as an integer multiple of the rotor revolutions can also be selected. Nodal behavior and harmonics can be processed and displayed for the X, Y, or Z-axis. For the purposes of this research, the Z-axis displacements and vibrations were the most useful.

In order to compare the validity of these models to existing data in the form of modified AVA coefficients, a fault must be introduced to the rotor system. The AVA coefficients are defined using inches-per-second (IPS) vibrations experienced in the airframe. To compare these models to the AVA coefficients the vibrations calculated in the model need to be converted to IPS. The process begins by using the TOP menus to gather harmonic data of the model. Acceleration data to the 12th harmonic was chosen to highlight detailed characteristics of the fault condition. TOP provides the

cos and *sin* Fourier coefficients of the vibration harmonic in a graphical and tabular manner. These coefficients are the a_k and b_k found in Equation 3.1, where k is the harmonic number and Ω is the rotor speed in revolutions-per-second. The magnitude of the acceleration harmonic is found by Equation 3.2, the square root of the sum of the squares of these coefficients.

$$x(t) = a_0 + a_1 cos\Omega t + b_1 sin\Omega t + a_2 cos2\Omega t + b_2 sin2\Omega t + ... + a_k cosk\Omega t + b_k sink\Omega t \quad (3.1)$$

$$d_k = \sqrt{(a_k)^2 + (b_k)^2} \quad (3.2)$$

To scale the acceleration to vibration in g-forces, the acceleration magnitude should be divided by the factor g, (32.17 ft/sec^2), to obtain vibration values. The resulting vibration value was now converted to inches from feet. To convert the harmonic from number-per-revolution to a frequency, the rotor speed was converted to revolutions per second using Equation 3.3 and multiplied by the harmonic number.

$$\Omega = 23.5619 \frac{rad}{sec} \div 2\pi \frac{rad}{revolution} \quad (3.3)$$

To simplify conversion to the time domain, the research sponsor recommended use of a web-based conversion tool found at 'http://www.spaceagecontrol.com/calcsinm.htm'. Applying the magnitude and harmonic frequency values determined from the TOP data to this conversion tool the equivalent vibration in IPS can be found. To balance this vibration an equivalent and opposite adjustment should be made. The adjustment should be scaled by the AVA conversion factor to determine the magnitude of the adjustment. This corrective action will then be applied to the model and the updated model will be run. An example of this process is found in Chapter IV. A favorable comparison between modified AVA coefficients derived from aircraft HUMS records, and the predictions and behavior of the fuselage models will provide significant validation to this model.

Numerous difficulties prevented reaching the final goal of comparison between these models and the modified AVA coefficients. Large computational times and a limited number of processors to perform the analysis caused a delay in the data generation. If and when the models are working to completion, researchers will be able to extract the displacements and/or nodal velocity of the accelerometer nodes in the fore or aft pylon to convert if necessary to attain a unit of measure of inches per second (IPS). The unit of IPS is required in order to compare to the AVA work of Hasty et al [22].

3.4.6 Combined Elastic Fuselage. As with the combined Rigid Fuselage Model, the various elements of elastic fuselage modeling and the three test conditions of interest were now combined into an elastic fuselage model with uniform inflow and static stall blade behavior. The model contains information for four flight regimes: ground track at 100% rotor RPM, hover, approximately 90 knot forward flight, and approximately 130 knots forward flight. Only the flight condition to be modeled at the required time will be an active line of code. As with the rigid fuselage model, five elastic fuselage models were created with variations of flow conditions and blade stall characteristics. Appendix B contains the script file for all three test conditions with comments describing when certain lines should be active or inactive. The results of these attempts at creating an elastic fuselage model will be described in Chapter IV.

3.4.7 Trim and the RCASTRIMMATRIX.MAT. A final and important section of code to be modified involved the matrix of trim values delineated as the RCASTRIMMATRIX.MAT. In the free flight condition the equations of motion must be solved and balanced for periodicity and forces/moments through algorithms and equations [25]. For a free flight condition, such as the flight conditions for this research, there are six degrees of freedom which define the aircraft state. These six degrees of freedom are the translational direction in the three linear coordinate axes of X, Y, and Z directions and the rotations about those three axes. A state of trimmed flight is reached when two sets of equations are satisfied within a defined set of tolerances.

Those tolerances are defined in the screen CONVERGETOL described earlier in this chapter. The first set of equations relate the periodic constraints for the dynamic response while the second set of equations define the trim target constraints. Trim variables are selected as control inputs or independent model variables which will affect the trim target response [25]. For these models, the trim variables are inputs by collective, longitudinal cyclic, lateral cyclic, and pedal (yaw) plus two aircraft orientation angles, ϕ and θ. Rotation about the X-axis (roll) is defined by the angle ϕ while rotation about the Y-axis (pitch) is identified as θ.

The process of trimming the aircraft is an iterative one beginning with the initial trim variables,V_t, determined from the control positions and other appropriate trim variables [25]. Using the many equations and algorithms mentioned, a periodic solution is derived and resulting forces and moments are determined. Through the iterative process, the forces and moments are compared to the targets to determine if they are within the defined tolerances. When that is the case, the aircraft is trimmed. Until such time, the trim variables will be incrementally modified until the tolerances are met. The resulting matrix of trim variables is saved as the RCASTRIMMATRIX.MAT. This process is graphically described in Figure 3.6. It should be apparent to the reader that using a pre-computed RCASTRIMMATRIX.MAT containing trim variables very close to those needed for the model in question will significantly reduce the computational complexity and time required to reach a solution.

The process of loading a pre-computed trim matrix is straight forward. Several versions of RCASTRIMMATRIX.MAT were computed and tried. As will be explained in the next chapter, the primary pre-computed trim matrix which was utilized for the rigid fuselage methods was derived from the multi-blade analysis CH-47D baseline rigid fuselage model with prescribed wake conditions and dynamic stall blade behavior. To load a saved, pre-computed trim matrix rather than determine a new one during the run process, the following lines of the script file are activated and deactivated in an obvious manner.

```
N
```

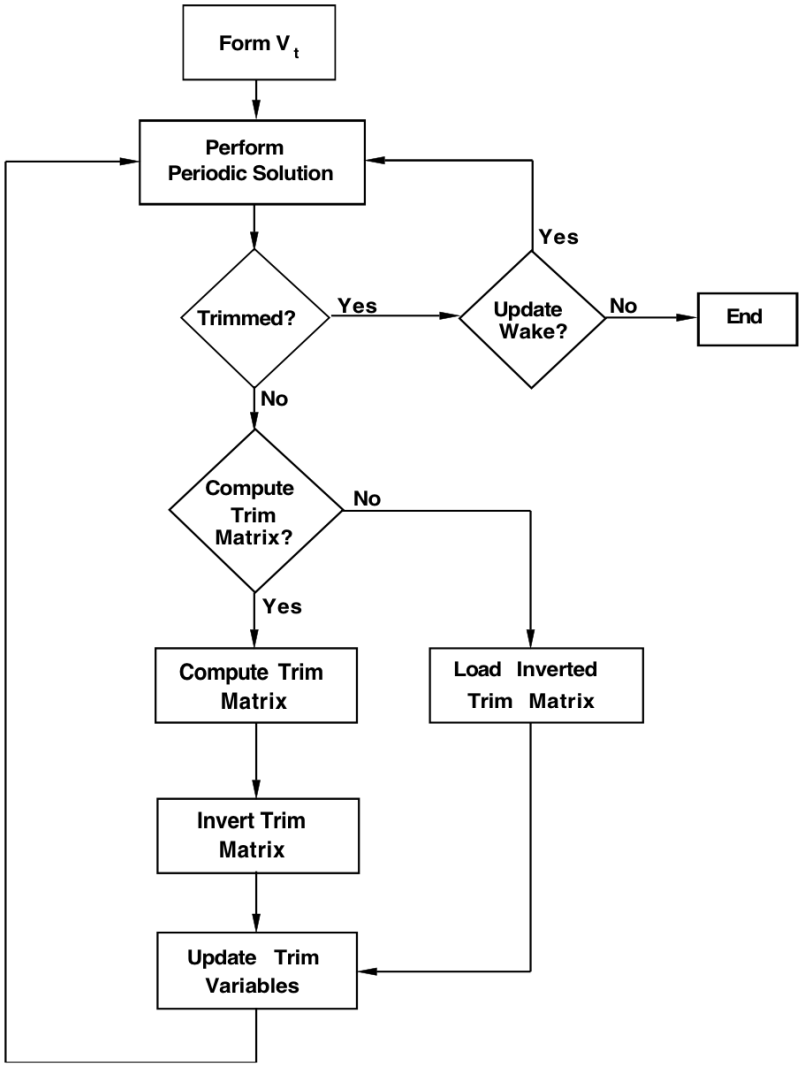

Figure 3.6: Trim Analysis Flow Chart [25]

```
!                LOAD AND/OR SAVE TRIM SENSITIVITY MATRIX
!
!    Specify whether a trim sesitivity matrix is to be imported from
!    a file, loaded from a previous case or saved if it is calculated.
!    Also enter the file name for the trimsensitivity matrix.
!
!  LOAD,     SAVE                 Trim Sensitivity
!  PREV,     PNS                  Matrix Filename
a  SAVE                           RCASTRIMMATRIX.MAT
!a    LOAD                            RCASTRIMMATRIX.MAT
```

For versions 9 and 10 of RCAS, the trim matrix must be consistently named 'RCASTRIM-MATRIX.MAT'.

IV. Results and Analysis

Several techniques and parameters were evaluated to determine the validity of the rigid and elastic fuselage models through their development. If the subject model compiled and ran to completion, then the screen output and log file would be checked. For a completely successful run the screen output and log file would include the statements " Trim solution has been reached" and "TRIMPASSED = 1" to indicate that the trim variables for the system were iterated to a solution which met the convergence criteria defined in the Analysis section of the script file. A successful solution would also create a results file with the '.SAV' file extension which would contain the data requested by the script file. The name of the .SAV file is dependent on the file name assigned in the screen SAVESC. From this file various aircraft characteristics could be compared for evaluation of the validity of the working model. If the computational run reached a conclusion but not one which met the trimmed solution parameters, then the output would indicate "TRIMPASSED=0".

It should be mentioned that this research had two versions of RCAS available for use. Like all software, RCAS receives regular software updates and revisions released periodically. Version 9 and Version 10 of RCAS were licensed to the Air Force Institute of Technology and loaded onto a Linux workstation for use in this research. No noticeable differences between operation of the two versions was noted, however the underlying software clearly contains differences which manifested during this research. Errors encountered in the model research often differed between version of RCAS and are noted in this chapter.

From the single-blade analysis baseline CH-47D model several sets of output were extracted and plotted for comparison purposes. The first was the nodal displacement of the rotor blade tip of blade 1 on the forward rotor, referenced as node 14 of blade1f and seen in Figure 4.1. Since changes were only planned for the forward rotor at this time, the resulting characteristics of the aft rotor were not observed when determining whether the fault coding successfully introduced the fault to the system. In the figure, blade displacement is plotted against the azimuthal location of the node

through a single revolution of the rotor. Zero degrees of azimuth is found in the direction aft along the longitudinal axis of the aircraft while 180 degrees is directly in front of the aircraft. The displacement values are relative to the rotor hub but are in the global coordinate system, hence a negative value with greater magnitude is higher above the rotor hub on the real system. The forward tilt of the rotor hub in forward flight can be seen by the difference in blade tip displacement directly in front of the aircraft (approximately -2 ft) versus the tip displacement aft of the rotor head (approximately -12 ft).

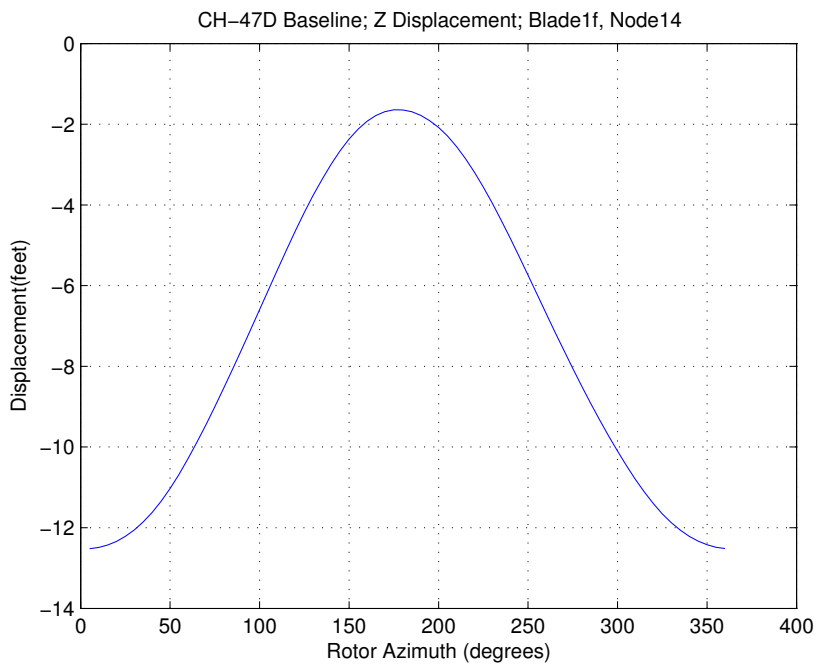

Figure 4.1: CH-47D Baseline Model Forward Rotor Z-Displacement

The vibration harmonics of node 30 of the forward rotor were also attained, where node 30 is the rotor hub node. Likewise the aft rotor hub node vibration harmonics were plotted. Both sets of nodal harmonics are seen in Figure 4.2. When comparing these results from the baseline model, the reader should be aware that the model was set-up for a forward flight condition of approximately 150 knots. Output generated from the models was typically calculated for a 90 knot forward flight condition. As noted in Section 3.4.5, testing initially included models at multiple flight

conditions to include the 150 knot case, however due to time constraints this plan was later reduced to only the 90 knot flight regime.

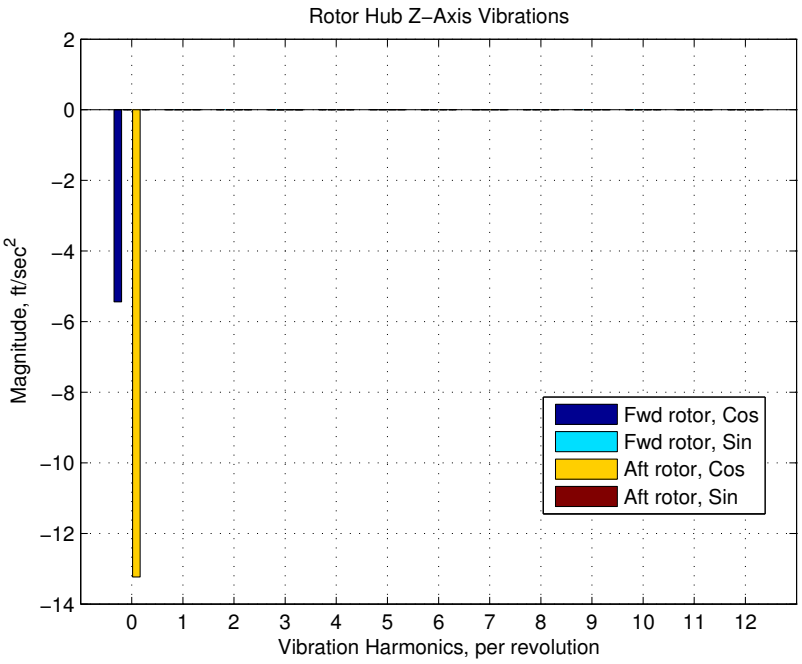

Figure 4.2: CH-47D Baseline Model Rotor Hub Harmonics

4.1 Multi-Blade Analysis and Inflow Changes

The multi-blade analysis screen entries were made as described in Chapter III and RCAS was run for the 90 knot case. Other variables remained unchanged. The RCAS software calculates exact solutions and, therefore, no significant differences in blade tip displacements should be observed between individual blades. Additionally, multiple runs to attain an average value were not necessary. The displacements of the three distinct forward blade tips can be seen in Figure 4.3. These blade displacements are relative to the aircraft center of gravity. Displacements will differ from the single-blade analysis due to differences in forward airspeed conditions. The rotor hub harmonics are plotted in Figure 4.4. The model which was run to achieve these results used identical blades for each of the six rotors, so no vibrations should be present due to blade differences or faults. As seen in the figure, no vibrations are present in the

multi-blade model which confirms the method of creating multiple individual blades without causing erroneous results.

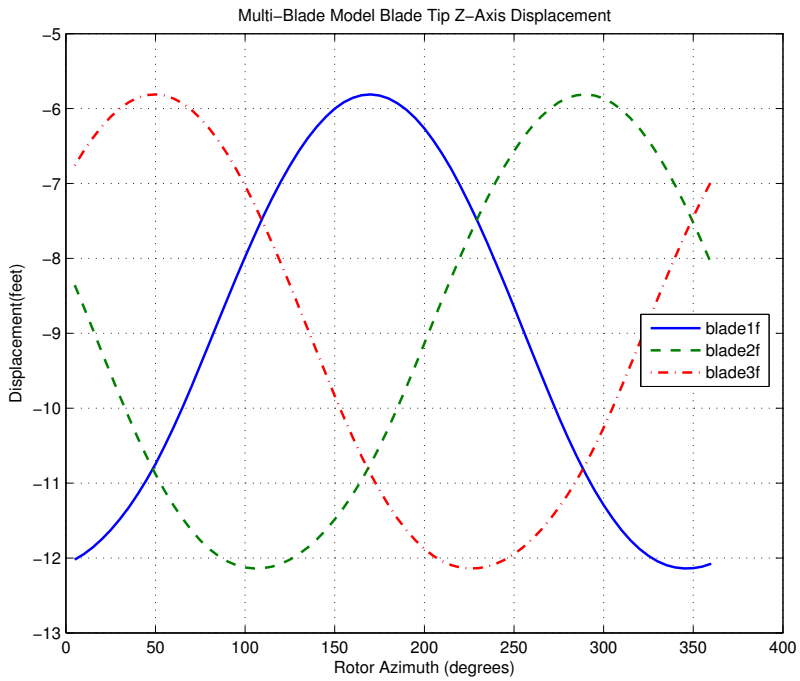

Figure 4.3: Multi-Blade Model Forward Rotor Blade Tip Displacements

Computational times increased from approximately 12 hours to over 55 hours when the multi-blade analysis option for six distinct blades was exercised in a prescribed wake condition with dynamic blade stall characteristics. Quick troubleshooting of code would not be possible if several days were going to be necessary between model runs. For this reason, the changes to the baseline CH-47D model were made which modeled the rotor inflow as a uniform momentum inflow condition. The forward rotor continued to be used for multi-blade analysis but the aft rotor was returned to a single-blade analysis condition. These changes reduced run times to approximately 7 hours using RCAS v9.

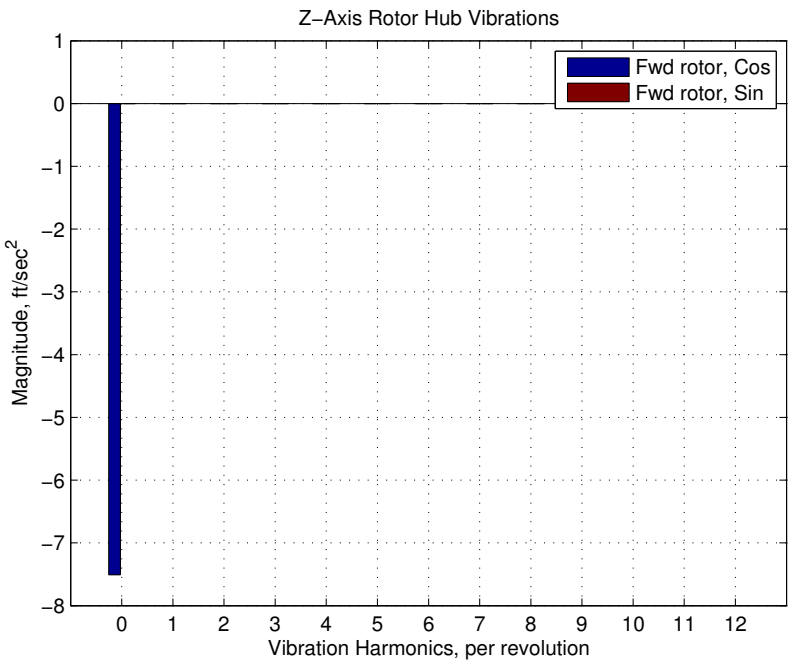

Figure 4.4: Multi-Blade Model Rotor Hub Z-Axis Harmonics

4.2 Rigid Body Mass Fault

The addition of a rigid body mass was a straightforward addition to the script file. However, diligence should be practiced when entering additional data entry screens and lines. The following lines of a script file illustrate this potential:

```
S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
```

```
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a    201                     CH47D_DAMPER_FILE
```

In Chapter III some basic screen entry descriptors were explained. Recall that the NEXT command is used between screens of a multi-screen data entry screen. In this example the DMPELE screen was a multi-screen command and the RBMELE screen was placed into the script file between pages of the damper element screen entry. Such a mistake will lead to an error preventing a successful run and therefore one should ensure that the RBMELE screen entry is placed before or after the DMPELE screen.

A test case using the RBM fault method was conducted. The 90-knot model used multiple independent blades to model the forward rotor and single-blade analysis for the aft rotor. A very small mass of 0.002 slugs was added near the tip of blade1f on the forward rotor. Analysis was conducted by RCAS for uniform inflow conditions and dynamic blade stall behavior. The computation successfully compiled and ran. However, a trimmed flight condition was not adequately reached. From the data saved at the end of the iterative process, plots were made and a judgement regarding the validity of the RBM fault methodology can be made. In Figure 4.5 the blade displacements for a single rotor evolution, also called the blade 'track', can be seen. With such a small mass there is not an expectation to see large variation in the blade tracks, but some variation should be present. This was the case as can be seen in the figure where the small mass at the blade tip does cause the blade momentum to carry it to a greater displacement.

The added blade mass should also cause vibrations to be felt in the aircraft due to the unbalanced mass condition of the forward rotor. Figure 4.6 notes the vibrations in the Z-axis experienced at the forward and aft rotor pylon accelerometer nodes. The three-per-revolution (3P) vibrations are indicative of an out-of-plane vibration [26]

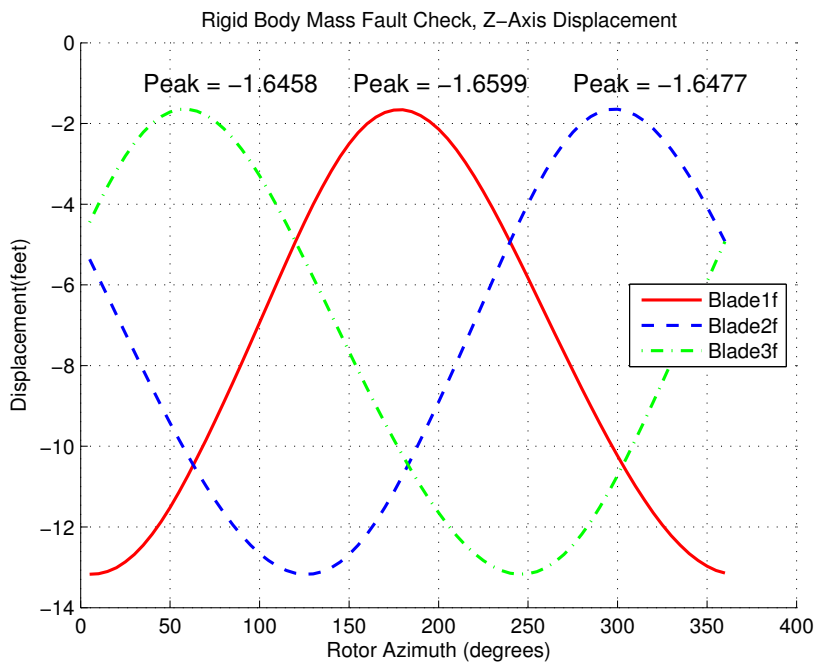

Figure 4.5: Testing Mass Input - Blade Tip Displacement Comparison

from the X-Y plane of the accelerometer. In section 2.2.2 it was discussed that a lateral vibration would be experienced from a mass imbalance. The 1P vibration of the unbalanced rotor condition can be clearly seen in Figure 4.7. Both Z-axis and Y-axis vibrations will be experienced due to the tilted rotor plane relative to the aircraft coordinate system. The presence of these vibrations indicates acceptable modeling of the rigid body mass fault.

The AVA software takes vibrations experienced at the 1P harmonic and calculates a set of adjustments to be made to blade masses, pitch links, and trim tabs in order to alleviate the vibrations experienced. The AVA software was not available for use at the time of this research, but the following is a simplified demonstration of the process which AVA uses to determine the set of adjustments. Using Equation 3.3 the 1P harmonic frequency is determined to be 3.75 rev/sec. Using the forward node, node 80, for this example calculation the *cos* and *sin* coefficients are noted and applied to Equation 3.2 to determine the magnitude of the 1P vibration. The results of

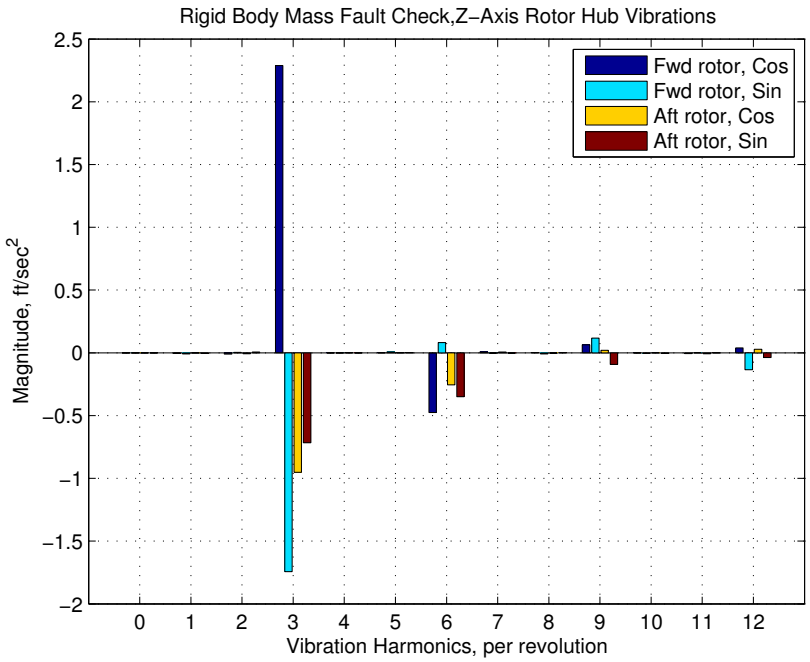

Figure 4.6: Testing Mass Input - Pylon Accelerometer Z-Axis Vibrations

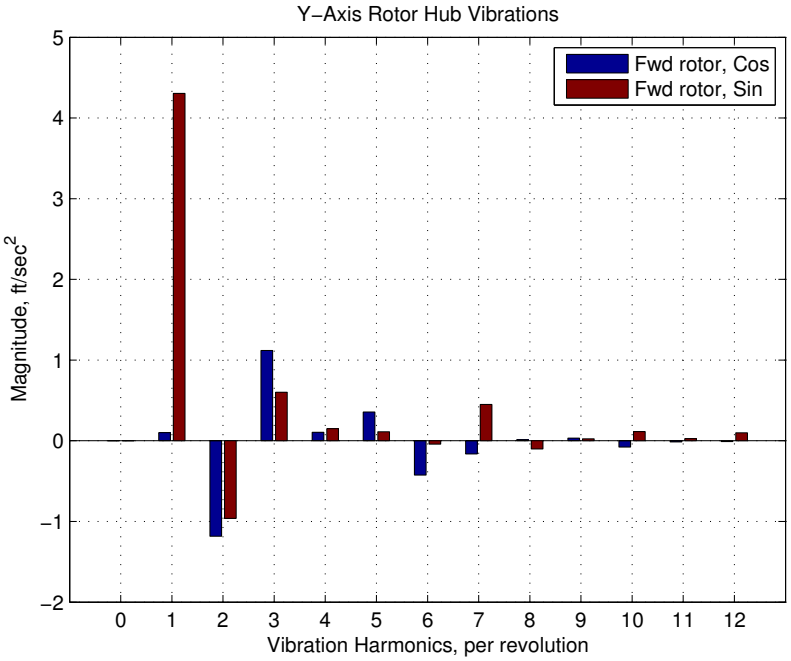

Figure 4.7: Testing Mass Input - Pylon Accelerometer Y-Axis Vibrations

this process, seen in Equation 4.1 are divided by g to produced a scaled vibration.

$$d_3 = \sqrt{(0.10175)^2 + (4.30387)^2} = 4.3051 \ ft/sec^2 \tag{4.1}$$

Combining this result and a conversion to inches, the following value is found:

$$accel_g = 4.3051 \ ft/sec^2 \div 32.17 \ ft/sec^2 = 0.13382 \tag{4.2}$$

This frequency and acceleration are entered into the web-tool noted in Section 3.4.5 to produce an output of **2.1928 IPS**. In this sample case, a change in rotor blade mass will be utilized to attempt to offset the lateral vibration. Using the modified AVA coefficient values determined by Hasty et al [22], an adjustment coefficient of 0.103 IPS/wt will be used for the sample calculation. The blade weights have a weight of approximately 0.1 lbs which for purposes of RCAS are converted to mass in units of slugs.

$$RBM' = 2.1928 \,\text{IPS} \div 0.103 \,\text{IPS/weight} \times 0.1 \,\text{lbs/wt} \times 32.17\text{slugs/lb} = \ 68.488 \ \text{slugs} \tag{4.3}$$

The number of blade weights per blade are limited to 10, or approximately 32 slugs. The mass calculated in Equation 4.3 will not be possible as a single blade adjustment. For this reason, the example will cease at this point. By using the full AVA program and its recommended blade adjustments in a similar manner as this example, corrections could be applied to the rotor system. If the corrections damped the vibration to a minimal and acceptable level this would serve to verify the accuracy of the model developed in this research to simulate blade mass faults.

4.3 Trim Tab Fault

Adding active entries to the rigid fuselage model for blade elevons was a fairly straightforward process with one exception. The input below is an example of a script file entry for the screen ELEVONSEG as described by the RCAS Users Manual and

the RCAS v9 and v10 entry screens accessed via interactive menus. Note the last entry column of the screen:

```
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID
a  11  X.XXXXX  X.XXX    X.XX          1          0
a  12  X.XXXXX  X.XXX    X.XX          1          0
```

The only option for an input to the elevon segment appears to be via a periodic input. For the purposes of this research a constant input was desired for the additional trim tab (elevon) deflection due to a trim tab bent to a non-optimal deflection angle. Again consulting the sponsor of this research, it was found that an additional entry to the screen ELEVONSEG was available in these versions of RCAS. As seen in the appendices, a data entry column for non-periodic inputs provides a means to input a constant angular deflection through the CONTROLMIXER screen.

The resulting entries needed for an elevon segment constant angular addition result in data entries similar to these:

```
S CONTROLMIXER
! Input pilot stick movement to swashplate pitch
! Control Value at zero   ------ Coefficients for Pilot Control -------
!  ID     pilot control    Coll.     Lat.     Long.      Pedal    Throt
a  13      0.1        0        0        0         0        0  ! blade1f

S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  X.XXXXX  X.XXX    X.XX          1          0          13
```

The addition of these entries to the script file of the rigid fuselage model was tested and minor syntax errors were corrected. However one error continued to occur regardless of changes to the script file:

```
Instantiating fields for AEROSYS...
Error: Must specify parent node index
Closing a.mdl
```

```
Closing drv.scope
(MODEL_ROTORF_BLADE1F)S>
```

By closely reading the error message and making some assumptions, it appears that during the aerodynamic model iterations or calculations (AEROSYS...) an error in the first blade of the forward rotor occurred. The error message appears to relate that the prior point aerodynamic information is not being relayed to the calculations at this point in question. At this point a review of dynamic stall theory is in order.

Dynamic blade stall is a time dependent condition influenced by such factors as relative airflow velocity and direction over the rotor blade. This unsteady flow condition results in several effects, such as a delay in boundary-layer separation and stall [27]. Adverse pressure gradients build near the leading edge and flow separation occurs there. The resulting pitching moment stall occurs before the lift stall and a nose down pitching reaction occurs. The reduced angle of attack causes flow to eventually reattach but there is a delay due to leading edge pressure gradients during the forward pitch motion [27]. The blade returns to a condition of lower angle of attack and once again produces lift. This cyclical process can result in significant vibrations or detrimental affects on the flight condition. Keep in mind that this process is also taking place as the blade rotates and airflow develops a more significant transverse component across the rotor blade. In general, dynamic blade stall is a complex phenomenon which requires sophisticated modeling techniques, such as the Leishman-Beddoes technique utilized by RCAS.

The technique and coding of RCAS to model dynamic stall seems to work for a normal airfoil, but the addition of the elevon segment to the airfoil and the interaction of the two structures seems to need additional development beyond that contained in RCAS v9 or v10. Testing this theory, the model was run again, though with the blade stall condition modified to a static stall model. The error did not return. For this reason the models in the appendices note that any use of trim tab modeling through the screen AEROSEG requires the model to use static stall conditions. At the time

of this writing, the trim tab models have successfully compiled but have not reached trimmed solutions for comparison to AVA coefficients. Further experimentation and software development using the trim tab model is highly recommended.

4.4 Pitch Link Fault

Adjusting the basic rigid fuselage model to account for the pitch link modifications was one of the most detailed changes to the model. Beginning with an understanding of the intended changes as described in Section 3.4.2, the additional nodes for the slides were created in the screens defining the finite element structural model. For every blade that was intended to receive the slide modification, the finite element structure needed to be altered. Once the additional node was added, it was important to update the screen SPRELE to use slide element 215 for the bottom node (SPELE node 1) of the spring element. Not doing so will not cause an error message and prevent the script file from running to completion; however, any input to the slide will provide zero input to the pitch link and subsequent pitch hinge rotation. This error was found on several early iterations of the updated rigid fuselage model.

Implementing this pitch link method to a single rotor blade of the forward rotor was successful. To test the script file, a +0.1 ft slide input was provided to blade1f. Recall that the coordinate system is oriented such that a positive Z-axis translation is downward in the normal sense, thus shortening the overall length of the pitch link. Negative inputs would provide a negative Z-axis movement which causes Node 215 to displace upward and away from Node 21, lengthening the pitch link. With this relatively large input to the pitch link, changes in blade tip displacement and vibrations of the fuselage accelerometer nodes should have been readily apparent.

In Figure 4.8 the blade tip displacements are clearly not identical to the baseline blade tip displacement seen in Figure 4.1. It is expected that the blade with the shortened pitch link will have less angle of attack on the rotor blade throughout the rotor movement and subsequently will experience a lower peak during forward motion and flapping. This result can be seen in Figure 4.8 which serves to verify the proper

behavior of the blade subjected to the slide modification. Both the original CH-47D baseline model and this pitch link model were setup and tested for a 152 knot level flight condition.

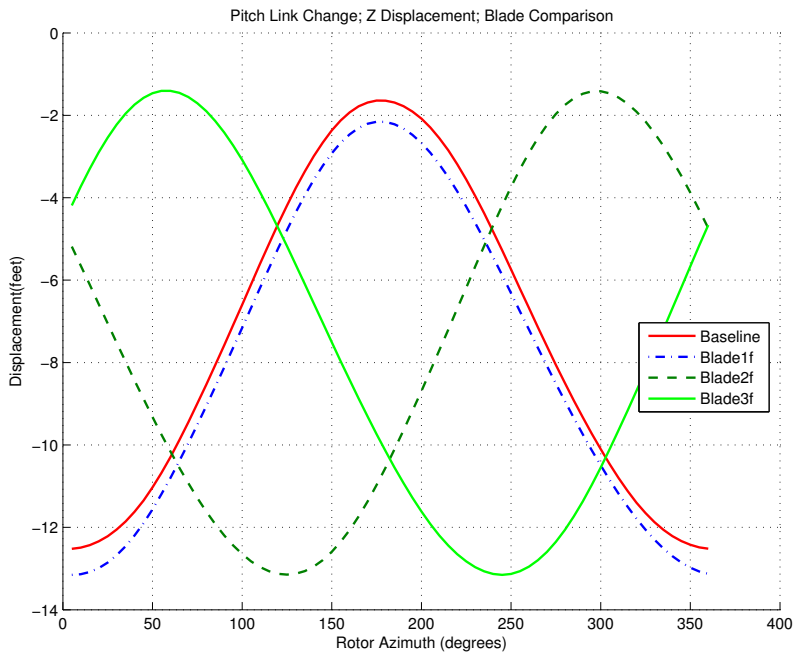

Figure 4.8: Testing Slide Input - Blade Tip Displacement Comparison

With one blade providing differential lift and drag on the forward rotor, a three-per-revolution vibration would be expected to be seen occurring in the forward rotor. In Figure 4.9 the reader can see that this is the case. For this case of a pitch link fault, the 3P harmonics are seen to be significant in the forward rotor pylon, but also have a dramatic impact on the aft rotor pylon vibrations. This is the type of data which may be useful to future researchers as they seek to find relationships linking nodal vibrations and displacements to specific fault types.

4.5 Combining Faults in a Unified Rigid Fuselage Model

The three versions of the rigid fuselage faults which were created independently and shown to be successful were combined into one script file for each aerodynamic and analytical condition. The script was also modified from the version of only individual

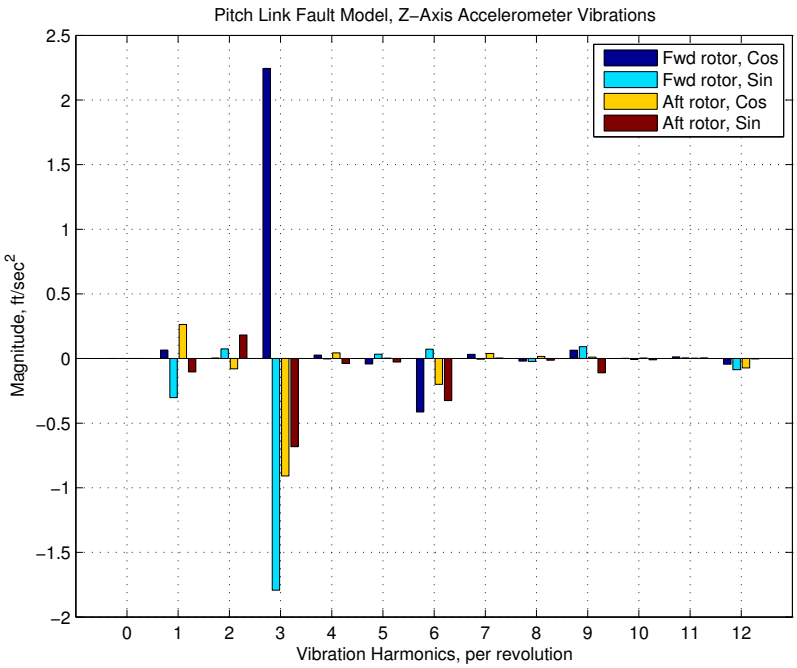

Figure 4.9: Testing Slide Input - Pylon Accelerometer Z-Axis Vibrations

forward rotor blades to a version having independent rotor blades on both the forward and aft rotor. This resulted in five rigid fuselage models as explained in Section 3.4.5.

Beginning with the first rigid fuselage model incorporating uniform momentum rotor inflow and static stall blade behavior, the script was run in both RCAS v9 and v10. Runs executed with RCAS v10 did not achieve a trimmed solution. Each run would either fail after several days due to an inability to converge to a trimmed solution in the allotted number of iterations or would stop execution due to a 'STOP 91' error. Subsequently, the iterative parameters were increased and the tolerances were reduced as found in the following section of screen CONVERGETOL:

```
S CONVERGETOL
!# of   # of   # of   -Displacement Tolerance-   -Velocity Tolerance-  Min.
!Trim   PSol   Time    translation  rotation    translation rotation  # of
!Iter   Iter   Step     (ft)         (rad)       (ft/sec)   (rad/sec) PS Rev
a 30     40     72      0.02          0.01          5.0        2.0       5
c 40     30     72      0.002         0.001         0.18       0.09      5
c 90     60     72      0.02          0.01          5.0        2.0       5
```

The change to parameters in the second CHANGE line were significant but still did not result in a trimmed solution. Despite the failure of the first version of the rigid fuselage model to reach a trimmed solution, computational runs were attempted for the uniform inflow, dynamic stall model as well as the prescribed wake, static stall model. Neither reached a trimmed solution. Run times for these models before RCAS failure averaged between 3 and 5 days.

An alternative method of reaching a solution was tried in which the rigid fuselage models would use the trim variable solution matrix developed from a more basic CH-47D model. In early experimentation and modeling of the CH-47D baseline model, the single-blade analysis, prescribed wake model was modified to use six independent blades for analysis in the prescribed wake condition. This intermediate model reached a trimmed solution and created a matrix of control trim values which were stored in a matrix under the default filename RCASTRIMMATRIX.MAT. As can be seen in the Appendices and the following segment of script file, models can create a new trim matrix when running, or use an existing trim matrix.

```
S TRIMVAR
N
!                LOAD AND/OR SAVE TRIM SENSITIVITY MATRIX
!
!    Specify whether a trim sesitivity matrix is to be imported from
!    a file, loaded from a previous case or saved if it is calculated.
!    Also enter the file name for the trimsensitivity matrix.
!
!  LOAD,     SAVE                 Trim Sensitivity
!  PREV,     PNS                  Matrix Filename
a  SAVE                           RCASTRIMMATRIX.MAT
!a    LOAD                            RCASTRIMMATRIX.MAT
```

In addition to activating the appropriate line of input, the new trim matrix must be copied to the appropriate location in the file structure when executing RCAS.

The script files contained in Appendix A and Appendix B are only a portion of the RCAS file structure which create a model and execute the analysis. The .rcas file extension signifies a complete model which includes data lookup tables and addi-

tional model data which are referenced in the script file. When the user executes the Model_Name.rcas in RCAS the software will compile, check for errors, create a directory of the same name, and extract the embedded data tables, matrices, and scripts for use in the computations and analysis. The RCASTRIMMATRIX.MAT matrix is created during the model run and is therefore not present upon initial creation of this directory. Before instructing RCAS to begin the analysis, the RCASTRIMMATRIX.MAT which was created from the six-blade CH-47D baseline model was copied to the working directory of the model being tested. The RCAS analysis was then started.

To date, this method has not proven successful as can be seen in Figure 4.10 where the output of a basic rigid fuselage model has been plotted. The model used multi-blade modeling on the forward rotor only, uniform momentum inflow, static stall blade characteristics, and loaded a pre-solved RCASTRIMMATRIX file. The system completed its run through the assigned number of iterations in just over 24 hours, but did not reach a steady state condition from which to determine responses for comparison ('TRIMPASSED = 0'). Displacements in this figure are relative to the forward rotor hub. In this figure, blade1 on the forward rotor does not indicate any signs of blade flapping. This is one indication that the solutions found by RCAS do not meet realistic expectations since a rotor blade with a horizontal hinge pin would naturally displace in the vertical plane. From this output, it would seem that RCAS may have presented an intermediate solution found for the other two blades of the rotor.

The vibration harmonics experienced at the forward and aft pylon accelerometers were also plotted. These Z-axis acceleration harmonics are found in Figure 4.11. Though this is not a trimmed solution, the reader does have an opportunity to compare the non-trimmed results to expected results. Curiously, in this non-trimmed solution the aft rotor pylon experiences a greater vibration at the 6P harmonic than the forward pylon accelerometer. If this were a trimmed solution such a note would warrant additional scrutiny. Since this blade tip displacements seen in Figure 4.10

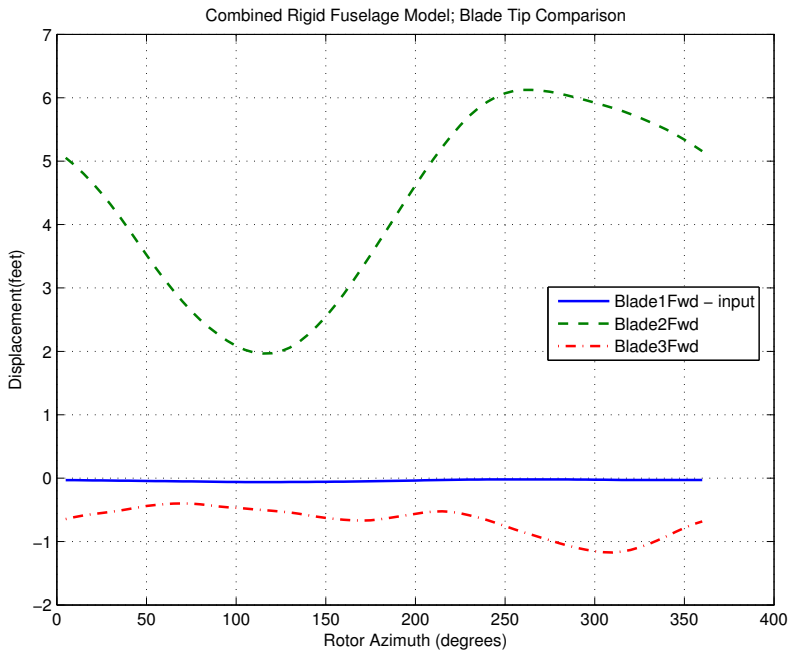

Figure 4.10: Unified Model Testing - Blade Tip Displacement Comparison

are clearly far from an accurate representation of the aircraft response, the vibration harmonics are not indicative of vibrations felt in the aircraft and are not suitable for analysis at this time.

Additional runs of this and other models continue to be attempted at the time of this writing. If this initial model eventually reaches a trimmed solution, the other rigid fuselage models will also be re-attempted using this method. Finally, each model will receive a range of faults entered into the different possible cases of the analysis section and computations will begin again using the earlier RCASTRIMMATRIX$\dot{M}$AT. If again successful, the nodal accelerations and vibrations of the model accelerometers will be converted to an inch-per-second (IPS) unit of measure. Using the AVA coefficients [22] a correction of additional blade weights, pitch link adjustments, or trim tab adjustments will be made to the model. The model will be re-run with these adjustments as well as the introduced fault. Resulting nodal displacements and accelerations will be observed. If the results are close to eliminating the vibrations

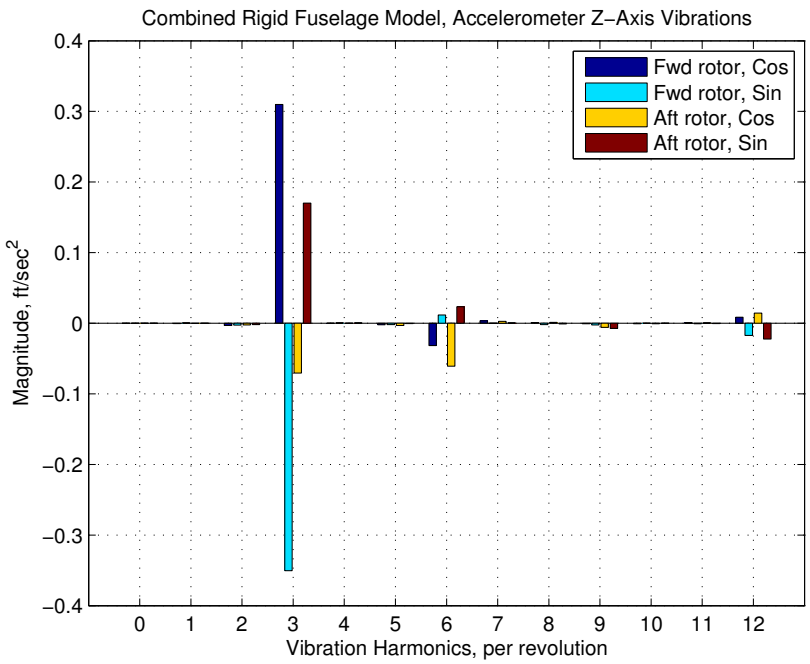

Figure 4.11: Unified Model Testing - Pylon Accelerometer Output

experienced at the accelerometer nodes, this will validate the capability of the rigid fuselage models to accurately model the CH-47D behavior.

4.6 Elastic Fuselage Model

As individual fault modeling progressed toward full functionality, efforts were made to work on the elastic fuselage model. Changes to the structural model were made as described in Section 3.4.4. The reorientation of the primitive structure axis required the most attention to detail to avoid simple mistakes in sign convention. Initial attempts to build the elastic fuselage model resulted in errors related to a possible mismatch of nodes between the structure and elastic fuselage. After some discussion of the nodal behavior of elastic structures, it was determined that the center node was not necessary for inclusion when evaluating behavior of the rotor hubs and individual blades. An eigenvector which describes the behavior of a particular node will fully represent the mode shape at that node and therefore does not require the evaluation of other eigenvectors in the elastic matrix [9]. Thus using only the two

eigenvectors for the rotor hub nodes enables the elastic fuselage model to predict elastic fuselage effects on the rotors and rotor blade responses.

The elastic fuselage changes were first made to a rigid fuselage model which only modeled the forward rotor as individual blades for blade analysis. Pitch link faults were incorporated to this first iteration of elastic fuselage model. The conditions of the model were set to minimize complexity; uniform inflow, static stall rotor blades, and a ground operating environment were selected or added as active data entry values. This first model variation compiled correctly but during iterations encountered an error related to 'FALOADS.' Reviewing the rigid fuselage model revealed a section of the script file which activated an additional model. The 'WORLD_MODEL_FUSRIGD_FUSEPS_FALOADS1_ALCOORD' model best fit the description of the error message. Based on the additional model name, this section of active code seems specific to fuselage air loads in a rigid fuselage environment. Given that the model under construction and experimentation was intended to model an elastic fuselage, the additional model was removed, which solved the 'FALOADS' error.

To date, no elastic fuselage models have successfully reached a trimmed solution. Errors have been inconsistent with some model variations reaching a conclusion but no converged solution, while other model variations have quit due to a 'floating point exception' or a 'STOP 91' error. Additional models are being tested where trim and iterative parameters are varied. If successful, the same process used for the rigid fuselage model of comparison to AVA coefficients will be used again for the elastic fuselage model results.

4.7 Summary Results

A review of representative combinations of cases which have been attempted is found in Table 4.1. Dozens of combinations were attempted when determining syntax and other formatting errors, however this table of models includes the most significant cases. The *Blades* category differentiates between the models which use

all individually analyzed blades and the models which individually analyze only the forward rotor. This is done by using a two word representation where the first word represents the forward rotor and the second word the aft rotor. For example, in the case 'Multi_Sgl' the forward rotor is composed of multiple individually designated rotors while the aft rotor is composed of a single rotor for purposes of analysis. The column marked *Solution?* is used because in some cases RCAS did not return a trimmed solution, but did return useful information at the completion of the maximum number of iterations. In other cases the RCAS would simply quit noting that a converged solution was not attained, while other cases returned an error message with possible usefulness. The *faults?* categories note whether or not the inputs for those types of faults were present and active, and if so what values were being supplied to the model. Due to the large number of variations tested for trim and periodic solution iterations, these categories are not included in the table. For the combined fuselage models, trim iterations frequently were tested as high as 90 iterations and periodic solution iterations up to 60 iterations in the screen CONVERGETOL. The number of trim updates designated in the multi-pages of screen TRIMVAR were as high as 60 updates.

Most of the results are straightforward, as has been discussed elsewhere in this chapter. However, two cases bring to light a potentially important issue. Note the models *H47all90_loadBASE01* and *H47all90_loadBASE03*. The only difference between these two models is the magnitude and sign of the pitch link change to a single rotor blade pitch link, yet one model encounters the 'STOP 91' error while the other reaches a suitable solution. This may indicate that the 'STOP 91' error is related to internal computational capabilities of the RCAS software and/or the system running this software.

Two model variations require further testing and possibly refinement. The trim tab fault models compile, which could lead to the inference that the fault modeling meets RCAS syntax requirements. The lack of a solution and the 'STOP 91' errors lead to the question of whether further RCAS version refinement may be necessary to

Table 4.1: Summary of Model Variations and Results

	Directory Name	RCAS ver.	Fuselage	Blades	Inflow	Blade Stall Model	Analysis	Compile?	TrimPassed?	Solution?	RCASTRIMMATRIX	Airspeed	Slide Fault?	RBM Fault?
		v9 / v10	Rigid / Elastic	Sgl_Sgl / Multi_Sgl / Multi_Multi	Uniform / Prescribed_Wake / Free Wake	Static / Dynamic	Trim / Periodic Solution	Y / N	Y / N	Y / N / error	Save / Load	ground / hover / 90kts / 150kts	No / (value)	No / (value)
Baseline	CH-47Dbaseline02	v9	Rigid	Sgl_Sgl	Prescribed_Wake	Dynamic	Trim	Y	Y	Y	Save	150	N	N
	CH-47D_baseline_mbV200	v9	Rigid	Multi_Multi	Prescribed_Wake	Dynamic	Trim	Y	Y	Y	Save	150	N	N
	mbCH-47Dbaseline90p	v9	Rigid	Multi_Multi	Prescribed_Wake	Dynamic	Trim	Y	N	Y	Save	90	N	N
	CH-47D_mb_V400	v9	Rigid	Multi_Sgl	Prescribed_Wake	Dynamic	Trim	Y			Save	150	N	N
Slide Tests	slide_test400	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	Y	Save	ground	0	N
	slide_test503	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	Y	Save	150	0.0833	N
	H47_PL_fh_POSn01	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Periodic Soln	Y	N/A	Y	Save	hover	(multi case)	N
	H47_PL_f89_POSn05	v10	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	error	Save	90	0	N
	H47_PL_ef90_POSn101	v9	Elastic	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	error	Save	90	(multi case)	N
	H47_PL_ef89_POSn08	v10	Elastic	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	error	Save	90	0	N
RBM Tests	H47_f_gRBM100	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	Y	Save	ground	0	0.0078
	H47_f_gRBM200	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	Y	Save	ground	0	0.0155
	H47_RBM_efg_UNI200	v9	Elastic	Multi_Sgl	Uniform	Dynamic	Periodic Soln	Y	N	error	Save	ground	0	0
Trim Tab	Multi_Sgl_TrimTab_V10	v9	Rigid	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	error	Save	150	0	N
	H47fwd_TabVerify101	v9	Rigid	Multi_Sgl	Uniform	Static	Trim	Y	N	STOP91	Save	150	0	N
	H47fwd_TabVerify300	v9	Rigid	Multi_Sgl	Uniform	Static	Trim	Y	N	STOP91	Save	150	0	N
Elastic	H47_all_gnd_eBASE02	v9	Elastic	Multi_Multi	Uniform	Static	Trim	Y	N	FPE	Save	ground	0	0
	H47fwd90_eBASEd03	v9	Elastic	Multi_Sgl	Uniform	Dynamic	Trim	Y	N	error	Save	90	0	0
	H47all90_loadEBASE00	v9	Elastic	Multi_Multi	Uniform	Static	Trim	Y	N	error	Load	90	0	0
Combined Models	H47_all_90_BASE04	v9	Rigid	Multi_Multi	Uniform	Static	Trim	Y	N	STOP91	Save	90	0	0
	H47all90_loadBASE01	v9	Rigid	Multi_Multi	Uniform	Static	Trim	Y	N	STOP91	Load	90	0.1	0
	H47all90_loadBASE03	v9	Rigid	Multi_Multi	Uniform	Static	Trim	Y	N	Y	Load	90	-0.05	0
	H47_fwd_90_loadBASE01	v9	Rigid	Multi_Sgl	Uniform	Static	Trim	Y	N	Y	Load	90	0	0
	H47_all_90_loadBASEp01	V9	Rigid	Multi_Multi	Prescribed Wake	Static	Trim	Y	N	STOP91	Load	90	0	0
	H47_all_90_BASEp01	v9	Rigid	Multi_Multi	Prescribed Wake	Static	Trim	Y	N	STOP91	Save	90	0	0
	H47_all_90_BASEd01	v9	Rigid	Multi_Multi	Uniform	Dynamic	Trim	Y	N	error	Save	90	0	0
	H47_all_90_BASEf01	v9	Rigid	Multi_Multi	Free Wake	Static	Trim	Y	N	STOP91	Save	90	0	0
	H47all90_loadEBASE00				running									
	H47all90_loadBASEpPS01				running									

FPE = floating point exception

sufficiently model trim tabs as elevon segments. The elevon segments do not seem to work properly with dynamic stall conditions. It may be possible that the analytical structure of the elevon segments also has weaknesses when using static stall modeling.

The second variation which requires further research is modeling of the elastic fuselage structure. As with the elevon segments, the models will compile but were unable to reach a converged solution. In most cases the model would run through the complete set of iterations and return an empty solution due to the lack of any convergence. This paper experimented with several different values of trim update and iterative solution data entries, but did not attempt to refine initial conditions or control mixer values as initial conditions changes. The values used were those found in other CH-47D models supplied by AMRDEC. Adjustments to these values may provide better solutions from RCAS.

V. Conclusions

This research was undertaken with the expectation of creating the models which have been discussed with the desire to begin building a database of vibration fault signatures. Limited success was achieved towards this goal. Assembling the CH-47D models capable of providing useful data for condition based maintenance practices has proven to be more challenging and time consuming than expected. As noted by the procedural steps of Chapter III and the output errors discussed in Chapter IV, the detailed assembly of each model requires a methodical and patient approach. The RCAS software package is an intricate tool with exacting demands on the analyst who is assembling the pieces of the puzzle which come together to form a simplified representation of a physical aircraft. The researcher would be well served to invest significant time exploring the capabilities and expectations of RCAS before beginning the assembly of complex simulations. Hundreds of model variations were built and tested over the past several months and it was found that the slightest change in iterative value or data entry can have a significant affect on the output of the calculations.

An area of improvement within the RCAS software is the capability of modeling dynamic stall characteristics over an airfoil with an attached elevon segment. The inability to simulate this flow characteristic may prove to be significant when attempting to solve vibration problems related to trim tab adjustment. At the time of this writing, the latest version of RCAS is being distributed along with updated user's manuals. An attempt to run the CH-47D rigid fuselage models with trim tab simulation on the new version of RCAS was not made, and therefore it is undetermined as to whether this apparent problem has been addressed. If it has not, then this capability should be addressed in order to enhance the accuracy of models when analyzing vibration characteristics, particularly in forward flight conditions.

Improvements in the functioning of these models may be found through changes to initial conditions and control positions as they are entered into screen CONTROLMIXER. The models have been shown to compile and seek a solution. In

some cases a trimmed, converged solution is found. In most, however, the trimmed solution is not met within defined limits but the results available indicate that with further computational time and more refined inputs, a complete and satisfactory solution may be possible. Future research should pay particular attention to the iterative and time values found in the analysis section. Smaller time increments during periodic solution analysis may increase the computational time, but allow the software to reach a converged solution.

Assembling complex computational models to simulate the aerodynamic and aeroelastic characteristics of the CH-47D is certainly within reach. With adjustments and tuning to the models discussed in this paper, it seems likely that a working model can be assembled and used by researchers for comparison of vibration characteristics. The resulting knowledge can then be integrated with existing health and usage monitoring systems to provide a means of improving the maintenance cycle of the CH-47D.

```
Rigid Fuselage Model

Abbreviated RCAS Model
**********************************************************************
MENU RCASROOT
!
COMMAND
!-------------------------------------------------------
! Structural Model Description
!-------------------------------------------------------
S SUBSYSIDS
a fusrigd
a rotorf
a rotora

S GFRAMEORIG
! G frame origin of the  node to which the G frame is attached.
!                    Primitive             Active Degrees of Freedom
!   Subsystem        Structure     Node    Translational  Rotational
!     Name             Name         ID        X  Y  Z       X  Y  Z
a    fusrigd           fuseps        1        1  1  1       1  1  1
N
!Type      ------ Translational ----    ------- Rotational --------
a DMP    4.440e+4  1.440e+5  4.440e+4  2.550e+6  2.160e+7  2.160e+7
a SPR    2.200e+6  2.200e+6  2.200e+6  6.300e+7  4.000e+8  4.000e+8

S SSORIGIN
!  Subsystem             Origin Coordinates
!    Name          x                  y               z
a   fusrigd        0                  0               0
a   rotorf         21.013             0         -7.1598
a   rotora        -17.8775            0         -11.8275

S SSORIENT
!  Subsystem     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
A   fusrigd      2       0         0       0         0       0
! The hub tilted 9 deg forward wrt fuselage (not fuselage tilt)
A   rotorf       2     171         0       0         0       0
! The hub tilted 4 deg forward wrt fuselage (not fuselage tilt)
A   rotora       2     176         0       0         0       0

S CONTROLMIXER
```

```
! Input pilot stick movement to swashplate pitch
! Control Value at zero   ------ Coefficients for Pilot Control -------
!  ID     pilot control    Coll.     Lat.     Long.      Pedal    Throt
a   1         0          .389557      0    -0.1193805      0        0
a   2         0             0     -.40003      0      -.6660200     0
!*************************************************************
! Control value 3, collective input to fwd swashplate, will vary
! for each altitude & airspeed combination
!*************************************************************
a   3       0         0         0        0        0        0  ! ground
!a   3     -.038      0         0        0        0        0  ! hover
!a   3     -.019006   0         0        0        0        0  ! 89kts
!a   3     -.06688    0         0        0        0        0  ! 136 kts
a   4        0     .389557      0   -0.1193805     0       0
a   5        0       0     -.40003     0      -.6660200     0
!*************************************************************
! Control value 6, collective input to aft swashplate, will vary
! for each altitude & airspeed combination
!*************************************************************
a   6       0        0        0        0         0        0   ! ground
!a   6    -.02       0        0        0         0        0   ! hover
!a   6     .005278   0        0        0         0        0   ! 89 kts
!a   6    -.061483   0        0        0         0        0   ! 136 kts
! Pitch link inputs to forward pitch link slides (blade 1f,2f,3f)
a   7       0.0       0        0        0         0        0  ! blade1f
a   8       0.0       0        0        0         0        0  ! blade2f
a   9       0.0       0        0        0         0        0  ! blade3f
! Pitch link inputs to aft pitch link slides (blade 1a,2a,3a)
a  10     0.0        0         0        0         0        0  ! blade1a
a  11     0.0        0         0        0         0        0  ! blade2a
a  12     0.0        0         0        0         0        0  ! blade3a
!*********************************************************
! Trim tab inputs only used with static stall aero condition
! Add ! to beginning of following lines when using
!  dynamic stall model iInput to forward trim tabs
a  13      0.0        0        0        0         0        0  ! blade1f
a  14      0.0        0        0        0         0        0  ! blade2f
a  15      0.0        0        0        0         0        0  ! blade3f
! Input to aft trim tabs
a  16      0.0        0        0        0         0        0  ! blade1a
a  17      0.0        0        0        0         0        0  ! blade2a
a  18      0.0        0        0        0         0        0  ! blade3a
!*********************************************************
```

```
S ROTNONCONST
!              Non-rotating                      Rotating
! Cnstr.  Subsystem Primitive  Node      Subsystem Primitive  Node
!  ID       Name      Name      ID         Name      Name      ID
a  1       fusrigd     fuseps    3        rotorf   blade1f     30
a  2       fusrigd     fuseps    5        rotora   blade1a     30

!*********************************************************************
!*********************************************************************
!                       FUSELAGE    SUBSYSTEM
!                            fusrigd
!*********************************************************************
!*********************************************************************

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
a fusrigd

S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    2

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a           fuseps

S PSORIGIN
!   Primitive       Primitive Origin Offset
!   Name          x            y            z
a   fuseps        0            0            0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
! fuselage rotated by 180 for elastic model only (elastic matrix)
a    fuseps       0        0         0       0         0       0
```

```
!*****************************************************************
!                  PRIMITIVE FOR FUSELAGE SUBSYSTEM
!                           fuseps
S PRIMITIVEID
A fuseps

S ELDATASETID
A fuseprop

S FENODE
! The data is based on 7 inch aft cg
!  node ID,   X,       Y,       Z
A      1      0.0      0       0.0
A      2     19.879    0       0.0
A      3     21.013    0    -7.1598
A      4    -18.7046   0    -1.2333
A      5    -17.8775   0   -11.8275
! Nodes added to represent accelerometers of HUMS
A      80    21.813    0    -4.6598
A      81   -19.7046   0    -9.3275

S RBMELE
! Generate rigid body mass element for fuselage mass & hub mass
! ELID,  node ID, prop ID
A    1      1       1
! Hub masses added at enode
A    6      3       2
A    7      5       3

S RIGIDBAR
! Fuselage is assumed to be rigid
!!  Element  Node1  Node2        Center of gravity offset
!!    ID      ID     ID        X            Y            Z
a     2       1      2         0            0            0
a     3       2      3         0            0            0
a     4       1      4         0            0            0
a     5       4      5         0            0            0
! Bars added to connect accelerometers to fuselage system
a     80      3      80        0            0            0
a     81      5      81        0            0            0


!*****************************************************************
```

```
!                      FWD ROTOR SUBSYSTEM
!*******************************************************************
 S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
a rotorf

 S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    1

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a       blade1f
a       blade2f
a       blade3f

S SINGLEBLADE
!!     Identical Blade      Number of
!!     Analysis Option      Blades
!!         (Y/N)           (2:9)
a           N               3

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
a  blade1f          30

S BLADECOMP
! Blade                   Primitive Structure Name(s)
! Index      1        2       3         4        5        6        7
a  1      blade1f    --      --        --       --       --       --
a  2      blade2f    --      --        --       --       --       --
a  3      blade3f    --      --        --       --       --       --

S PSORIGIN
!  Torque Offset of 1.58 inch
!   Primitive       Primitive Origin Offset
!   Name          x            y            z
a blade1f        0.0          0.131667      0
a blade2f        0.114026967 -0.0658335     0
```

```
a blade3f       -0.114026967 -0.0658335     0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   blade1f       3       0         0       0         0       0
a   blade2f       3     -120        0       0         0       0
a   blade3f       3     -240        0       0         0       0

S CONNCONST
! Define connectivity constraints between Primitives
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
a      1              blade2f      30            blade1f      30
a      2              blade3f      30            blade1f      30

S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
a        23.5619

!*************************************************************
!                       PRIMITIVE BLADE 1  FWD ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade1f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl1prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1         0.0        0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
```

```
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! Above, pitch bearing and controlled pitch hinge for pitch
! link extension/retractcion.
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
```

```
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide & slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a    201                     CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
```

```
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3       F        0           0             0
a  51     4      5       P        0           0             0
a  52     6      7       L        0           0             0
! Swashplate controlled pitch hinge
a  53    18     19       P        1           0             0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
```

```
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!=================== Number of Active DOF for each Direction =========
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Reference                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
A  12             0                    GCB_NLB_CH47.TAB
A  13             0                    GCB_NLB_CH47.TAB
A  14             0                    GCB_NLB_CH47.TAB
A  15             0                    GCB_NLB_CH47.TAB
A  16             0                    GCB_NLB_CH47.TAB
A  17             0                    GCB_NLB_CH47.TAB
A  18             0                    GCB_NLB_CH47.TAB
A  19             0                    GCB_NLB_CH47.TAB
A  20             0                    GCB_NLB_CH47.TAB
A  21             0                    GCB_NLB_CH47.TAB
A  22             0                    GCB_NLB_CH47.TAB
A  23             0                    GCB_NLB_CH47.TAB
A  24             0                    GCB_NLB_CH47.TAB
A  25             0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                53
a    2       SPLATR         0.0           HIN                53
a    3       SPLONG         0.0           HIN                53
a    7       DIRECT         0.0           SLD                211
```

```
!*********************************************************************
!                       PRIMITIVE BLADE 2  FWD ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade2f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl2prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1         0.0      0.0         0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
```

```
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24       1.67708  -.520797     0.0
! Outboard
a    25       3.333    -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27        0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18        1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19        1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20        1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate PL node
a    21        0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22        0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-PL
a    215      0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
```

```
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a   201      24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a   201                     CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
```

```
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!=============== Number of Active DOF for each Direction ============
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
```

```
A  12            0                    GCB_NLB_CH47.TAB
A  13            0                    GCB_NLB_CH47.TAB
A  14            0                    GCB_NLB_CH47.TAB
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                53
a    2       SPLATR         0.0           HIN                53
a    3       SPLONG         0.0           HIN                53
a    8       DIRECT         0.0           SLD                211

!*********************************************************************
!                          PRIMITIVE BLADE 3  FWD ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade3f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl3prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
```

```
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
```

```
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a   201                     CH47D_DAMPER_FILE
```

```
S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0             0
a  51     4      5        P        0           0             0
a  52     6      7        L        0           0             0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0             0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
```

```
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!================= Number of Active DOF for each Direction =========
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4            0                     GCB_NLB_CH47.TAB
A   5            0                     GCB_NLB_CH47.TAB
A   6            0                     GCB_NLB_CH47.TAB
A   7            0                     GCB_NLB_CH47.TAB
A   8            0                     GCB_NLB_CH47.TAB
A   9            0                     GCB_NLB_CH47.TAB
A  10            0                     GCB_NLB_CH47.TAB
A  11            0                     GCB_NLB_CH47.TAB
A  12            0                     GCB_NLB_CH47.TAB
A  13            0                     GCB_NLB_CH47.TAB
A  14            0                     GCB_NLB_CH47.TAB
A  15            0                     GCB_NLB_CH47.TAB
A  16            0                     GCB_NLB_CH47.TAB
A  17            0                     GCB_NLB_CH47.TAB
A  18            0                     GCB_NLB_CH47.TAB
A  19            0                     GCB_NLB_CH47.TAB
A  20            0                     GCB_NLB_CH47.TAB
A  21            0                     GCB_NLB_CH47.TAB
A  22            0                     GCB_NLB_CH47.TAB
A  23            0                     GCB_NLB_CH47.TAB
A  24            0                     GCB_NLB_CH47.TAB
A  25            0                     GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                53
a    2       SPLATR         0.0           HIN                53
a    3       SPLONG         0.0           HIN                53
```

```
a    9       DIRECT         0.0           SLD                211

!*****************************************************************
!                      AFT ROTOR SUBSYSTEM
!*****************************************************************
!==================================================

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
a rotora

 S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    1

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a       blade1a
a       blade2a
a       blade3a

S SINGLEBLADE
!!     Identical Blade      Number of
!!     Analysis Option      Blades
!!         (Y/N)           (2:9)
a           N               3

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
a  blade1a          30

S BLADECOMP
! Blade                  Primitive Structure Name(s)
! Index      1        2       3         4        5        6        7
a  1      blade1a    --      --        --       --       --       --
a  2      blade2a    --      --        --       --       --       --
a  3      blade3a    --      --        --       --       --       --

S PSORIGIN
```

```
!  Torque Offset of 1.58 inch
! Aft rotor PS origin same as FWD for offsets
!   Primitive       Primitive Origin Offset
!   Name          x            y           z
a blade1a       0.0          0.131667      0
a blade2a       0.114026967 -0.0658335     0
a blade3a      -0.114026967 -0.0658335     0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   blade1a       3       0         0       0         0       0
a   blade2a       3      120        0       0         0       0
a   blade3a       3      240        0       0         0       0

S CONNCONST
! Define connectivity constraints between Primitives
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
a      1              blade2a     30            blade1a      30
a      2              blade3a     30            blade1a      30

S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
a       -23.5619

!=====================================================
!                    PRIMITIVE BLADE 1 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade1a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl1prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001

S FENODE
```

```
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1         0.0      0.0         0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
```

```
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!                  CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                 File Name for
```

```
!    ID                    nonlinear table
a   201                   CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0             0
a  51     4      5        P        0           0             0
a  52     6      7        L        0           0             0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0             0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
```

```
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!============== Number of Active DOF for each Direction ===========
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4            0                    GCB_NLB_CH47.TAB
A   5            0                    GCB_NLB_CH47.TAB
A   6            0                    GCB_NLB_CH47.TAB
A   7            0                    GCB_NLB_CH47.TAB
A   8            0                    GCB_NLB_CH47.TAB
A   9            0                    GCB_NLB_CH47.TAB
A  10            0                    GCB_NLB_CH47.TAB
A  11            0                    GCB_NLB_CH47.TAB
A  12            0                    GCB_NLB_CH47.TAB
A  13            0                    GCB_NLB_CH47.TAB
A  14            0                    GCB_NLB_CH47.TAB
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
```

```
a    4       SPCOLL         0.0           HIN                53
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
a   10       DIRECT         0.0           SLD               211

!==================================================
!                   PRIMITIVE BLADE 2 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade2a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl2prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
```

```
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
```

```
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                   File Name for
!    ID                     nonlinear table
a   201                    CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
```

```
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!============== Number of Active DOF for each Direction ============
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
```

```
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
A  12             0                    GCB_NLB_CH47.TAB
A  13             0                    GCB_NLB_CH47.TAB
A  14             0                    GCB_NLB_CH47.TAB
A  15             0                    GCB_NLB_CH47.TAB
A  16             0                    GCB_NLB_CH47.TAB
A  17             0                    GCB_NLB_CH47.TAB
A  18             0                    GCB_NLB_CH47.TAB
A  19             0                    GCB_NLB_CH47.TAB
A  20             0                    GCB_NLB_CH47.TAB
A  21             0                    GCB_NLB_CH47.TAB
A  22             0                    GCB_NLB_CH47.TAB
A  23             0                    GCB_NLB_CH47.TAB
A  24             0                    GCB_NLB_CH47.TAB
A  25             0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    4       SPCOLL         0.0           HIN                53
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
a   11       DIRECT         0.0           SLD                211

!==============================================
!                    PRIMITIVE BLADE 3 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade3a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl3prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001
```

```
S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
```

```
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.
```

```
!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a   201                     CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
```

```
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!============= Number of Active DOF for each Direction =========
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4            0                    GCB_NLB_CH47.TAB
A   5            0                    GCB_NLB_CH47.TAB
A   6            0                    GCB_NLB_CH47.TAB
A   7            0                    GCB_NLB_CH47.TAB
A   8            0                    GCB_NLB_CH47.TAB
A   9            0                    GCB_NLB_CH47.TAB
A  10            0                    GCB_NLB_CH47.TAB
A  11            0                    GCB_NLB_CH47.TAB
A  12            0                    GCB_NLB_CH47.TAB
A  13            0                    GCB_NLB_CH47.TAB
A  14            0                    GCB_NLB_CH47.TAB
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
```

```
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    4       SPCOLL         0.0           HIN                53
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
a   12       DIRECT         0.0           SLD               211
!
!*********************************************************************
!                        PROPERTIES SET 2  FUSELAGE
!*********************************************************************
 S ELEPROPID
! List the names of element property data sets.
! element_prop_ID
a fuseprop

 S RBMPRP
! Mass at cg & hub  totalwt=33000lbs
! This data has been updated (cg data corresponds to 33000lbs)
!    mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
A 1   809.633    0  0  0     26368. 461.0 18840. 206570. 56.0 160900.
A 2   54.1000    0  0  0      40.   0     0.     37.     0    37.
A 3   61.9000    0  0  0      40.   0     0.     37.     0    37.


!*********************************************************************
!             PROPERTIES SET 1   BLADE 1 FWD ROTOR
!*********************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl1prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
```

```
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order, and
! tor shp fct order
a    1                 1               0                        1

!*********************************************************************
!             PROPERTIES SET 1   BLADE 2 FWD ROTOR
!*********************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl2prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
```

```
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order,
! and tor shp fct order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 3 FWD ROTOR
!*******************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl3prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order, and
! tor shp fct order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 1 AFT ROTOR
!*******************************************************************
```

```
S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a abl1prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order, and
! tor shp fct order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 2 AFT ROTOR
!*******************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a abl2prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
```

```
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order, and
! tor shp fct order
a    1                 1               0                        1

!*****************************************************************
!             PROPERTIES SET 1   BLADE 3 AFT ROTOR
!*****************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a abl3prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)
```

```
S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fct id,axial shp fct order,bending shp fct order, and
! tor shp fct order
a    1                 1               0                        1

!*********************************************************************
!                        DEFINE AERODYNAMIC MODEL
!*********************************************************************

S AEROMODCOMP
! List of Supercomponent of the system
a   fusead
a   adrotorf
a   adrotora

S SCORIGIN
!  Supercomponent          Origin Coordinates
!       Name          x            y            z
a   fusead           0            0            0
a   adrotorf         21.013       0         -7.1598
a   adrotora        -17.8775      0         -11.8275

S SCORIENT
! Supercomponent   rotation 1        rotation 2        rotation 3
!       Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   fusead          2       0         0       0         0       0
a   adrotorf        2     171         0       0         0       0
a   adrotora        2     176         0       0         0       0

!               Airfoil Tables
s AIRFOIL
!                        2-D AIRFOIL TABLES (Table Look-Up)
!  Airfoil ID  ------------- Airfoil Data File Name --------------
a VR8TM6                      VR8TABM6.C81
a VR7TM6                      VR7TABM6.C81
```

```
a VR7TM4P5                  VR7TABM4P5.C81
N
!                 SPECIFY AIRFOIL COEFFICIENTS (Linear Aerodynamics)
!  Airfoil   -- Linear Airfoil Coefficients --     Zero Lift Angle
!    ID      C_radial    CL_a      CD       CM     of Attack (deg)
a  VR8TM6      0         X.XX     X.XXXX   X.XXX       0
a  VR7TM6      0         X.XX     X.XXXX   X.XXX       0
a  VR7TM4P5    0         X.XX     X.XXXX   X.XXX       0
N
!   Airfoil           Nonlinear UnSteady and Dynamic Stall
!     ID            Airfoil Data File Name (Leishman-Beddos)
a  VR8TM6                          VR8TABM6.LEI
a  VR7TM6                          VR7TABM6.LEI
a  VR7TM4P5                        VR7TABM4P5.LEI

!            AERODYNAMIC INTERFERENCE FOR SUPERCOMPONENTS
!
!  Enter row IDs, and for each row input the name of the supercompont
!  which creates aerodynamic interference, the name of the supercompont
!  that is affected by the aerodynamic interference and the type of
!  aerodynamic interference model.
!  Examples:
!   Row       From             To             Interference
!   ID   Supercomponent  Supercomponent         Model
!    1       rotor1          rotor2        simple-rotor-to-rotor
!    2       ground          rotor2       blockage-ground-effect
!    3       bodya           rotor1        body-source-sink
!    4       winga           rotor2        simple-horseshoe-vortex
!    5       rotor1          bodya         cylindrical-vortex-sheet
!    6       rotor1          bodya             vortex-wake

S INTERFERENCE
!  Row       From             To                 Interference
!  ID    Supercomponent   Supercomponent             Model
a   1    ADROTORF    ADROTORA  simple-rotor-to-rotor     0.000     0.000
a   2    ADROTORF    FUSEAD    cylindrical-vortex-sheet  0.000     0.000
a   3    ADROTORA    ADROTORF  simple-rotor-to-rotor     0.000     0.000
a   4    ADROTORA    FUSEAD    cylindrical-vortex-sheet  0.000     0.000
N
! Interf  Far   Horseshoe  Vortex     Block/
! update  wake  vortex     sheet      ground
! intrvl  opt   core size  thickness  effect
!                                     factor
```

```
a   1     0      .1        .1          1.
N
!    Aero-body-dimensions    Source
!    lx       ly       lz    update
!                            rate
a    50.75     7.5     7.5     12

!==================================================
!               FUSELAGE AERODYNAMICS
!==================================================
S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          fusead

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a        fusrigd

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body  4 => AUX ROT
a     3

S COMPID
! List the Components which comprise the Supercomponent  Wing
! Component     Primitive   CP Root   Blade tip         Right End
!  Name(s)      Structure    El_id     node_id            Node_ID
a  fusecp         fuseps       1           0                 0

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  fusecp         0            0            0

S CPORIENT
! Component     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  fusecp        0      0         0       0         0       0

S INFLOW
! inflow option
! 0 => no inflow 1 => Uniform, 2 => uniform for full wing,
! 3 => dynamic inflow, 4 => Classical wake,
! 5 => prescribed generalized wake, 6 => free wake
```

```
a        0

S AEROPTION
! Dyn Stall opt
!      0 => static stall
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                           separation
!      3 => Leishmann model - w/ separation
!                                           + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           0                 1          0

!-----------------------------------------------------------------------
!                 Define Aerodynamic Component FUSECP

S AEROCOMPID
! Component name for defining or modifying
a FUSECP

S COMPTYPE
! 1 => lifting surface,  2 => body    3 => AUX ROT
a 2

s BODYAEROTAB
!       option 1 and external file for aerodynamic coefficients or
a  1 F_CH47_BODY_BODY_AERO.TAB  0.0  0.0  0.0  0.0  0.0  0.0  0.0

!=========================================================
!       FORWARD ROTOR MODELING
!=========================================================
!======== AERODYNAMIC SUPERCOMPONENT ================
!                   FWD ROTOR
```

```
S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          adrotorf

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body, 4=> aux rotor
a 1

S COMPID
! List the Components which comprise the Supercomponent
! Component     Primitive   CP Root   Blade tip
!  Name(s)      Structure    El_id     node_id
a  ablade1f     blade1f        0           14
a  ablade2f     blade2f        0           14
a  ablade3f     blade3f        0           14

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  ablade1f      0.0          0.131667      0
a  ablade2f      0.114026967 -0.0658335     0
a  ablade3f     -0.114026967 -0.0658335     0

S CPORIENT
! Component     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  ablade1f       3      0         0       0         0       0
a  ablade2f       3    -120        0       0         0       0
a  ablade3f       3    -240        0       0         0       0

S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a        1

S AEROPTION
! Dyn Stall opt
!      0 => static stall
```

```
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                          separation
!      3 => Leishmann model - w/ separation
!                                          + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           5                0
c     0           0        0           3                0
!*********************************************************************
! Deactivate the following line for dynamic stall modeling
c     0           0        0           0                0

S INFLOWCONV
! Define input circulation convergence parameters
! damping factor, convergence tolerance, number of iterations
a  0.05                    0.001                299
c  0.05                    0.0001                299
c  0.05                    0.0004                299

S THRUSTAVE
! thrust ave option, no. time steps, initial thrust,
! and no. Revs for TPP averaging
a         2                72              16745.0                 1

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a         rotorf

!==================================================
! ******************************************************************
! Activate SCREENS and data entry lines in the
! PRESWAKE and FREEWAKE screens when
! modeling non-uniform inflow models.
```

```
! ******************************************************************
!S PRESWAKE
! Multiscreen: 1  of 8    Type: Non-iterative    Screen: PRESWAKE
!
!                      SPECIFY VORTEX WAKE OPTIONS FOR ROTOR
!                           PRESCRIBED AND/OR FREE WAKE
! CURRENT_AEROSUPERCOMPONENT_ID: ADROTOR
! +---------------- Wake Geometry Options ----------------+
! | Single |  Wake  | Flag for | Constant  | Inboard Wake |
! |   or   |  Geom. | Straight | or Linear | Vortex Sheet |
! |  Dual  |  Model | or Curve |  Segment  |     or       |
! |  Peak  | Option |  Vortex  | Vorticity | Vortex Line  |
! | (1/2)  | (1/7)  |  (0/1)   |   (0/1)   |   (0/1)      |
! +-------------------------------------------------------+
! Classical vortex wake with no distortion, single peak
!a     1        1         0          1            0
N
! +---------------------- Wake Geometry Specs ------------------------+
! |  Number   |  Near Wake | Rollup Wake | Number of  |   Initial   |
! |  of Wake  |  Azimuthal |  Azimuthal  | Revs for   |   Radial    |
! | Azimuthal |  Coverage  |  Coverage   | Far Wake   | Position of |
! | Steps/Rev |   (0:180)  |   (0:360)   |  (0:20)    | Rollup Wake |
! +-------------------------------------------------------------------+
!a      72        60             120           3.0           1.0
N
! +-------------- Inflow Calculation Specs ----------------+
! | Flag for |  1/4 or 3/4   | Max.  Bound | Min. Sepration|
! | Inplane  | Chord colloc. | Circulation |   Between     |
! | Velocity |  points for   |  Fraction   |  Colocation   |
! | Calcula. | Induced Vel.  |  for Tip    |  points and   |
! |  (0/1)   | Calculations  |   Vortex    | Vortex Sheets |
! +-------------------------------------------------------+
!a    1             0                0.8            0.01
N
! +---------------------- Core Type and Size-------------------+
! |  Tip   | Inb'rd |  Tip  | Tip Vortex | Inbrd | Inbrd | Near | Dual |
! | Vortex | Vortex | Vortx |  Core for  | Trailed| Shed | Wake | Peak |
! |  Core  |  Core  |  Core |   Inboard  | Vortex | Wake | Core | Core |
! |  Type  |  Type  |  Size |  Coloc.Pts.|  Core  | Core | Size | Size |
! +-----------------------------------------------------------------+
!a     0       0     0.02982    0.02982       0.     0.   0.02982   0.
N
! +---------------------------------------+
```

```
! |--Tip Vortex Core Model and Size for --|
! |--- Inboard Wake Collocation Points ---|
! |---------------------------------------|
! |  Option | Core Size at | Core Size at |
! |  (0/1)  | Inner Radius | Outer Radius |
! +---------------------------------------+
!a      1          0.76          0.88
N
! +--------- Exclude/Include Wake Model (0/1) ----------+
! |  Tip   |  Near Wake   | Rollup Wake  |   Far Wake   |
! | Vortex |--------------|--------------|--------------|
! |  Wake  | shed | trail | shed | trail | shed | trail |
! +-------------------------------------------------------+
!a     1       0      1       0      1       0      1
N
! +------------------- Prescribed Wake Geometry Data -----------------+
! | Vortex   |----- Factors -----|----------- Constants --------------|
! | Location |  f1    |   f2   |   K1  |   K2   |    K3   |    K4     |
! +-----------------------------------------------------------------+
!A     1         1         1        1        1        1        1
!A     2         1         1        1        1        1        1
!A     3         1         1        1        1        1        1
N
! Exclude ground effect
! +-------------- Ground Effect Parameters ---------------+
! | Include  | Minimum   | Include  |  Ground  |  Ground  |
! |  Ground  | Wake/Grnd |  Ground  |  Vortex  |  Vortex  |
! | Effects  | Clearance |  Vortex  |   Core   | B Factor |
! +-------------------------------------------------------+
!a      0           0.2        0          0.1          0.8

!=====================================================
!============= AERODYNAMIC COMPONENT ==============
!                         ablade1f

S AEROCOMPID
! Component name for defining or modifying
a ablade1f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1
```

```
S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID       ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
```

```
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          13
a  12  .0375939  .667    .60          1          0          13
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!=============== AERODYNAMIC COMPONENT ==============
!                           ablade2f

S AEROCOMPID
! Component name for defining or modifying
a ablade2f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
```

```
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
```

```
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          14
a  12  .0375939  .667    .60          1          0          14
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!============== AERODYNAMIC COMPONENT ===============
!                           ablade3f

S AEROCOMPID
! Component name for defining or modifying
a ablade3f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
```

```
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID       ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ********************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
```

```
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          15
a  12  .0375939  .667    .60          1          0          15
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!=====================================================
!=========== AERODYNAMIC SUPERCOMPONENT ==========
!                                AFT ROTOR

S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          adrotora

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body, 4=> aux rotor
a 1

S COMPID
! List the Components which comprise the Supercomponent
! Component     Primitive   CP Root   Blade tip
!  Name(s)      Structure    El_id     node_id
a  ablade1a     blade1a        0           14
a  ablade2a     blade2a        0           14
a  ablade3a     blade3a        0           14

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  ablade1a      0.0          0.131667      0
a  ablade2a      0.114026967 -0.0658335     0
a  ablade3a     -0.114026967 -0.0658335     0

S CPORIENT
! Component     rotation 1        rotation 2        rotation 3
```

```
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  ablade1a       3      0         0       0         0       0
a  ablade2a       3     120        0       0         0       0
a  ablade3a       3     240        0       0         0       0

S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a        1

!S DYNINFDATA
! 7 and 7 will produce a 36 state model
!  Number of                 Number of
! Polynomials                Harmonics
!A    1                          1

S AEROPTION
! Dyn Stall opt
!      0 => static stall
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                          separation
!      3 => Leishmann model - w/ separation
!                                          + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           5                0
c     0           0        0           3                0
!*********************************************************************
! Deactivate the following line (use !) for dynamic stall modeling
```

```
c     0           0        0           0                0

S INFLOWCONV
! Define input circulation convergence parameters
! damping factor, convergence tolerance, number of iterations
a  0.05                    0.001                299
c  0.05                    0.0001                299
c  0.05                    0.0004                299

S THRUSTAVE
! thrust ave opt., no. time steps, init. thrust, no. Revs for TPP avging
a         2                72              16745.0                 1

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a         rotora

!=====================================================
! ******************************************************************
! Activate SCREENS and data entry lines in the PRESWAKE and
! FREEWAKE screens when modeling non-uniform inflow models.
! ******************************************************************
!S PRESWAKE
! Multiscreen: 1  of 8    Type: Non-iterative    Screen: PRESWAKE
!
!                 SPECIFY VORTEX WAKE OPTIONS FOR ROTOR
!                      PRESCRIBED AND/OR FREE WAKE
! CURRENT_AEROSUPERCOMPONENT_ID: ADROTOR
! +---------------- Wake Geometry Options ----------------+
! | Single |  Wake  | Flag for | Constant  | Inboard Wake |
! |   or   |  Geom. | Straight | or Linear | Vortex Sheet |
! |  Dual  |  Model | or Curve |  Segment  |     or       |
! |  Peak  | Option |  Vortex  | Vorticity | Vortex Line  |
! | (1/2)  | (1/7)  |  (0/1)   |   (0/1)   |   (0/1)      |
! +-------------------------------------------------------+
! Classical vortex wake with no distortion, single peak
!a     1        1         0          1            0
N
! +---------------------- Wake Geometry Specs ------------------------+
! |  Number   |  Near Wake | Rollup Wake | Number of  |   Initial   |
! |  of Wake  |  Azimuthal |  Azimuthal  | Revs for   |   Radial    |
! | Azimuthal |  Coverage  |  Coverage   | Far Wake   | Position of |
! | Steps/Rev |   (0:180)  |   (0:360)   |  (0:20)    | Rollup Wake |
```

```
! +-------------------------------------------------------------+
!a      72        60             120           3.0           1.0
N
! +-------------- Inflow Calculation Specs ----------------+
! | Flag for |  1/4 or 3/4   | Max.  Bound | Min. Sepration|
! | Inplane  | Chord colloc. | Circulation |   Between     |
! | Velocity |  points for   |  Fraction   |  Colocation   |
! | Calcula. | Induced Vel.  |  for Tip    |  points and   |
! |  (0/1)   | Calculations  |   Vortex    | Vortex Sheets |
! +-----------------------------------------------------+
!a    1             0                0.8            0.01
N
! +---------------------- Core Type and Size-------------------+
! |  Tip   | Inb'rd |  Tip  | Tip Vortex | Inbrd | Inbrd | Near | Dual |
! | Vortex | Vortex | Vortx |  Core for  | Trailed| Shed | Wake | Peak |
! |  Core  |  Core  |  Core |   Inboard  | Vortex | Wake | Core | Core |
! |  Type  |  Type  |  Size |  Coloc.Pts.|  Core  | Core | Size | Size |
! +-----------------------------------------------------------------+
!a     0       0     0.02982    0.02982       0.     0.   0.02982   0.
N
! +---------------------------------------+
! |--Tip Vortex Core Model and Size for --|
! |--- Inboard Wake Collocation Points ---|
! |---------------------------------------|
! |  Option | Core Size at | Core Size at |
! |  (0/1)  | Inner Radius | Outer Radius |
! +---------------------------------------+
!a      1          0.76          0.88
N
! +--------- Exclude/Include Wake Model (0/1) ----------+
! |  Tip   |  Near Wake   | Rollup Wake  |   Far Wake   |
! | Vortex |--------------|--------------|--------------|
! |  Wake  | shed | trail | shed | trail | shed | trail |
! +-----------------------------------------------------+
!a     1       0      1       0      1       0      1
N
! +------------------- Prescribed Wake Geometry Data -----------------+
! | Vortex   |----- Factors -----|----------- Constants --------------|
! | Location |  f1    |   f2   |   K1  |   K2   |    K3   |    K4     |
! +-------------------------------------------------------------------+
!A     1         1         1        1        1        1        1
!A     2         1         1        1        1        1        1
!A     3         1         1        1        1        1        1
```

```
N
! Exclude ground effect
! +-------------- Ground Effect Parameters ---------------+
! | Include  | Minimum   | Include  |  Ground  |  Ground  |
! |  Ground  | Wake/Grnd |  Ground  |  Vortex  |  Vortex  |
! | Effects  | Clearance |  Vortex  |   Core   | B Factor |
! +-------------------------------------------------------+
!a      0           0.2        0          0.1          0.8


!=========================================================
!============== AERODYNAMIC COMPONENT ==================
!                         ablade1a

S AEROCOMPID
! Component name for defining or modifying
a ablade1a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
```

```
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  ELment  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          16
a  12  .0375939  .667    .60          1          0          16
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
```

```
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!============== AERODYNAMIC COMPONENT ==============
!                        ablade2a

S AEROCOMPID
! Component name for defining or modifying
a ablade2a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
```

```
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          17
a  12  .0375939  .667    .60          1          0          17
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6
```

```
!============== AERODYNAMIC COMPONENT =============
!                        ablade3a

S AEROCOMPID
! Component name for defining or modifying
a ablade3a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID       ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
```

```
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          18
a  12  .0375939  .667    .60          1          0          18
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!=========================================================
!=============== Additional Model ============================
!=========================================================

S ADDRSCOPEMODEL
a   WORLD_MODEL_FUSRIGD_FUSEPS_FALOADS1_ALCOORD  =  1
```

```
!=========================================================
!=============== ANALYSIS DATA ============================
!=========================================================

S SELANALYSIS
!  Trim analysis
!  Trim Options: 1 - Trim; 2 - Periodic Solution; 3 - Static Analysis
! Case_id Trim, Maneuver, Stability, Init_condn, Scope Script_Filename
a     1     1       0          0         D               NO
! ******************************************************************
! Example of multi-case analysis below
!a     2     1       0          0         D               NO
!a     3     1       0          0         D               NO
!a     4     1       0          0         D               NO
!a     5     1       0          0         D               NO
!a     6     1       0          0         D               NO
!a     7     1       0          0         D               NO
! ******************************************************************
N
! Case_id    Case_Title
a   1         ground_6blades_base
! ****************************************************
! Example of multi-case analysis continues below
!a   2         ground_5n
!a   3         ground_10n
!a   4         ground_15n
!a   5         ground_35n
!a   6         ground_70n
!a   7         ground_1slug
!N
!Multiscreen: 3  of 4    Type: Iterative      Screen: SELANALYSIS
!                       DEFINE CASE VARIABLES
! Case_Var   --Screen Name--  Data_Group_id   Screen  Field   Row
!    _ID                       ("--" if none)   Nbr    Nbr    Nbr
!a    1       CONTROLMIXER        --             1      2      7
!a    2       RBMELE            blade1f          1      2      1

!N
!Multiscreen: 4  of 4    Type: Iterative      Screen: SELANALYSIS
!                  SPECIFY VALUES FOR THE CASE VARIABLE
!Note: The values specified in this screen for the defined variables
!      will supersede the information given in the respective screen.
```

```
!Row ID    Case_Var_ID     Case ID                Value
!                                          (Numeric or Character)
!a  1            1             1                     0
!a  2            1             2                     0.0019841271
!a  3            1             3                     0.003968254
!a  4            1             4                     0.0059523813
!a  5            1             5                     0.0138888896
!a  6            1             6                     0.0277777792
!a  7            2             7                     1.00
! End of multi-case analysis example code
! ***************************************************************

S SYSTEMFLAGS
! Global element formulation flags
! gravity, aero (1=Yes, 0=No)
a    1               1

S INITCOND
! Initial Pilot Controls , ft
!  collective, lateral, longitudinal, pedal, throttle
a     0.0       0.0          0.0          0.0        0.0  ! ground
!a     0.13133   0.0         0.0           0.0        0.0  ! hover
!a     0.216     0.0049      0.0042       -0.007      0.0  ! 89 kts
!a     0.393     0.004      -0.049        -0.008      0.0  ! 136kts
N
! G position Frame wrt I
!  X  Y    Z    Roll   Pitch   Yaw
a  0  0    0     0.0     0.0      0.0  ! ground/hover
!a  0  0    0    -.004    0.027    0.0  ! 89kts
!a  0  0    0    -.0075  -0.052    0.0  ! 136kts
N
! G velocity Frame wrt I
! forward velocity is defined in screen CONSTWIND
! Vx Vy Vz OmegaX OmegaY OmegaZ
a  0  0  0   0      0      0

S CONSTWIND
! Constant Wind velocity with respect to I frame in I coord.
!     Vx,       Vy,       Vz
a     0.        0.        0.  ! ground/hover
!a   -150.070     0.        0.  ! 89 kts
!a   -230.320     0.        0. ! 136 kts
```

```
S TRIMVAR
! trimvar=pilots coll,lateral,long.directional
! 1 =coll, 2=latcy, 3=longcy, 4=pedal, 5=throttle, 6=roll,
! 7=pitch,8=yaw,9=climbvel
! VarID  PertVal  DampFact  TargetID  TargetVal  TargetTol
a   1      0.02       0.7       3        0.0        20.0
a   2      0.02       0.7       4        0.0        100.0
a   3      0.02       0.7       5        0.0        100.0
a   4      0.02       0.7       6        0.0        300.0
a   6      0.01       0.7       2        0.0        20.0
a   7      0.01       0.7       1        0.0        20.0
N
! Specify the target ID and the concatenated name of the trim target.
! The trim target name consists of the subsystem name, primitive
! structure name, node name, and force or moment name.
! NODE5 is a node name. PFRC(2) is a force name, and PMOM(1)
! is a moment name. Contantenation should be done by underscores.
!
N
!                LOAD AND/OR SAVE TRIM SENSITIVITY MATRIX
!
!    Specify whether a trim sesitivity matrix is to be imported from
!    a file, loaded from a previous case or saved if it is calculated.
!    Also enter the file name for the trimsensitivity matrix.
!
!  LOAD,     SAVE                 Trim Sensitivity
!  PREV,     PNS                  Matrix Filename
a  SAVE                           RCASTRIMMATRIX.MAT
!a    LOAD                            RCASTRIMMATRIX.MAT
N
!                USER DEFINED TRIM LOOP AND UPDATES
!    Enter row IDs, and for each row enter option to compute trim
!    sensitivity matrix, inflow model during the calculation of trim
!    sensitivity matrix, number of trim variable updates and inflow
!    model during the trim updates.
!
!  Row   Number of  Inflow model for  Option to Compute   Inflow model
!  ID  Trim Updates   Trim updates    Trim Matrix (0/1)  for Trim Matrix
a  1       60            uniform             0            uniform
! ACTIVATE the following line if modeling with prescribed wake condition
!a  2      30            preswake             0            uniform
! ACTIVATE the following line if modeling with a free wake condition
!a  3      40            freewake             0             uniform
```

```
!N

S CONVERGETOL
!# of  # of  # of  -Displacement Tolerance-   -Velocity Tolerance-  Min.
!Trim  PSol  Time   translation  rotation    translation rotation  # of
!Iter  Iter  Step    (ft)         (rad)       (ft/sec)  (rad/sec) PS Rev
a 30    40    72     0.02          0.01          5.0       2.0       5
c 40    30    72     0.002         0.001         0.18      0.09      5
c 90    60    72     0.02          0.01          5.0       2.0       5

S INTEGPARAM
! Define Newmark-Beta/HHT integration parameters
! no. nonlinear state iterations, Newmark constants, displacement
! and velocity tolerances, UNDER RELAXTION FACTOR,
! NR iterations
!  iter,  NMB_a,  NMB_d,  HHT_a,  disp-tol, vel-tol, U_relax fac
a    99    .25     .5      -.03     1.e-5     1.e-4      1.0
c    99    .25     .5      -.03     1.e-6     1.e-6      1.0

S STATICEQUI
! Input data for static equilibrium.
! row    no. of    relaxation  convergence         Minimum
! ID   iterations    factor     tolerance         Stiffness
a  1        5           .1       1.01               10000
a  2        5           .2       1.01                5000
a  3        5           .3       1.01                2000
a  4        5           .5       1.01                1000
a  5       15           .6       1.01                 500
a  6       15           .7       1.01                 200
a  7       15           .8       1.01                   0
a  8       15           .8       1.01                   0
a  9       15           .8       1.01                   0
a 10       15           .8       1.01                   0
a 11       15           .8       1.01                   0
a 12       15           .8       1.01                   0

S AEROSTATCONST
! Define aerostatic conditions for standard sea level
! Spec-type, altitude, temp, air density, sound velocity
a       1        0       0       0              0

 S COMMPERIOD
!DEFINE THE COMMON PERIOD OF ALL ROTORS FOR TRIM
```

```
!   Name       Rotor Period Ratio    Tolerance
a  rotorf            1                  .1

S BATCHOUTPUT
!  Row                    Output
!   ID                   Filename
a    1                   fwd_mom_vib.par
a    2                   aft_mom_vib.par
a    3                   fwd_mom_stdy.par
a    4                   aft_mom_stdy.par
a    5                   f_hub.par
a    6                   m_hub.par
a    7                   pll_dmp.par
a    8                   cf.par

S UDFOUTPUTS
!  Row   Analysis    ------------- Rscope Variable -------------
!   ID    Type                        Name
a     1      TRM         world_model_rotorf_blade1f_e200spr_sprforce
a     2      TRM         world_model_rotora_blade1a_e200spr_sprforce
a     3      TRM         world_model_rotorf_blade1f_e201dmp_dmpforce
a     4      TRM         world_model_rotora_blade1a_e201dmp_dmpforce

S PERIODICOUTPUT
!  Row   Subsystem   Prim. Struc.            output
!  ID      Name        Name                 category
a   1      all         all                  vibration
a   2      all         all                  airloads
!a   3      all         all                  sys.dyn.resp
a   4      all         all                  internal.loads

S SAVESC
! Form of SC Data             Directory and File Name     Number of
! (RDB or FILES)                  for SC Data            Output Steps
!   <SCFORM>                      <SCFILNAM>             in One File
a   RDB                     RGDFUSE_6BLADE_BASELINE.SAV       72

S RUNALLCASES
!    Run All Cases Flag (0/1)
a               1

S STOPANALYSISAT
!                    SPECIFY STOPANALYSIS BREAKPOINT
```

```
!
! Enter a number between 0 and 8 to specify how far the program should
! proceed through the analysis.
!
!   0 ->      Go through all the analysis
!   1 ->      Stop after the model is loaded
!   2 ->      Stop after blade modes are generated/ before assembly
!   3 ->      Stop after assembly is complete
!   4 ->      Stop after static equilibrium is completed and
!             before trim or maneuver is started
!   5 ->      Stop after periodic solution is completed and
!             before trim or maneuver is started
!   6 ->      Stop after trim is complete and
!             before maneuver is started
!   7 ->      Stop after maneuver is completed
!   8 ->      Stop after stability is completed
!       Analysis Breakpoint
!         indicator (0/8)
a   0

EXIT

COMMAND

MENU RUNANALYSIS
```

```
Elastic fuselage, uniform inflow, static stall BASE model

Abbreviated RCAS Model
**********************************************************************
MENU RCASROOT
!
COMMAND
!-------------------------------------------------------
! Structural Model Description
!-------------------------------------------------------
S SUBSYSIDS
a fusCH47D
a rotorf
a rotora

S GFRAMEORIG
! G frame origin of the  node to which the G frame is attached.
!                    Primitive             Active Degrees of Freedom
!   Subsystem        Structure     Node    Translational  Rotational
!     Name             Name         ID        X  Y  Z       X  Y  Z
a    fusrigd           fuseps        1        1  1  1       1  1  1
N
!Type      ------ Translational ----    ------- Rotational --------
a DMP    4.440e+4  1.440e+5  4.440e+4  2.550e+6  2.160e+7  2.160e+7
a SPR    2.200e+6  2.200e+6  2.200e+6  6.300e+7  4.000e+8  4.000e+8

S SSORIGIN
!  Subsystem             Origin Coordinates
!    Name          x            y            z
a   fusCH47D       0            0            0
a   rotorf         21.013       0         -7.1598
a   rotora        -17.8775      0         -11.8275

S SSORIENT
!  Subsystem     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
A   fusCH47D     2       0         0       0         0       0
! The hub tilted 9 deg forward wrt fuselage (not fuselage tilt)
A   rotorf       2     171         0       0         0       0
! The hub tilted 4 deg forward wrt fuselage (not fuselage tilt)
A   rotora       2     176         0       0         0       0

S CONTROLMIXER
```

```
! Input pilot stick movement to swashplate pitch
! Control Value at zero   ------ Coefficients for Pilot Control --------
!  ID     pilot control    Coll.     Lat.     Long.      Pedal    Throt
a   1         0          .389557      0    -0.1193805      0        0
a   2         0             0     -.40003      0      -.6660200     0
!*****************************************************************
! Control value 3, collective input to fwd swashplate, will vary
! for each altitude & airspeed combination
!*****************************************************************
a   3       0         0         0        0        0        0  ! ground
!a   3     -.038      0         0        0        0        0  ! hover
!a   3     -.019006   0         0        0        0        0  ! 89kts
!a   3     -.06688    0         0        0        0        0  ! 136 kts
a   4        0     .389557      0   -0.1193805     0       0
a   5        0       0     -.40003     0      -.6660200     0
!*****************************************************************
! Control value 6, collective input to aft swashplate, will vary
! for each altitude & airspeed combination
!*****************************************************************
a   6       0        0        0        0         0        0   ! ground
!a   6    -.02       0        0        0         0        0   ! hover
!a   6     .005278   0        0        0         0        0   ! 89 kts
!a   6    -.061483   0        0        0         0        0   ! 136 kts
! Pitch link inputs to forward pitch link slides (blade 1f,2f,3f)
a   7       0.0       0        0        0         0        0  ! blade1f
a   8       0.0       0        0        0         0        0  ! blade2f
a   9       0.0       0        0        0         0        0  ! blade3f
! Pitch link inputs to aft pitch link slides (blade 1a,2a,3a)
a  10     0.0        0         0        0         0        0  ! blade1a
a  11     0.0        0         0        0         0        0  ! blade2a
a  12     0.0        0         0        0         0        0  ! blade3a
!*********************************************************
! Trim tab inputs only used with static stall aero condition
! Add ! to beginning of following lines when using
!  dynamic stall model iInput to forward trim tabs
a  13      0.0        0        0        0         0        0  ! blade1f
a  14      0.0        0        0        0         0        0  ! blade2f
a  15      0.0        0        0        0         0        0  ! blade3f
! Input to aft trim tabs
a  16      0.0        0        0        0         0        0  ! blade1a
a  17      0.0        0        0        0         0        0  ! blade2a
a  18      0.0        0        0        0         0        0  ! blade3a
!*********************************************************
```

```
S ROTNONCONST
!              Non-rotating                      Rotating
! Cnstr.  Subsystem Primitive  Node      Subsystem Primitive  Node
!  ID       Name      Name      ID         Name      Name      ID
a  1       fusCH47D    fuseps    13       rotorf   blade1f     30
a  2       fusCH47D    fuseps    15       rotora   blade1a     30

!*******************************************************************
!                        FUSELAGE    SUBSYSTEM
!                             fusCH47D
!*******************************************************************

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
a fusCH47D

S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    2

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a           fuseps
a           bodyps

S PSORIGIN
!   Primitive       Primitive Origin Offset
!   Name          x            y            z
a   fuseps        0            0            0
a   bodyps        0            0            0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
! fuselage rotated by 180 for elastic model only (elastic matrix)
a    fuseps       2     180        0       0         0       0
a    bodyps       0      0         0       0         0       0

!*******************************************************************
```

```
!                  PRIMITIVE FOR FUSELAGE SUBSYSTEM
!                           fuseps
S PRIMITIVEID
A fuseps

S ELDATASETID
A fuseprop


S FENODE
! The data is based on 7 inch aft cg
!  node ID,   X,       Y,       Z
A      1      0.0      0       0.0
A      2    -19.879    0       0.0
A      3    -21.013    0     7.1598
A      4     18.7046   0     1.2333
A      5     17.8775   0    11.8275
A     11      0.0      0       0.0
A     13    -21.013    0     7.1598
A     15     17.8775   0     11.8275
! Nodes added to represent accelerometers of HUMS
A      80   -21.813    0     4.6598
A      81   -19.7046   0     9.3275

S RBMELE
! Generate rigid body mass element for fuselage mass & hub mass
! ELID,  node ID, prop ID
A    1      1       1
! Hub masses added at enode
A    6      13       2
A    7      15       3

S RIGIDBAR
!!  Element  Node1  Node2        Center of gravity offset
!!    ID      ID     ID        X            Y            Z
a     2       1      2         0            0            0
a     3       2      3         0            0            0
a     4       1      4         0            0            0
a     5       4      5         0            0            0
! Bars added to connect accelerometers to fuselage system
a     80      3      80        0            0            0
a     81      5      81        0            0            0
```

```
S EJOINT
! Model - Elastic fuselage behavior at left & right rotor
!   Elem.  Bnode  Enode   Eigenvector
!    ID     ID     ID     Seqence ID
a    20     3      13          1
a    21     5      15          2

S ELASTICFUSE
! NO. of  Prim. Struc.  Node   --------------------------
!  Dofs     name        id     ----- Data File Name -----
a  40      FUSEPS        1        EFUSE_CH47D_33K.MAT

!=====================================================================
!========================= PRIMITIVE STRUCTURE ========================
!  For Aero Coordinates same      bodyps
!=====================================================================

S PRIMITIVEID
! Select primitive to be defined
a  bodyps

S ELDATASETID
! Select a property set
a   fuseprop

S FENODE
! Bodyps node for fuselage aero
!  Kept same as rigid fuselage deck
!  node ID,   X,       Y,       Z
A      1      0.0      0       0.0

S RBMELE
! Generate rigid body mass element.
! ELID,  node ID, prop ID
A   1      1       4



!*********************************************************************
!                      FWD ROTOR SUBSYSTEM
!*********************************************************************
 S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
```

```
! to this subsystem until another subsystem is selected.
a rotorf

S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    1

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a       blade1f
a       blade2f
a       blade3f

S SINGLEBLADE
!!     Identical Blade      Number of
!!     Analysis Option      Blades
!!         (Y/N)           (2:9)
a           N               3

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
a  blade1f          30

S BLADECOMP
! Blade                   Primitive Structure Name(s)
! Index      1        2       3         4        5        6        7
a  1      blade1f    --      --        --       --       --       --
a  2      blade2f    --      --        --       --       --       --
a  3      blade3f    --      --        --       --       --       --

S PSORIGIN
!  Torque Offset of 1.58 inch
!   Primitive       Primitive Origin Offset
!   Name          x            y            z
a blade1f        0.0          0.131667      0
a blade2f        0.114026967 -0.0658335     0
a blade3f       -0.114026967 -0.0658335     0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
```

```
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   blade1f       3       0         0       0         0       0
a   blade2f       3     -120        0       0         0       0
a   blade3f       3     -240        0       0         0       0

S CONNCONST
! Define connectivity constraints between Primitives
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
a      1              blade2f      30            blade1f      30
a      2              blade3f      30            blade1f      30


S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
a        23.5619

!*************************************************************
!                      PRIMITIVE BLADE 1  FWD ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade1f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl1prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1         0.0        0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
```

```
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! Above, pitch bearing and controlled pitch hinge for pitch
! link extension/retractcion.
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
```

```
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide & slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk
S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0

N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                   File Name for
!    ID                     nonlinear table
a    201                    CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
```

```
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)
```

```
S GCBEAMDEF
!=================== Number of Active DOF for each Direction =========
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing     proprietary     data     omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
A  12             0                    GCB_NLB_CH47.TAB
A  13             0                    GCB_NLB_CH47.TAB
A  14             0                    GCB_NLB_CH47.TAB
A  15             0                    GCB_NLB_CH47.TAB
A  16             0                    GCB_NLB_CH47.TAB
A  17             0                    GCB_NLB_CH47.TAB
A  18             0                    GCB_NLB_CH47.TAB
A  19             0                    GCB_NLB_CH47.TAB
A  20             0                    GCB_NLB_CH47.TAB
A  21             0                    GCB_NLB_CH47.TAB
A  22             0                    GCB_NLB_CH47.TAB
A  23             0                    GCB_NLB_CH47.TAB
A  24             0                    GCB_NLB_CH47.TAB
A  25             0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                53
a    2       SPLATR         0.0           HIN                53
a    3       SPLONG         0.0           HIN                53
a    7       DIRECT         0.0           SLD               211

!*********************************************************************
!                       PRIMITIVE BLADE 2  FWD ROTOR
```

```
S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade2f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl2prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1         0.0      0.0         0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
```

```
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24       1.67708  -.520797     0.0
! Outboard
a    25       3.333    -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27        0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18        1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19        1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20        1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate PL node
a    21        0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22        0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-PL
a    215      0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
```

```
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a   201      24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a   201                     CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0             0
a  51     4      5        P        0           0             0
a  52     6      7        L        0           0             0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0             0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
```

```
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!========================= Number of Active DOF for each Direction ====
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
A  12             0                    GCB_NLB_CH47.TAB
A  13             0                    GCB_NLB_CH47.TAB
A  14             0                    GCB_NLB_CH47.TAB
```

```
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                53
a    2       SPLATR         0.0           HIN                53
a    3       SPLONG         0.0           HIN                53
a    8       DIRECT         0.0           SLD                211

!*******************************************************************
!                          PRIMITIVE BLADE 3  FWD ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade3f

S ELDATASETID
! Select an element property data set.
! Data set_ID
a fbl3prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200            0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
```

```
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
```

```
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
a   201                     CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
```

```
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
```

```
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!========================= Number of Active DOF for each Direction ====
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
A  11             0                    GCB_NLB_CH47.TAB
A  12             0                    GCB_NLB_CH47.TAB
A  13             0                    GCB_NLB_CH47.TAB
A  14             0                    GCB_NLB_CH47.TAB
A  15             0                    GCB_NLB_CH47.TAB
A  16             0                    GCB_NLB_CH47.TAB
A  17             0                    GCB_NLB_CH47.TAB
A  18             0                    GCB_NLB_CH47.TAB
A  19             0                    GCB_NLB_CH47.TAB
A  20             0                    GCB_NLB_CH47.TAB
A  21             0                    GCB_NLB_CH47.TAB
A  22             0                    GCB_NLB_CH47.TAB
A  23             0                    GCB_NLB_CH47.TAB
A  24             0                    GCB_NLB_CH47.TAB
A  25             0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    1       SPCOLL         0.0           HIN                 53
a    2       SPLATR         0.0           HIN                 53
a    3       SPLONG         0.0           HIN                 53
a    9       DIRECT         0.0           SLD                 211

!*****************************************************************
```

```
!                      AFT ROTOR SUBSYSTEM
!*******************************************************************
!==================================================

S SELSUBSYS
! Select a subsystem. Note that all the following data will pertain
! to this subsystem until another subsystem is selected.
a rotora

 S SUBSYSTYP
! Select subsystem type.
! 1=rotor, 2=fuselage, 3=control
a    1

S SUBSYSCOMP
! List the names of the primitive structures for the subsystem.
! primitive structure name
a       blade1a
a       blade2a
a       blade3a

S SINGLEBLADE
!!     Identical Blade      Number of
!!     Analysis Option      Blades
!!         (Y/N)           (2:9)
a           N               3

S CORNODE
! identify center node for the rotor subsystem
! Prim_str_ID     Node_ID
a  blade1a          30

S BLADECOMP
! Blade                  Primitive Structure Name(s)
! Index      1        2       3         4        5        6        7
a  1      blade1a    --      --        --       --       --       --
a  2      blade2a    --      --        --       --       --       --
a  3      blade3a    --      --        --       --       --       --

S PSORIGIN
!  Torque Offset of 1.58 inch
! Aft rotor PS origin same as FWD for offsets
!   Primitive       Primitive Origin Offset
```

```
!   Name          x            y           z
a blade1a       0.0          0.131667      0
a blade2a       0.114026967 -0.0658335     0
a blade3a      -0.114026967 -0.0658335     0

S PSORIENT
!   Primitive     rotation 1        rotation 2        rotation 3
!     Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   blade1a       3       0         0       0         0       0
a   blade2a       3      120        0       0         0       0
a   blade3a       3      240        0       0         0       0

S CONNCONST
! Define connectivity constraints between Primitives
! constraint ID, DOFL( PS name, node ID ), DOFR( PS name, node ID)
a      1              blade2a     30            blade1a      30
a      2              blade3a     30            blade1a      30

S ROTORPARAM
!  Rotor Rotational Speed (rad/sec)
a       -23.5619

!=================================================================
!                   PRIMITIVE BLADE 1 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade1a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl1prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
```

```
a    30         0.0     -0.131667    0.0
a     1         0.0      0.0         0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
```

```
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!                  CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                 File Name for
!    ID                   nonlinear table
a   201                  CH47D_DAMPER_FILE
```

```
S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0             0
a  51     4      5        P        0           0             0
a  52     6      7        L        0           0             0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0             0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
```

```
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!========================== Number of Active DOF for each Direction ====
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4            0                     GCB_NLB_CH47.TAB
A   5            0                     GCB_NLB_CH47.TAB
A   6            0                     GCB_NLB_CH47.TAB
A   7            0                     GCB_NLB_CH47.TAB
A   8            0                     GCB_NLB_CH47.TAB
A   9            0                     GCB_NLB_CH47.TAB
A  10            0                     GCB_NLB_CH47.TAB
A  11            0                     GCB_NLB_CH47.TAB
A  12            0                     GCB_NLB_CH47.TAB
A  13            0                     GCB_NLB_CH47.TAB
A  14            0                     GCB_NLB_CH47.TAB
A  15            0                     GCB_NLB_CH47.TAB
A  16            0                     GCB_NLB_CH47.TAB
A  17            0                     GCB_NLB_CH47.TAB
A  18            0                     GCB_NLB_CH47.TAB
A  19            0                     GCB_NLB_CH47.TAB
A  20            0                     GCB_NLB_CH47.TAB
A  21            0                     GCB_NLB_CH47.TAB
A  22            0                     GCB_NLB_CH47.TAB
A  23            0                     GCB_NLB_CH47.TAB
A  24            0                     GCB_NLB_CH47.TAB
A  25            0                     GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    4       SPCOLL         0.0           HIN                53
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
```

```
a   10       DIRECT         0.0           SLD                 211

!=================================================
!                    PRIMITIVE BLADE 2 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade2a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl2prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001

S FENODE
! Generate nodes directly.
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
```

```
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
```

```
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                   File Name for
!    ID                     nonlinear table
a   201                    CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
```

```
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!========================== Number of Active DOF for each Direction ====
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4             0                    GCB_NLB_CH47.TAB
A   5             0                    GCB_NLB_CH47.TAB
A   6             0                    GCB_NLB_CH47.TAB
A   7             0                    GCB_NLB_CH47.TAB
A   8             0                    GCB_NLB_CH47.TAB
A   9             0                    GCB_NLB_CH47.TAB
A  10             0                    GCB_NLB_CH47.TAB
```

```
A  11            0                    GCB_NLB_CH47.TAB
A  12            0                    GCB_NLB_CH47.TAB
A  13            0                    GCB_NLB_CH47.TAB
A  14            0                    GCB_NLB_CH47.TAB
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    4       SPCOLL         0.0           HIN                53
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
a   11       DIRECT         0.0           SLD                211

!==================================================
!                    PRIMITIVE BLADE 3 AFT ROTOR

S PRIMITIVEID
! Select a primitive structure
! Primitive structure_ID
a blade3a

S ELDATASETID
! Select an element property data set.
! Data set_ID
a abl3prp

S PSMODALDAMP
! Row ID    Mode numbers    Damping ratio
a    1         1:200           0.001

S FENODE
! Generate nodes directly.
```

```
!  node_id        X         Y         Z
! 30 is the center node, blade root is at node1
a    30         0.0     -0.131667    0.0
a     1           0.0      0.0       0.0
! The  flap hinges are at connection point of node 2 AND 3
a     2         0.6667     0.0       0.0
a     3         0.6667     0.0       0.0
! The  pitch bearing at connection point of node 4 AND 5
a     4         1.084      0.0       0.0
a     5         1.084      0.0       0.0
! The  lag  hinges are at connection point of node 6 AND 7
a     6         2.4584     0.0       0.0
a     7         2.4584     0.0       0.0
! blade is from 8 - 14
! Node 14  is the tip of the blade.
a     8         3.000      0.0       0.0
a     9         3.333      0.0       0.0
a    10         4.200      0.0       0.0
a    11         6.000      0.0       0.0
a    12         7.600      0.0       0.0
a    13         9.000      0.0       0.0
a    44         10.600     0.0       0.0
a    45         12.000     0.0       0.0
a    46         13.600     0.0       0.0
a    47         15.000     0.0       0.0
a    48         16.600     0.0       0.0
a    49         18.000     0.0       0.0
a    50         19.600     0.0       0.0
a    51         21.000     0.0       0.0
a    52         22.600     0.0       0.0
a    53         24.000     0.0       0.0
a    54         25.600     0.0       0.0
a    55         27.000     0.0       0.0
a    56         28.200     0.0       0.0
a    57         29.07      0.0       0.0
a    14         30.00      0.0       0.0
!   Nonlinear hydraulic damper
! Nodes 24 & 25 are damper connection points
! Inboard
a    24         1.67708 -.520797     0.0
! Outboard
a    25         3.333   -.90         0.0
! Pitchlink & swashplate modeling
```

```
!  Swashplate center node
a    27         0.0       0.0      -1.557
!  Swashplate pitch reference node about which it pitches
a    18         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & blade axis
a    19         1.084     0.0      -1.557
! On Swashplate corresponds to pitch bearing  & pitch arm offset
a    20         1.084    .854166    -1.557
! node 21 is swashplate end of pitchlink , Swashplate pitchlink node
a    21         0.6667   .854166    -1.557
! node 22 is the pitch horn
a    22         0.6667   .854166     0.0
! node 215 is the connection pt between S/P-slide and slide-pitch link
a    215        0.6667   .854166    -1.557

S SPRELE
!
! Linear spring element, Pitchlink translation spring
! Element   node1  node2   Transl/rotation   Type   Linear Stiffness
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)    Coefficient
a   200      215     22        TR         L       2.11308e+05 ! PitchLnk

S RBMELE
! Rigid body mass element
! Element   node   property
!   ID       ID       ID
a   780      45       22     ! Seed fault
a   781       8       23     ! Mass to correct blade imbalance

S DMPELE
!   Nonlinear hydraulic damper
! Element   node1  node2   Transl/rotation   Type   Linear damping
!   ID       ID     ID     (TR/RX/RY/RZ)     (L/N)   Coefficient
a  201       24     25         TR              N      0.0
N
!             SPECIFY NONLINEAR DAMPER PROPERTY
!
!    For each nonlinear damper, specify the file name which contains
! the force versus displacement or moment versus angle or rotation data.

!              CURRENT_PRIMITIVE_STRUCTURE_ID:
!  Element                    File Name for
!    ID                      nonlinear table
```

```
a   201                    CH47D_DAMPER_FILE

S HINGE
! Model the hub hinges
! Elem.  Node1  Node2   Hinge   Free or     Spring        Damper
!  ID     ID     ID     Type   Controlled   Constant      Constant
a  50     2      3        F        0           0              0
a  51     4      5        P        0           0              0
a  52     6      7        L        0           0              0
! Swashplate controlled pitch hinge
a  53    18     19        P        1           0              0

S SLIDE
!Elem  Node1  Node2  Slide   Free or Spring Damper
! ID    ID     ID    Axis   Controlled  Constant     Constant
a 211   21     215     Z        1         0             0

S RIGIDBAR
!  Element  Node1  Node2        Center of gravity offset
!    ID      ID     ID        X       Y       Z
! Pitch link attachment  with pitch horn mass modeled
a    61       5     22      .854133   0       0 !pitch arm element
! damper attachment arms
a    62       5     24       0        0       0 ! damper attach inboard
a    63       8     25       0        0       0 ! damper attach outboard
! Swashplate modeling (pitch is between node 18 & 19)
a    39       30     1      0        0        0 ! Torque offset
a    40       30    27      0        0        0 ! Blade root to SP cntr
a    41       27    18      0        0        0 ! SP center to PL node
a    42       19    20      0        0        0 ! SP pitch arm
a    43       20    21      0        0        0 ! To bottom PL node
N
! Mass at pitch horn
! From drawing ( pitclink-steel, bolt steel+ Pitch horn arm Al)
!       mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
! EL ID     Mass     Ixx      Ixy      Ixz      Iyy       Iyz       Izz
A   111    0.323     0.1      0.0     0.0      0.1       0.0       0.1

S NLBEAMDEF
!Elem   1st   2nd    Shape   NGauss  MatProp   End Node Active DOFs
! ID    Node  Node  Func ID  Points    ID      ue v w  phi w' v'
a  1     1     2       1       6        1      0  1 1   1  1  1
a  2     3     4       1       6        1      0  1 1   1  1  1
```

```
a  3     5     6       1       6        1      0  1 1   1  1  1
N
! Structural twist is defined relative to the E frame
! PRP-INDEX, ELID, PRP-LOC, PRPID, STR-TWIST
! prop index  elemID  prop loc  propID  twist(rad) | X[in] EIF EIC GJ m
(Boeing     proprietary     data     omitted)

S GCBEAMDEF
!========================= Number of Active DOF for each Direction ====
!Elem   1st   2nd   Ngauss   Axial   Lag  Flap  Torsion  Shr12   Shr13
! ID    Node  Node  points  (0/1/2) (0/2) (0/2) (0/1/2) (0/1/2) (0/1/2)
(Boeing proprietary data omitted)
N
! Specify the structural property data table (file)
!Element      Refernce                    Property
!  ID          origin                     Filename
A   4            0                    GCB_NLB_CH47.TAB
A   5            0                    GCB_NLB_CH47.TAB
A   6            0                    GCB_NLB_CH47.TAB
A   7            0                    GCB_NLB_CH47.TAB
A   8            0                    GCB_NLB_CH47.TAB
A   9            0                    GCB_NLB_CH47.TAB
A  10            0                    GCB_NLB_CH47.TAB
A  11            0                    GCB_NLB_CH47.TAB
A  12            0                    GCB_NLB_CH47.TAB
A  13            0                    GCB_NLB_CH47.TAB
A  14            0                    GCB_NLB_CH47.TAB
A  15            0                    GCB_NLB_CH47.TAB
A  16            0                    GCB_NLB_CH47.TAB
A  17            0                    GCB_NLB_CH47.TAB
A  18            0                    GCB_NLB_CH47.TAB
A  19            0                    GCB_NLB_CH47.TAB
A  20            0                    GCB_NLB_CH47.TAB
A  21            0                    GCB_NLB_CH47.TAB
A  22            0                    GCB_NLB_CH47.TAB
A  23            0                    GCB_NLB_CH47.TAB
A  24            0                    GCB_NLB_CH47.TAB
A  25            0                    GCB_NLB_CH47.TAB

S CONTROLCONNECT
! Control   Swashplate   Swashplate   Element Type         Element
!   ID      or Direct    Phase(deg)  (HIN/AUX/ENG ...)    or ACP ID
a    4       SPCOLL         0.0           HIN                 53
```

```
a    5       SPLATR         0.0           HIN                53
a    6       SPLONG         0.0           HIN                53
a   12       DIRECT         0.0           SLD               211

!*******************************************************************
!                        PROPERTIES SET 2  FUSELAGE
!*******************************************************************
 S ELEPROPID
! List the names of element property data sets.
! element_prop_ID
a fuseprop

 S RBMPRP
! Mass at cg & hub  totalwt=33000lbs
! This data has been updated (cg data corresponds to 33000lbs)
!    mass(slugs)  C.G. offset   Ixx  Ixy  Ixz     Iyy   Iyz   Izz
A 1   809.633    0  0  0     26368. 461.0 18840. 206570. 56.0 160900.
A 2   54.1000    0  0  0      40.   0     0.     37.     0    37.
A 3   61.9000    0  0  0      40.   0     0.     37.     0    37.
! dummy for aero
A 4    1.e-6     0  0  0       0    0     0       0      0     0


!*******************************************************************
!             PROPERTIES SET 1   BLADE 1 FWD ROTOR
!*******************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl1prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
```

```
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1

!*********************************************************************
!             PROPERTIES SET 1   BLADE 2 FWD ROTOR
!*********************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl2prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
```

```
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 3 FWD ROTOR
!*******************************************************************
S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a fbl3prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 1 AFT ROTOR
!*******************************************************************

S ELEPROPID
```

```
! List the names of element property data sets.
! element_prop_id
a abl1prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1

!*******************************************************************
!             PROPERTIES SET 1   BLADE 2 AFT ROTOR
!*******************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a abl2prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix
```

```
S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)

S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1


!*******************************************************************
!             PROPERTIES SET 1   BLADE 3 AFT ROTOR
!*******************************************************************

S ELEPROPID
! List the names of element property data sets.
! element_prop_id
a abl3prp

S RBMPRP    ! Blade faults and corrective masses
! Prop  mass(slugs) C.G. offset   Ixx  Ixy  Ixz  Iyy  Iyz  Izz
A  22    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fault
A  23    0.0     0   0   0     0.0  0.0  0.0   0.0  0.0  0.0 ! Fix

S NLBEAMPRP
! prop ID  area   I_eta   I_zeta I_eta,zeta torsion et_eta et_zeta
(Boeing     proprietary     data     omitted)
N
! Nonlinear beam mass sectional data
! prop ID  m/l   Km_eta  Km_zeta  Km_etzet  em_eta em_zeta
(Boeing     proprietary     data     omitted)
```

```
S MATPROPER
! Input material properties (E, G), lb/ft^2.
! material id, Young's Modulus, shear Modulus
a       1           1.0E06           1.0E06

S NLBSHAPE
! Nonlinear beam shape functions. Define the orders of the axial,
! bending, and torsion shape functions.
! Shape fcn id,axial shp fcn order,bending shp fcn order, and
! tor shp fcn order
a    1                 1               0                        1

!*********************************************************************
!                        DEFINE AERODYNAMIC MODEL
!*********************************************************************

S AEROMODCOMP
! List of Supercomponent of the system
a   fusead
a   adrotorf
a   adrotora

S SCORIGIN
!  Supercomponent          Origin Coordinates
!       Name          x            y            z
a   fusead           0            0            0
a   adrotorf         21.013       0         -7.1598
a   adrotora        -17.8775      0         -11.8275

S SCORIENT
! Supercomponent   rotation 1        rotation 2        rotation 3
!       Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a   fusead          2       0         0       0         0       0
a   adrotorf        2     171         0       0         0       0
a   adrotora        2     176         0       0         0       0

!               Airfoil Tables
s AIRFOIL
!                        2-D AIRFOIL TABLES (Table Look-Up)
!  Airfoil ID  --------------- Airfoil Data File Name ----------------
a VR8TM6                       VR8TABM6.C81
a VR7TM6                       VR7TABM6.C81
a VR7TM4P5                   VR7TABM4P5.C81
```

```
N
!                 SPECIFY AIRFOIL COEFFICIENTS (Linear Aerodynamics)
!  Airfoil   -- Linear Airfoil Coefficients --     Zero Lift Angle
!    ID      C_radial    CL_a      CD       CM     of Attack (deg)
a  VR8TM6      0         X.XX     X.XXXX   X.XXX       0
a  VR7TM6      0         X.XX     X.XXXX   X.XXX       0
a  VR7TM4P5    0         X.XX     X.XXXX   X.XXX       0
N
!   Airfoil           Nonlinear UnSteady and Dynamic Stall
!     ID            Airfoil Data File Name (Leishman-Beddos)
a  VR8TM6                          VR8TABM6.LEI
a  VR7TM6                          VR7TABM6.LEI
a  VR7TM4P5                        VR7TABM4P5.LEI

!            AERODYNAMIC INTERFERENCE FOR SUPERCOMPONENTS
!
!  Enter row IDs, and for each row input the name of the supercompont
!  which creates aerodynamic interference, the name of the supercompont
!  that is affected by the aerodynamic interference and the type of
!  aerodynamic interference model.
!  Examples:
!   Row       From             To                Interference
!   ID    Supercomponent   Supercomponent           Model
!    1        rotor1           rotor2        simple-rotor-to-rotor
!    2        ground           rotor2        blockage-ground-effect
!    3        bodya            rotor1         body-source-sink
!    4        winga            rotor2        simple-horseshoe-vortex
!    5        rotor1           bodya         cylindrical-vortex-sheet
!    6        rotor1           bodya               vortex-wake

S INTERFERENCE
!  Row       From             To                  Interference
!  ID    Supercomponent   Supercomponent              Model
a   1    ADROTORF    ADROTORA  simple-rotor-to-rotor     0.000     0.000
a   2    ADROTORF    FUSEAD    cylindrical-vortex-sheet  0.000     0.000
a   3    ADROTORA    ADROTORF  simple-rotor-to-rotor     0.000     0.000
a   4    ADROTORA    FUSEAD    cylindrical-vortex-sheet  0.000     0.000
N
! Interf  Far   Horseshoe  Vortex     Block/
! update  wake  vortex     sheet      ground
! intrvl  opt   core size  thickness  effect
!                                     factor
a   1     0      .1        .1          1.
```

```
N
!    Aero-body-dimensions    Source
!    lx       ly       lz    update
!                            rate
a    50.75     7.5     7.5     12

!==================================================
!               FUSELAGE AERODYNAMICS
!==================================================
S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          fusead

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a        fusCH47D

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body  4 => AUX ROT
a     3

S COMPID
! List the Components which comprise the Supercomponent    Wing
! Component     Primitive   CP Root   Blade tip           Right End
!  Name(s)      Structure    El_id     node_id             Node_ID
a  fusecp         fuseps       1           0                  0

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  fusecp         0            0            0

S CPORIENT
! Component     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  fusecp        0      0         0       0         0       0

S INFLOW
! inflow option
! 0 => no inflow 1 => Uniform, 2 => uniform for full wing,
! 3 => dynamic inflow, 4 => Classical wake,
! 5 => prescribed generalized wake, 6 => free wake
```

```
a        0

S AEROPTION
! Dyn Stall opt
!      0 => static stall
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                           separation
!      3 => Leishmann model - w/ separation
!                                           + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           0                 1          0

!-----------------------------------------------------------------------
!                 Define Aerodynamic Component FUSECP

S AEROCOMPID
! Component name for defining or modifying
a FUSECP

S COMPTYPE
! 1 => lifting surface,  2 => body    3 => AUX ROT
a 2

s BODYAEROTAB
!       option 1 and external file for aerodynamic coefficients or
a  1 F_CH47_BODY_BODY_AERO.TAB  0.0  0.0  0.0  0.0  0.0  0.0  0.0

!=========================================================
!       FORWARD ROTOR MODELING
!=========================================================
!======== AERODYNAMIC SUPERCOMPONENT ================
!                   FWD ROTOR
```

```
S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          adrotorf

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body, 4=> aux rotor
a 1

S COMPID
! List the Components which comprise the Supercomponent
! Component     Primitive   CP Root   Blade tip
!  Name(s)      Structure    El_id     node_id
a  ablade1f     blade1f        0           14
a  ablade2f     blade2f        0           14
a  ablade3f     blade3f        0           14

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  ablade1f      0.0          0.131667      0
a  ablade2f      0.114026967 -0.0658335     0
a  ablade3f     -0.114026967 -0.0658335     0

S CPORIENT
! Component     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  ablade1f       3      0         0       0         0       0
a  ablade2f       3    -120        0       0         0       0
a  ablade3f       3    -240        0       0         0       0

S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a        1

S AEROPTION
! Dyn Stall opt
!      0 => static stall
```

```
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                          separation
!      3 => Leishmann model - w/ separation
!                                          + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           5                0
c     0           0        0           3                0
!*********************************************************************
! Deactivate the following line for dynamic stall modeling
c     0           0        0           0                0

S INFLOWCONV
! Define input circulation convergence parameters
! damping factor, convergence tolerance, number of iterations
a  0.05                    0.001                299
c  0.05                    0.0001                299
c  0.05                    0.0004                299

S THRUSTAVE
! thrust ave option, no. time steps, initial thrust,
! and no. Revs for TPP averaging
a         2                72              16745.0                 1

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a         rotorf

!==================================================
! ******************************************************************
! Activate SCREENS and data entry lines in the
! PRESWAKE and FREEWAKE screens when
! modeling non-uniform inflow models.
```

```
! ******************************************************************
!S PRESWAKE
! Multiscreen: 1  of 8    Type: Non-iterative    Screen: PRESWAKE
!
!                      SPECIFY VORTEX WAKE OPTIONS FOR ROTOR
!                           PRESCRIBED AND/OR FREE WAKE
! CURRENT_AEROSUPERCOMPONENT_ID: ADROTOR
! +---------------- Wake Geometry Options ----------------+
! | Single |  Wake  | Flag for | Constant  | Inboard Wake |
! |   or   |  Geom. | Straight | or Linear | Vortex Sheet |
! |  Dual  |  Model | or Curve |  Segment  |     or       |
! |  Peak  | Option |  Vortex  | Vorticity | Vortex Line  |
! | (1/2)  | (1/7)  |  (0/1)   |   (0/1)   |   (0/1)      |
! +-------------------------------------------------------+
! Classical vortex wake with no distortion, single peak
!a     1        1         0          1            0
N
! +---------------------- Wake Geometry Specs -----------------------+
! |  Number   |  Near Wake | Rollup Wake | Number of  |   Initial   |
! |  of Wake  |  Azimuthal |  Azimuthal  | Revs for   |   Radial    |
! | Azimuthal |  Coverage  |  Coverage   | Far Wake   | Position of |
! | Steps/Rev |   (0:180)  |   (0:360)   |  (0:20)    | Rollup Wake |
! +-------------------------------------------------------------------+
!a      72        60             120           3.0           1.0
N
! +-------------- Inflow Calculation Specs ----------------+
! | Flag for |  1/4 or 3/4   | Max.  Bound | Min. Sepration|
! | Inplane  | Chord colloc. | Circulation |   Between     |
! | Velocity |  points for   |  Fraction   |  Colocation   |
! | Calcula. | Induced Vel.  |  for Tip    |  points and   |
! |  (0/1)   | Calculations  |   Vortex    | Vortex Sheets |
! +-------------------------------------------------------+
!a    1             0                0.8            0.01
N
! +---------------------- Core Type and Size-------------------+
! |  Tip   | Inb'rd |  Tip  | Tip Vortex | Inbrd | Inbrd | Near | Dual |
! | Vortex | Vortex | Vortx |  Core for  | Trailed| Shed | Wake | Peak |
! |  Core  |  Core  |  Core |   Inboard  | Vortex | Wake | Core | Core |
! |  Type  |  Type  |  Size |  Coloc.Pts.|  Core  | Core | Size | Size |
! +-----------------------------------------------------------------+
!a     0       0     0.02982    0.02982       0.     0.   0.02982   0.
N
! +---------------------------------------+
```

```
! |--Tip Vortex Core Model and Size for --|
! |--- Inboard Wake Collocation Points ---|
! |---------------------------------------|
! |  Option | Core Size at | Core Size at |
! |  (0/1)  | Inner Radius | Outer Radius |
! +---------------------------------------+
!a      1          0.76          0.88
N
! +--------- Exclude/Include Wake Model (0/1) ----------+
! |  Tip   |  Near Wake   | Rollup Wake  |   Far Wake   |
! | Vortex |--------------|--------------|--------------|
! |  Wake  | shed | trail | shed | trail | shed | trail |
! +-------------------------------------------------------+
!a     1       0      1       0      1       0      1
N
! +------------------- Prescribed Wake Geometry Data -----------------+
! | Vortex   |----- Factors -----|----------- Constants --------------|
! | Location |  f1    |   f2   |   K1  |   K2   |    K3   |    K4     |
! +-----------------------------------------------------------------+
!A     1         1         1        1        1        1        1
!A     2         1         1        1        1        1        1
!A     3         1         1        1        1        1        1
N
! Exclude ground effect
! +-------------- Ground Effect Parameters ---------------+
! | Include  | Minimum   | Include  |  Ground  |  Ground  |
! |  Ground  | Wake/Grnd |  Ground  |  Vortex  |  Vortex  |
! | Effects  | Clearance |  Vortex  |   Core   | B Factor |
! +-------------------------------------------------------+
!a      0           0.2        0          0.1          0.8!

=====================================================
!============= AERODYNAMIC COMPONENT ==============
!                         ablade1f

S AEROCOMPID
! Component name for defining or modifying
a ablade1f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1
```

```
S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID       ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
```

```
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          13
a  12  .0375939  .667    .60          1          0          13
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!=============== AERODYNAMIC COMPONENT ==============
!                           ablade2f

S AEROCOMPID
! Component name for defining or modifying
a ablade2f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
```

```
a     4        10.50000      0.0          0.0
a     5        12.00000      0.0          0.0
a     6        13.50000      0.0          0.0
a     7        15.00000      0.0          0.0
a     8        16.50000      0.0          0.0
a     9        18.00000      0.0          0.0
a    10        19.00000      0.0          0.0
a    11        20.00000      0.0          0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0          0.0
a    17        25.50000      0.0          0.0
a    18        26.50000      0.0          0.0
a    19        27.00000      0.0          0.0
a    20        28.00000      0.0          0.0
a    21        29.07000      0.0          0.0
a    22        30.00000      0.0          0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
```

```
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          14
a  12  .0375939  .667    .60          1          0          14
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!============== AERODYNAMIC COMPONENT ===============
!                           ablade3f

S AEROCOMPID
! Component name for defining or modifying
a ablade3f

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
```

```
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ********************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
```

```
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          15
a  12  .0375939  .667    .60          1          0          15
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6


!=====================================================
!=========== AERODYNAMIC SUPERCOMPONENT ==========
!                                AFT ROTOR

S AEROSUPCOMPID
! Supercomponent name to be define or modified
a          adrotora

S SUPCMPTYP
! 1 => rotor, 2 => wing, 3 => body, 4=> aux rotor
a 1

S COMPID
! List the Components which comprise the Supercomponent
! Component     Primitive   CP Root   Blade tip
!  Name(s)      Structure    El_id     node_id
a  ablade1a     blade1a        0          14
a  ablade2a     blade2a        0          14
a  ablade3a     blade3a        0          14

S CPORIGIN
! Component         Component Origin Offset
!   Name          x            y            z
a  ablade1a      0.0          0.131667      0
a  ablade2a      0.114026967 -0.0658335     0
a  ablade3a     -0.114026967 -0.0658335     0

S CPORIENT
```

```
! Component     rotation 1        rotation 2        rotation 3
!    Name      axis angle(deg)   axis angle(deg)   axis angle(deg)
a  ablade1a       3      0         0       0         0       0
a  ablade2a       3     120        0       0         0       0
a  ablade3a       3     240        0       0         0       0

S INFLOW
! 0. No inflow (wings).
! 1. Uniform momentum inflow (half wings and rotors)
! 2. Uniform momentum inflow (full wings)
! 3  Peters and He inflow model (rotors only).
! 5. Alternate Prescribed vortex wake ( only rotors).
! 6. Free vortex Wake (Only Rotor)
a        1

!S DYNINFDATA
! 7 and 7 will produce a 36 state model
!  Number of                 Number of
! Polynomials                Harmonics
!A    1                          1

S AEROPTION
! Dyn Stall opt
!      0 => static stall
!      1 => Leishmann model - attached airloads only
!      2 => Leishmann model - w/ trailing edge separation
!                                          separation
!      3 => Leishmann model - w/ separation
!                                          + vortex shedding
!      4 => Leishmann model - w/ trailing edge
!                       separation + correction for static table
!      5 => Leishmann model - w/ separation + vortex
!                      shedding + correction for static table
!      6 => ONERA model
! aerodynamic options (tip loss, airfoil tables)
!  Yawed    Tip      Linear          Nonlinear         Linear   Compress
!  Flow     Loss    Unsteady    Unsteady/Dyn Stall     Airfoil  -ibility
! Effects  Option   Effects    Leishman-beddos/Onera   Coeffs   Effects
!  (0:1)   (0:1)    (0:1)            (0:6)             (0:1)     (0:1)
! yawed flow, tip loss, u/s aero, dynamic stall, linear coefficients
a     0           0        0           5                 0
c     0           0        0           3                 0
!*********************************************************************
```

```
! Deactivate the following line (use !) for dynamic stall modeling
c     0           0        0           0                0

S INFLOWCONV
! Define input circulation convergence parameters
! damping factor, convergence tolerance, number of iterations
a  0.05                    0.001                299
c  0.05                    0.0001                299
c  0.05                    0.0004                299

S THRUSTAVE
! thrust ave opt., no. time steps, init. thrust, no. Revs for TPP avging
a         2                72              16745.0                 1

S SUPCMPTOSS
! Subsystem name for the current supercomponent
a         rotora

!=========================================================
! ***********************************************************************
! Activate SCREENS and data entry lines in the PRESWAKE and
! FREEWAKE screens when modeling non-uniform inflow models.
! ***********************************************************************
!S PRESWAKE
! Multiscreen: 1  of 8    Type: Non-iterative    Screen: PRESWAKE
!
!                 SPECIFY VORTEX WAKE OPTIONS FOR ROTOR
!                      PRESCRIBED AND/OR FREE WAKE
! CURRENT_AEROSUPERCOMPONENT_ID: ADROTOR
! +---------------- Wake Geometry Options ----------------+
! | Single |  Wake  | Flag for | Constant  | Inboard Wake |
! |   or   |  Geom. | Straight | or Linear | Vortex Sheet |
! |  Dual  |  Model | or Curve |  Segment  |     or       |
! |  Peak  | Option |  Vortex  | Vorticity | Vortex Line  |
! | (1/2)  | (1/7)  |  (0/1)   |   (0/1)   |   (0/1)      |
! +-------------------------------------------------------+
! Classical vortex wake with no distortion, single peak
!a     1        1         0          1            0
N
! +---------------------- Wake Geometry Specs ------------------------+
! |  Number   |  Near Wake | Rollup Wake | Number of  |   Initial   |
! |  of Wake  |  Azimuthal |  Azimuthal  | Revs for   |   Radial    |
! | Azimuthal |  Coverage  |  Coverage   | Far Wake   | Position of |
```

```
! | Steps/Rev |   (0:180)  |   (0:360)   |  (0:20)    | Rollup Wake |
! +-------------------------------------------------------------+
!a      72        60             120           3.0           1.0
N
! +-------------- Inflow Calculation Specs ----------------+
! | Flag for |  1/4 or 3/4   | Max.  Bound | Min. Sepration|
! | Inplane  | Chord colloc. | Circulation |   Between     |
! | Velocity |  points for   |  Fraction   |  Colocation   |
! | Calcula. | Induced Vel.  |  for Tip    |  points and   |
! |  (0/1)   | Calculations  |   Vortex    | Vortex Sheets |
! +-------------------------------------------------------+
!a    1             0                0.8            0.01
N
! +---------------------- Core Type and Size------------------+
! |  Tip   | Inb'rd |  Tip  | Tip Vortex | Inbrd | Inbrd | Near | Dual |
! | Vortex | Vortex | Vortx |  Core for  | Trailed| Shed | Wake | Peak |
! |  Core  |  Core  |  Core |   Inboard  | Vortex | Wake | Core | Core |
! |  Type  |  Type  |  Size |  Coloc.Pts.|  Core  | Core | Size | Size |
! +-------------------------------------------------------------------+
!a     0       0     0.02982    0.02982       0.     0.   0.02982   0.
N
! +---------------------------------------+
! |--Tip Vortex Core Model and Size for --|
! |--- Inboard Wake Collocation Points ---|
! |---------------------------------------|
! |  Option | Core Size at | Core Size at |
! |  (0/1)  | Inner Radius | Outer Radius |
! +---------------------------------------+
!a      1          0.76          0.88
N
! +--------- Exclude/Include Wake Model (0/1) ----------+
! |  Tip   |  Near Wake   | Rollup Wake  |   Far Wake   |
! | Vortex |--------------|--------------|--------------|
! |  Wake  | shed | trail | shed | trail | shed | trail |
! +-------------------------------------------------------+
!a     1       0      1       0      1       0      1
N
! +------------------- Prescribed Wake Geometry Data -----------------+
! | Vortex   |----- Factors -----|----------- Constants --------------|
! | Location |  f1    |   f2   |   K1  |   K2   |    K3   |    K4     |
! +-----------------------------------------------------------------+
!A     1         1         1        1        1        1        1
!A     2         1         1        1        1        1        1
```

```
!A     3         1         1        1        1        1        1
N
! Exclude ground effect
! +-------------- Ground Effect Parameters ---------------+
! | Include  | Minimum   | Include  |  Ground  |  Ground  |
! |  Ground  | Wake/Grnd |  Ground  |  Vortex  |  Vortex  |
! | Effects  | Clearance |  Vortex  |   Core   | B Factor |
! +-------------------------------------------------------+
!a      0           0.2        0          0.1          0.8


!=========================================================
!============== AERODYNAMIC COMPONENT ==================
!                        ablade1a

S AEROCOMPID
! Component name for defining or modifying
a ablade1a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
```

```
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  ELment  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ******************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          16
a  12  .0375939  .667    .60          1          0          16
! ******************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
```

```
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!============== AERODYNAMIC COMPONENT ==============
!                        ablade2a

S AEROCOMPID
! Component name for defining or modifying
a ablade2a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0
```

```
S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ********************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          17
a  12  .0375939  .667    .60          1          0          17
! ********************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6
```

```
!============== AERODYNAMIC COMPONENT =============
!                        ablade3a

S AEROCOMPID
! Component name for defining or modifying
a ablade3a

S COMPTYPE
! 1 => lifting surface,  2 => body,  3=> AUX ROT
a 1

S AERONODE
! Aerodynamic node ids and their coordinate wrt component
! nodes IDs        x          y           z
a     1         6.00000      0.0         0.0
a     2         7.50000      0.0         0.0
a     3         9.00000      0.0         0.0
a     4        10.50000      0.0         0.0
a     5        12.00000      0.0         0.0
a     6        13.50000      0.0         0.0
a     7        15.00000      0.0         0.0
a     8        16.50000      0.0         0.0
a     9        18.00000      0.0         0.0
a    10        19.00000      0.0         0.0
a    11        20.00000      0.0         0.0
a    12        20.00000     -0.026042   -0.000341
a    13        21.25000     -0.026042   -0.000341
a    14        21.25000     -0.026042   -0.000115
a    15        22.50000     -0.026042   -0.000115
a    16        24.00000      0.0         0.0
a    17        25.50000      0.0         0.0
a    18        26.50000      0.0         0.0
a    19        27.00000      0.0         0.0
a    20        28.00000      0.0         0.0
a    21        29.07000      0.0         0.0
a    22        30.00000      0.0         0.0

S AEROSEG
! Seg.   Aerodyn Node IDs    Chord     Airfoil  Element  Twist
! ID   (Inboard)(Outboard)   (ft)        ID      ID     (rad)
a  1       1        2   2.2704459170  VR7TM4P5    0     X.XXXX
a  2       2        3   2.6666666667  VR7TM4P5    0     X.XXXX
```

```
a  3       3        4   2.6666666667  VR7TM4P5    0     X.XXXX
a  4       4        5   2.6666666667  VR7TM4P5    0    X.XXXX
a  5       5        6   2.6666666667  VR7TM4P5    0     X.XXXX
a  6       6        7   2.6666666667  VR7TM4P5    0     X.XXXX
a  7       7        8   2.6666666667   VR7TM6     0     X.XXXX
a  8       8        9   2.6666666667   VR7TM6     0     X.XXXX
a  9       9       10   2.6666666667   VR7TM6     0     X.XXXX
a 10      10       11   2.6666666667   VR7TM6     0     X.XXXX
! tab
a 11      12       13   2.7708333333   VR7TM6     0     X.XXXX
a 12      14       15   2.7708333333   VR8TM6     0     X.XXXX
! tab ends
a 13      15       16   2.6666666667   VR8TM6     0    X.XXXX
a 14      16       17   2.6666666667   VR8TM6     0   X.XXXX
a 15      17       18   2.6666666667   VR8TM6     0    X.XXXX
a 16      18       19   2.6666666667   VR8TM6     0    X.XXXX
a 17      19       20   2.6666666667   VR8TM6     0    X.XXXX
a 18      20       21   2.6666666667   VR8TM6     0    X.XXXX
a 19      21       22   2.6666666667   VR8TM6     0    X.XXXX

! ********************************************************************
! Do not use ELEVONSEG unless using static stall condition
S ELEVONSEG
! Segm   Chord   -Def. Factors-  Theodorsen   Periodic  Nonperiodic
!  ID    Ratio   Lift Pitch Mom  Wake Option  Input ID   Input ID
a  11  .0375939  .667    .60          1          0          18
a  12  .0375939  .667    .60          1          0          18
! ********************************************************************

S AIRFOILINTERP
! Radial/Spanwise    Airfoil
! Airfoil Boundary     ID
a     6.42          VR7TM4P5
a    15.0           VR7TM4P5
a    15.6           VR7TM6
a    25.5           VR7TM6
a    30.0           VR8TM6

!====================================================================
!========================== ANALYSIS DATA ============================
!====================================================================

S SELANALYSIS
```

```
!  Trim analysis
!  Trim Options: 1 - Trim; 2 - Periodic Solution; 3 - Static Analysis
! Case_id Trim, Maneuver, Stability, Init_condn, Scope Script_Filename
a     1     1       0          0         D               NO
! ******************************************************************
! Example of multi-case analysis below
!a     2     1       0          0         D               NO
!a     3     1       0          0         D               NO
!a     4     1       0          0         D               NO
!a     5     1       0          0         D               NO
!a     6     1       0          0         D               NO
!a     7     1       0          0         D               NO
! ******************************************************************
N
! Case_id    Case_Title
a   1         ground_6blades_base
! ****************************************************
! Example of multi-case analysis continues below
!a   2         ground_5n
!a   3         ground_10n
!a   4         ground_15n
!a   5         ground_35n
!a   6         ground_70n
!a   7         ground_1slug
!N
!Multiscreen: 3  of 4    Type: Iterative      Screen: SELANALYSIS
!                       DEFINE CASE VARIABLES
! Case_Var   --Screen Name--  Data_Group_id   Screen  Field   Row
!    _ID                       ("--" if none)   Nbr    Nbr    Nbr
!a    1       CONTROLMIXER        --             1      2      7
!a    2       RBMELE            blade1f          1      2      1

!N
!Multiscreen: 4  of 4    Type: Iterative      Screen: SELANALYSIS
!                  SPECIFY VALUES FOR THE CASE VARIABLE
!Note: The values specified in this screen for the defined variables
!      will supersede the information given in the respective screen.
!Row ID    Case_Var_ID     Case ID                Value
!                                            (Numeric or Character)
!a  1            1             1                     0
!a  2            1             2                     0.0019841271
!a  3            1             3                     0.003968254
!a  4            1             4                     0.0059523813
```

```
!a  5            1             5                     0.0138888896
!a  6            1             6                     0.0277777792
!a  7            2             7                     1.00
! End of multi-case analysis example code
! ************************************************************

S SYSTEMFLAGS
! Global element formulation flags
! gravity, aero (1=Yes, 0=No)
a    1               1

S INITCOND
! Initial Pilot Controls , ft
!  collective, lateral, longitudinal, pedal, throttle
a     0.0       0.0          0.0          0.0        0.0  ! ground
!a     0.13133   0.0         0.0           0.0        0.0  ! hover
!a     0.216     0.0049      0.0042       -0.007      0.0  ! 89 kts
!a     0.393     0.004      -0.049        -0.008      0.0  ! 136kts
N
! G position Frame wrt I
!  X  Y    Z    Roll   Pitch   Yaw
a  0  0    0     0.0     0.0      0.0  ! ground/hover
!a  0  0    0    -.004    0.027    0.0  ! 89kts
!a  0  0    0    -.0075  -0.052    0.0  ! 136kts
N
! G velocity Frame wrt I
! forward velocity is defined in screen CONSTWIND
! Vx Vy Vz OmegaX OmegaY OmegaZ
a  0  0  0   0      0      0

S CONSTWIND
! Constant Wind velocity with respect to I frame in I coord.
!     Vx,       Vy,       Vz
a     0.        0.        0.  ! ground/hover
!a   -150.070     0.        0.  ! 89 kts
!a   -230.320     0.        0. ! 136 kts

S TRIMVAR
! trimvar=pilots coll,lateral,long.directional
! 1 =coll, 2=latcy, 3=longcy, 4=pedal, 5=throttle, 6=roll,
! 7=pitch,8=yaw,9=climbvel
! VarID  PertVal  DampFact  TargetID  TargetVal  TargetTol
a   1      0.02       0.7       3        0.0        20.0
```

```
a   2      0.02       0.7       4        0.0        100.0
a   3      0.02       0.7       5        0.0        100.0
a   4      0.02       0.7       6        0.0        300.0
a   6      0.01       0.7       2        0.0        20.0
a   7      0.01       0.7       1        0.0        20.0
N
! Specify the target ID and the concatenated name of the trim target.
! The trim target name consists of the subsystem name, primitive
! structure name, node name, and force or moment name.
! NODE5 is a node name. PFRC(2) is a force name, and PMOM(1)
! is a moment name. Contantenation should be done by underscores.
!
N
!                LOAD AND/OR SAVE TRIM SENSITIVITY MATRIX
!
!    Specify whether a trim sesitivity matrix is to be imported from
!    a file, loaded from a previous case or saved if it is calculated.
!    Also enter the file name for the trimsensitivity matrix.
!
!  LOAD,     SAVE                 Trim Sensitivity
!  PREV,     PNS                  Matrix Filename
a  SAVE                           RCASTRIMMATRIX.MAT
!a    LOAD                            RCASTRIMMATRIX.MAT
N

!                USER DEFINED TRIM LOOP AND UPDATES
!    Enter row IDs, and for each row enter option to compute trim
!    sensitivity matrix, inflow model during the calculation of trim
!    sensitivity matrix, number of trim variable updates and inflow
!    model during the trim updates.
!
!  Row   Number of  Inflow model for  Option to Compute   Inflow model
!  ID  Trim Updates   Trim updates    Trim Matrix (0/1)  for Trim Matrix
a  1       60            uniform             0            uniform
! ACTIVATE the following line if modeling with prescribed wake condition
!a  2      30            preswake             0            uniform
! ACTIVATE the following line if modeling with a free wake condition
!a  3      40            freewake             0             uniform
!N

S CONVERGETOL
!# of  # of  # of  -Displacement Tolerance-   -Velocity Tolerance-  Min.
!Trim  PSol  Time   translation  rotation    translation rotation  # of
```

```
!Iter  Iter  Step    (ft)         (rad)       (ft/sec)  (rad/sec) PS Rev
a 30    40    72     0.02          0.01          5.0       2.0       5
c 40    30    72     0.002         0.001         0.18      0.09      5
c 90    60    72     0.02          0.01          5.0       2.0       5

S INTEGPARAM
! Define Newmark-Beta/HHT integration parameters
! no. nonlinear state iterations, Newmark constants, displacement
! and velocity tolerances, UNDER RELAXTION FACTOR,
! NR iterations
!  iter,  NMB_a,  NMB_d,  HHT_a,  disp-tol, vel-tol, U_relax fac
a    99    .25     .5      -.03     1.e-5     1.e-4      1.0
c    99    .25     .5      -.03     1.e-6     1.e-6      1.0

S STATICEQUI
! Input data for static equilibrium.
! row    no. of    relaxation  convergence         Minimum
! ID   iterations    factor     tolerance         Stiffness
a  1        5           .1       1.01               10000
a  2        5           .2       1.01                5000
a  3        5           .3       1.01                2000
a  4        5           .5       1.01                1000
a  5       15           .6       1.01                 500
a  6       15           .7       1.01                 200
a  7       15           .8       1.01                   0
a  8       15           .8       1.01                   0
a  9       15           .8       1.01                   0
a 10       15           .8       1.01                   0
a 11       15           .8       1.01                   0
a 12       15           .8       1.01                   0

S AEROSTATCONST
! Define aerostatic conditions for standard sea level
! Spec-type, altitude, temp, air density, sound velocity
a       1        0       0       0              0

 S COMMPERIOD
!DEFINE THE COMMON PERIOD OF ALL ROTORS FOR TRIM
!   Name       Rotor Period Ratio    Tolerance
a  rotorf            1                  .1

S BATCHOUTPUT
!  Row                    Output
```

```
!   ID                  Filename
a    1                  fwd_mom_vib.par
a    2                  aft_mom_vib.par
a    3                  fwd_mom_stdy.par
a    4                  aft_mom_stdy.par
a    5                  f_hub.par
a    6                  m_hub.par
a    7                  pll_dmp.par
a    8                  cf.par

S UDFOUTPUTS
!  Row   Analysis    ------------- Rscope Variable -------------
!   ID    Type                        Name
a     1      TRM           world_model_rotorf_blade1f_e200spr_sprforce
a     2      TRM           world_model_rotora_blade1a_e200spr_sprforce
a     3      TRM           world_model_rotorf_blade1f_e201dmp_dmpforce
a     4      TRM           world_model_rotora_blade1a_e201dmp_dmpforce

S PERIODICOUTPUT
!  Row   Subsystem   Prim. Struc.            output
!  ID      Name        Name                 category
a   1      all         all                  vibration
a   2      all         all                  airloads
!a   3      all         all                  sys.dyn.resp
!a   4      all         all                  internal.loads

S SAVESC
! Form of SC Data             Directory and File Name     Number of
! (RDB or FILES)                  for SC Data            Output Steps
!   <SCFORM>                       <SCFILNAM>            in One File
a   RDB                      EFUSE_6BLADE_BASELINE.SAV       72

S RUNALLCASES
!    Run All Cases Flag (0/1)
a               1

S STOPANALYSISAT
!                    SPECIFY STOPANALYSIS BREAKPOINT
!
! Enter a number between 0 and 8 to specify how far the program should
! proceed through the analysis.
!
!   0 ->      Go through all the analysis
```

```
!   1 ->      Stop after the model is loaded
!   2 ->      Stop after blade modes are generated/ before assembly
!   3 ->      Stop after assembly is complete
!   4 ->      Stop after static equilibrium is completed and
!             before trim or maneuver is started
!   5 ->      Stop after periodic solution is completed and
!             before trim or maneuver is started
!   6 ->      Stop after trim is complete and
!             before maneuver is started
!   7 ->      Stop after maneuver is completed
!   8 ->      Stop after stability is completed
!       Analysis Breakpoint
!         indicator (0/8)
a   0



EXIT

COMMAND

MENU RUNANALYSIS
```

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Vita

Major Stephen M. Dickerson graduated from the University of Texas at Austin with a Bachelor of Science in Civil Engineering in May 1995. He was commissioned in the United States Marine Corps and reported to The Basic School (TBS) at Quantico, Virginia in October 1995. He was awarded his Naval Aviator wings in NAS Whiting Field in October 1998. He then reported to Marine Helicopter Training Squadron 302 to begin pilot training in the CH-53E Super Stallion.

Major Dickerson reported to Marine Heavy Helicopter Squadron (HMH) 464 in March 1999. He detached to Marine Medium Helicopter Squadron (HMM) 162 (Reinforced) and the 22nd Marine Expeditionary Unit (Special Operations Capable) for deployment from December 2000 to May 2001. Major Dickerson returned to HMH-464 and in March 2002 he deployed as an Individual Augment to Combined Forces Land Component Command in Kuwait. From here he received assignment to Combined Joint Task Force 180 at Bagram, Afghanistan. He returned to HMH-464 in September 2002 and deployed to OPERATION IRAQI FREEDOM (OIF) in January 2003, then to Combined Joint Task Force Horn of Africa (CJTF-HOA) in October 2003. In July 2004 he reported to Marine Unmanned Aerial Vehicle Squadron (VMU) 2 as a Mission Commander and the Aviation Safety Officer. With VMU-2 he deployed to OIF 04-06 in February 2005 and OIF 05-07 in March 2006 as the squadron Operations Officer. In February 2007 he reported to HMH-462 as the Director of Safety and Standardization; in June he became the squadron Aircraft Maintenance Officer. In April 2008 he deployed with HMH-462 to OIF 08.2, and in July relocated from Iraq to Kandahar Airfield, Afghanistan for OPERATION ENDURING FREEDOM.

In May 2009 he began his studies at the Air Force Institute of Technology. Upon graduation he will be assigned as an instructor at the U.S. Navy/Marine Corps School of Aviation Safety, NAS Pensacola, Florida.

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14. ABSTRACT
The Department of Defense (DoD) has mandated the use of maintenance practices based on component condition rather than component time in service or age. This new practice is known as Condition Based Maintenance, and it relies on accurate detection and identification of material deficiencies in system components. Rotor system components in rotary-wing aircraft can be difficult to monitor due to the rotational environment experienced by the sensors and the difficulty of signal transmission. Current methods are able to detect the existence of a fault in the rotor system but cannot link the vibrations experienced in the airframe to a specific material defect. This results in inefficient maintenance practices associated with identifying the faulty components for repair or replacement. This research seeks to create a model which will enable the identification of component deficiencies in the rotating system from vibration characteristics experienced in the fuselage, in order to increase maintenance efficiencies leading to cost savings and increased operational readiness for in-service CH-47D aircraft.

15. SUBJECT TERMS
CH-47D, Condition Based Maintenance, helicopter, vibration analysis

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