ROTORCRAFT FLIGHT RESEARCH WITH EMPHASIS ON ROTOR SYSTEMS

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Introduction

NASA and the Army have been engaged in flight research with rotorcraft for six decades beginning in the autogiro days at Langley and continuing today with both conventional helicopters and advanced concepts like X-Wing and Tilt Rotor at Ames. An important part of that research, at least over the last 25 years, has been research directed at the rotor systems. One of the first important contributions in rotor flight research was made at Langley in the late fifties and early sixties with the H-34 with pressure instrumented blades installed. The work continued through the sixties with an emphasis on hingeless rotor concepts and into the seventies with a heavy emphasis on two bladed rotors and the problems associated therewith. In the late sixties an idea was formulated for a complex, new research tool called RSRA (Rotor Systems Research Aircraft). The idea germinated and funding was provided for construction of the RSRA in the mid-seventies. The RSRA became operational after a change of primary location to Ames in the early eighties. While it has extensive capabilities, the complexities of the RSRA have resulted in a less than effective tool. As funding and manpower to support the RSRA have declined, new options to pick up the slack in research capability turned in the direction of the Army UH-60.

This paper will deal with this history of rotor systems flight research aircraft and with the contributions that they have made over the last 25 years.

Symbol List

b	number of blades
c	blade chord (inches or ft.)
C_l	blade section lift coefficient
C_{Lr}	rotor lift coefficient
$\overline{C}_L$	mean lift coefficient
C_m	blade moment coefficient
C_n	normal force coefficient
C_p	blade pressure coefficient
$C_p{}^*$	critical pressure coefficient
C_T	rotor thrust coefficient
$(D/L)o_m$	measured profile drag/lift ratio
$(D/L)o_T$	theoretical profile drag/lift ratio
f_g	normal load factor (g)
g	acceleration of gravity
M_{TIP}, M	blade tip Mach Number
PSIA	absolute pressure measurement
p	aircraft rolling velocity (rad./sec.)
q	aircraft pitching velocity (rad./sec.)
r	radial location on blade (ft.)
R	rotor radius (ft.)
t	airfoil thickness (in.)
TM	Torsional Moment (lb.-in.)
V, V_r	aircraft forward velocity (ft./sec. or knots)
x	chordwise coordinate of airfoil from nose (in.)
y	normal to chord coordinate of airfoil from chordline (in.)

Presented at the 1987 NASA/Army Rotorcraft Technology Conference, Ames Reseach Center, March 17-19, 1987.

Symbols (cont.)

(Figure 54 abbreviations)

EB	edgewise bending gage location
NB	normal bending gage location
TB	torsional bending gage location
AE	edgewise accelerometer location
AN	normal accelerometer location

Greek

α	rotor angle of attack (degrees)
$\alpha_{(1.0)(270^0)}$	retreating blade angle at tip (degrees)
Γ	blade bound circulation
μ	rotor tip speed ratio
ψ	rotor azimuth (degrees or radians)
ρ/ρ_0	air density ratio
σ	rotor solidity $bc/\pi R$
Ω	rotor rotational speed (rad./sec. or RPM)

General Description of a Rotor Systems Flight Research Aircraft

Two types of flight research configurations are represented in the group of aircraft to be discussed: those that addressed specific problems such as blade vortex interactions of 2 bladed configurations, and those that served as research tools to investigate generic problems. In general the programs have been of the second type.

The general classification of those vehicles utilized to conduct rotor systems research will have, as a minimum, some rotor strain gages for the measurement of blade bending and will probably have the means to measure pitch angle and flapping plus an assortment of other aircraft parameters such as airspeed, roll and pitch rate, and cg accelerometers. These are the minimum requirements for undertaking any type of quantitative investigation. However, some qualitative information can be obtained with flow visualization methods and, of course, the conduct of rotor acoustic testing can be accomplished without any instrumentation on the aircraft if ground tracking is available.

Generally speaking, the more instrumentation available, the more that can be determined about a particular phenomenon. The number of combinations of rotor types as illustrated in the matrix in table I requires that an extensive amount of testing be accomplished to fully explore a problem area.

Phenomena of Interest in Rotor System Flight Investigations

While the number of phenomena in the rotor system that are of interest are very large, the number reduces to 5 significant types of problems as listed in Table II: vibration, noise, performance, aeroelastic stability, and gust response. Figure 1 illustrates the types of phenomena that occur in the rotor system that ultimately can result in aircraft problems. Table II also attempts to define the phenomena that are the root causes of the various problems.

The 5 problems identified in Table II provide the greatest limitation on the conventional helicopter, and any improvement in the understanding of the root causes that affect these problems will potentially be of great benefit. All of the problems and related phenomena are interelated to the point where it is extremely difficult to design an aircraft that is free of some limitation without adversely affecting one or more of the others. The other complication, of course, is that the rotor must be designed to operate in a number of flight conditions from hover to high speed. Ultimately, the need is to be able to predict the individual phenomena and all of the interactions to the point where the design can be optimized for a given mission. The development of such prediction methods requires that the phenomena be fully explored both through small and full scale isolated rotor testing and through full–up aircraft testing in flight.

NASA(NACA)/Army Rotor Systems Flight Research Programs

Rotary wing flight research began in the 30s at Langley with early efforts with autogiros with the primary emphasis on rotor performance. Wheatley in two papers (references 1 and 2) from the early thirties describes a performance test program and theoretical prediction effort and correlation effort using the Pitcairn PC-2 autogiro. The instrumentation of that era was crude, however, the analysis of Wheatley and early researchers was the foundation for most of the prediction programs in use today. One correlation effort from Wheatley's work (reference 2) is shown in figure 2. Figure 2 shows theoretical and experimental values of rotor lift coefficient and angle of attack plotted against tip speed ratio. Even with the crude instrumentation and rather unsophisticated analysis, the correlation was very good at low tip speed ratios.

The mid-to-late forties saw the beginning of conventional helicopter flight research with the availability of the Sikorsky R-4. Gustafson in references 3, 4, and 5 reported on flight tests beginning in 1944 principally directed at performance testing. In reference 5, Gustafson and Gessow report on a flight test activity with the R-4 (figure 3) directed at blade stalling. Figure 4 from reference 5 illustrates a correlation effort between predicted and measured stall. In the figure, the ratio of drag to lift measured to predicted is plotted against retreating blade tip angle of attack. The observed divergence from a value of 1 is interpreted as the initiation of stall at the tip when the drag to lift prediction becomes very unreliable. Tuft photos taken on the blade comfirmed this observation.

The fifties saw a diversification of the types of testing; the first instances of important dynamics testing began. One such flight test is discussed in reference 6 by Yeates. Yeates reports in this reference on ground and flight tests of the tandem rotor shown in figure 5. The aircraft was instrumented for vibration in both the ground (shake tests) and flight tests. The fuselage response was measured and compared for two sets of blades, one wood and one metal. Yeates in figure 6 illustrates that the fuselage response shows the effect of rotor/fuselage coupling in the flight test (2 peaks) and not in the ground test (1 peak) where the rotor was not installed.

Ludi, as reported in reference 7, moved further in the direction of full rotor system flight testing with a large single rotor helicopter test in the mid fifties. The test aircraft shown in figure 7 was flown with strain gaged blades for the measurement of flapwise, chordwise, and torsional blade moments with a particular emphasis on retreating blade stall. In figure 8 from reference 7, Ludi employs a technique similar to that employed by Gustafson. However instead of employing the ratio of measured to theoretical values of drag/lift ratio to determine the divergence due to stall, Ludi normalizes the measured blade torsional moment by dividing by the measured moment at a tip speed ratio of .24 where the rotor is not stalled. The torsional moments are observed to increase at a fairly slow rate until the tip speed ratio exceeds .24 where the moments increase much more rapidly indicating a stalled condition on the retreating side.

As illustrated in the preceding paragraphs there was considerable flight research relative to the rotor system in NACA prior to 1960, however much of the focus was on aircraft performance and the instrumentation was relatively limited. That changed around 1960 with the H-34 program. Rotor system flight research has been ongoing in NASA/NACA for over fifty years; this paper will deal principally with those experiments that have taken place in the second half of that time frame, beginning with the H-34.

The research vehicles that will be dealt with are illustrated in figure 9. This figure shows the vehicles of interest against a chronological axis with a qualitative evaluation of the research capabilty of each aircraft. The discussion begins with the H-34 and will end with the most current program, the UH-60. In the discussion, an attempt will be made to illustrate the highlights of the research and the contributions that were made.

H-34

The H-34 program was the most extensive rotorcraft flight test effort ever attempted when it was undertaken in the early sixties. The aircraft shown in figure 10 was extensively instrumented with, not only conventional instrumentation such as accelerometers, strain gages, airspeed, etc., but also one blade incorporated differential pressure transducers for the measurement of section pressure distributions. Early wind tunnel tests (Reference 8) had employed blade mounted pressure transducers, but this was the first flight test blade. The complete list of aircraft intrumentation can be found in reference 9. The aircraft was a conventional single rotor helicopter with a four bladed rotor. The complete description of the aircraft can be found in reference 9.

The flight test program was conducted at NASA Langley with one of the primary purposes being to develop data with which 2D airfoil pressure distributions could be compared. As reported in reference 10 by Schieman and Kelley, this was successfully undertaken. Reference 10 reports on the discrepancies uncovered on the retreating blade where section normal force coefficients exceeded the 2D stall lift conditions.

The tabulated results from the flight test are contained in reference 9. These results and the results of the companion wind tunnel test of the H-34 rotor in the 40 x 80 Wind Tunnel have become a benchmark data set for use in the validation of airloads prediction methods. Several investigators have utilized these results in their validation efforts. Included in the investigations utilizing the H-34 data is the work of Sadler (Reference 11) in comparing airloads predictions in steady maneuvers utilizing a free wake analysis with the flight test results. One such comparison is illustrated in figure 11 (Reference 11). Ward in reference 12 examined 6 cases of level and maneuvering flight data from the H-34. In figure 12 (Ref. 12), Ward shows a comparison of torsional moments, and section loading and moment coefficients for level flight and a 1.5 g pull-up maneuver which illustrates significant oscillations in the fourth quadrant for the maneuver case. In figure 13 (Ref. 12) Ward relates this behavior to vortex intersections in the fourth quadrant. More recent efforts by Hooper (Reference 13) and Esculier and Bousman (Reference 14) make extensive use of the flight and wind tunnel results in the analysis of vibratory airloads and the estimation of blade structural loads.

Despite a number of drawbacks to the data set including the frequency response of the pressure data, the accuracies of the data, the limited airspeed, and the differential transducers, the data set has been shown to be extremely valuable.

XH-13

The early sixties also saw the kindling of significant interest in the hingeless "rigid" rotor system. Very stiff non-articulated rotors with all of their inherent problems had been by-passed with the advent of the articulated rotor for autogiros. However, the development of flexible metal blades, that were far from rigid, emerged in the early sixties and permitted the further investigation of rotors which took advantage of the increased control available with a hingeless rotor.

One of the first test vehicles to employ a hingeless rotor was the modified H-13 shown in figure 14 (Reference 15). A close up of the hingeless rotor hub and slipring assembly is shown in figure 15 (Ref. 16). The aircraft was flight tested at Langley in the early sixties and the results are reported by Ward and Huston in several publications (Ref. 15-18).

As described in reference 15, the aircraft was instrumented principally for structural loads on the blade, hub, shaft, and control links; however, normal aircraft state instrumentation was also employed. A complete list of instrumentation can be found in reference 18. In reference 18, Ward focuses on the chordwise blade loads which are shown to be critical in maneuvers as illustrated in figure 16 (Ref. 18). In the figure the time histories of several parameters are plotted for a rolling maneuver from flight data. Included is the chordwise blade bending at the blade root. It is immediately obvious that the build-up in oscillatory chordwise blade bending has exceeded the endurance limit for the blade. Ward also develops in the Appendix to reference 18 a methodology for calculating the chordwise bending moments based on an equivalent hinge offset.

The tests with the rudimentary hingeless rotor H-13 led directly to the aquisition by NASA of one of three XH-51 hingeless rotor helicopters to be described in the following section.

XH-51N

The XH-51 was an advanced hingeless rotor helicopter developed for military evaluation of the hingeless rotor concept. In early 1965 NASA acquired the 3rd XH-51 produced, and the aircraft was flight tested at Langley and at the RAE in England through 1970. The XH-51N is shown in figure 17. In reference 19, Snyder describes the extensive rotor and airframe instrumentation utilized in the testing and provides a complete description of the aircraft. The aircraft was instrumented for flapwise and chordwise bending, and the mast and pitch links were also strain gaged. Likewise, the tail rotor was strain gaged for flapwise and chordwise bending. Several components of the control system were instrumented for loads and position. Accelerometers, rate gyros and vibration pickups were also utilized. Unlike the other 4 aircraft produced, the XH-51N maintained the original 3-bladed configuration, while the others were built or modified for 4 blades, including the XH-51A Compound Helicopter tested under an Army program.

The aircraft had a number of unique features including the hingeless rotor. The aircraft employed a mechanical gyro in the control system such that the pilot did not control the rotor directly, but provided force inputs to the gyro shown in figure 18; the gyro then provided control inputs to the rotor based on inputs from the pilot or from rotor feedback provided by the forward sweep of the blades. This control system was the fore runner of the control system utilized on the AH-56 Cheyenne that resulted in severely limiting problems for that aircraft. Kelley in reference 20 describes some of the control problems experienced with the XH-51N during maneuvering flight.

Another unique feature of the XH-51N was the cabin isolation system illustrated in figure 19 (Ref. 21) which was utilized to control cabin vibration. Another vibration control device employed after the fact on the XH-51N were the blade mounted masses as illustrated in figure 20 which were utilized to detune the 2nd flap bending frequency of the rotor. During the research flying with the XH-51N, the aircraft was flown both with and without the cabin isolation system and the blade masses.

Both the rotor loads and the flight dynamics of hingeless rotor configurations in maneuvering flight were investigated during the flight investigations with the aircraft. Snyder in reference 19 reported on the rotor loads encountered with the aircraft in Nap of the Earth maneuvers. Figure 21 from reference 19 illustrates that the XH-51N had even more severe chordwise and flapwise rotor bending problems than the H-13 hingeless rotor helicopter. Both the flapwise and chordwise bending moments consistently exceeded the endurance limit for the measured hub plate during maneuvers, and loads were always monitored in real time utilizing telemetry.

Ward and Snyder (Ref. 22) and Ward (Ref. 23) analytically investigated hingeless rotor blade response for an excitation caused by a concentrated force (simulated vortex) moving from blade tip to root. This work was stimulated by the high vibratory loadings experienced with the XH-51N.

One of the last experiments to be run on the XH-51N was the investigation of an active cabin isolation system to replace the passive spring utilized to isolate the cabin as was previously illustrated in figure 19. Hanks and Snyder report on the baseline aircraft tests with and without isolation and on the ground tests of the active isolation system in reference 21. Figure 22 (Ref. 21) illustrates the excessive cabin vibration levels experienced with the isolation system locked out and the blade mass removed. In the figure, cabin vibration amplitude is plotted against airspeed, and it can be seen that levels in excess of 1 g at 18 Hz are experienced in transition. This is typical of hingeless rotor helicopters with high effective hinge offset and one of the problems still to be faced with the newer bearingless rotor systems. Reduction of the effective hinge offset, as has been achieved with some of the newer designs, can help allieviate the vibration problem.

Another idea that was stimulated by the work on the XH-51N and its high vibratory loads was the concept of reducing the strength of the tip vortex through the use of the "ogee" tip. The "ogee" tip was conceived by John Ward and initial tests of the tip along with conventional tips were conducted in a small scale smoke tunnel. These preliminary tests(documented in an unpublished report by Snyder and Pegg) indicated a reduction in vorticity of as much as 40% over a conventional square tip and were encouraging enough to initiate work on a full scale evaluation utilizing a UH-1H which is discussed in the following section.

UH-1H

The UH-1H helicopter was acquired at Langley in the early 70s as a test bed for the "ogee" tip rotor. The aircraft was instrumented and baseline flight testing was initiated. The aircraft and instrumentation system are described by Mantay in reference 24. Rotor structural parameters and aircraft state parameters were measured. In addition, an in-flight acoustics measurement system (fig. 23) was mounted on the aircraft. For the "ogee" tip flights only, tip pressures were measured. A ground acoustic array was also employed.

The full scale "ogee" tip was fabricated in-house at Langley and tested both in-flight and on the Langley rotor whirl tower. Figures 23 and 24 (Ref. 24) show the test aircraft and the two test rotor configurations, respectively. Figure 25 (Ref. 24) illustrates the improvement provided by the "ogee" tip over the conventional tip for vibratory pitch link loads at low thrust coefficient values. The improvement was considerably reduced at higher rotor thrust coefficients. A similar trend was indicated with both the noise and power measurements. The results of these tests led to a follow-on investigation by the Army on an advanced rotor for the AH-1S.

In the same time frame as the "ogee" tip flight testing, a second program utilizing an AH-1G was undertaken at Langley to investigate advanced rotor airfoils. The AH-1G program is discussed in the following section.

AH-1G (Langley)

The AH-1G "Cobra" (figure 26) was acquired at Langley in the early seventies and was to become the most extensively tested vehicle since the H-34. The primary purpose for the acquisition was to undertake a series of advanced airfoil flight evaluations. As described by Morris in Reference 25, the acquired Cobra was instrumented with an onboard instrumentation system and a baseline flight test program was conducted. In this initial report (Reference 25) Morris reports on the investigation of the baseline performance characteristics of the Cobra. In following investigations, Morris conducted investigations with 3 different advanced airfoils. Special Cobra blades were fabricated to conform to the desired airfoil coordinates. The procedure is illustrated in figure 27 from reference 25. In this figure the basic spar is illustrated in the upper part of the figure. The lower part of the figure illustrates the glove build-up to the desired coordinates and also illustrates the installation of transducers. This particular section is the first airfoil tested with the Cobra–the NLR-1T. Reference 26 also describes the SRBI (Special Rotor Blade Instrumentation System) which was utilized for the testing. The SRBI (figure 28) is a rotor head mounted instrumentation package that provides the data processing for those sensors in the rotating system. The system was intended to provide the capability for telemetering data into the fuselage without the need for sliprings. However, this aspect of the system had to be abandoned and sliprings were utilized to transmit the multiplexed data into the fuselage for recording.

Figure 29 from reference 26 illustrates the installation of pressure transducers at one radial station (r/R = .9) on the blade. Each of the three rotors tested with advanced airfoils utilized this installation. The primary data for the investigation of blade section aerodynamics was provided by the pressure instrumentation. The results of the investigation of blade section aerodynamics of the NLR-1T are reported in reference 27 by Morris, Stevens, and Tomaine. The geometric characteristics of the NLR-1T are shown in figure 30 (Reference 27). The report covers a substantial number of comparisons and results relative to the section aerodynamics including normal force coefficients at different tip speed ratios, investigations of shock locations, and comparisons with theory. An illustration of a comparison with theory is shown in figure 31 from the report. The figure shows a comparison of measured and calculated chordwise pressure coefficient distributions for 4 different tip speed ratios–μ=.24 to .33 at the 70 degree azimuth location. As shown, the correlation is fairly good, but worsens with higher tip speed ratios.

Figure 32 and 33 illustrate the geometric characteristics of the other two airfoils tested- the 10-64C and RC-SC2 respectively. The performance and loads results for these two airfoils are reported in references 28 and 29, respectively. The blade section aerodynamics results for these two airfoils are reported by Morris, et al, in references 30 and 31.

The seven reports, references 25 through 31, represent a significant contribution and contain a broad range of data on these three advanced airfoils. This effort was only the beginning for what became known as the "White Cobra". In 1978, the aircraft was transfered to Ames Research Center from Langley, and plans were formulated for the second major rotor pressure data acquistion program undertaken by NASA. This program is discussed in the following section.

AH-1G (Ames)

In the mid-seventies, the Army, through Bell Helicopter, undertook a monumental data acquisition effort with an AH-1G Cobra which was called the Operational Loads Survey (OLS), reference 32. Along with extensive fuselage instrumentation, two rotor blades were instrumented with strain gages, accelerometers, hot wire probes, and pressure transducers. There were more transducers involved in this test then in any previous test anywhere. When the "White Cobra" arrived at Ames in 1978 plans were formulated to acquire the rotor from the OLS for additional testing. Since the emphasis of the NASA program was on the tip aerodynamics, several more radial stations in the tip area were instrumented with chordwise pressure arrays.(fig. 34.) The instrumentation installed on the "White Cobra" for the NASA/Army Tip Aero Acoustic Test (TAAT) is described in detail in reference 33. In reference 33, Cross and Watts present a significant sampling of the data acquired during the TAAT flight program along with a complete description of the test and with an analysis of several key phenomena. A multitude of problems were encountered during this investigation that hampered the data reduction effort. The time available to conduct the test was limited by the availability of data processing equipment and, consequently, the test was conducted under less than ideal conditions, and the capability to repeat conditions and to identify problems with data were restricted. One of the problems related to calibration changes on the pressure transducers between the OLS test and the TAAT, and the way that the problem was addressed is discussed by Watts in reference 34.

The data analysis effort for both the OLS and TAAT programs utilized DATAMAP, reference 35, as a primary tool and all data from these programs is available through DATAMAP. A sample of analyzed pressure data from the TAAT program utilizing DATAMAP taken from reference 33 is shown in figure 35. In the figure, blade pressure coefficients are plotted against rotor azimuth for each position on the chordwise array at radial station 99% for the test point at 159 knots. The influence of the shock on the blade is obvious from the figure.

In addition to performance and aerodynamic data acquired during the program, a major effort was expended on acoustic testing with the YO-3A, airborne acoustic platform. The YO-3A (fig. 36) is described by Cross and Watts in reference 36.

Utilizing the capability to access the TAAT and OLS data via a VAX computer and DATAMAP at Ames, several researchers have conducted investigations and analytical correlation efforts with the blade pressure data. Two of these activities are reported in references 37 and 38. In reference 37, Schillings of Texas A&M makes comparisons of predictions from a 2D transonic code, TRANDES, with the TAAT data. Figure 37 from reference 37, illustrates two extremes in the correlation effort. Figure 37 shows a comparison at the 75% radius position of predicted versus measured chordwise distribution of pressure coefficients. At this radial position, where the flow is reasonably 2 dimensional, the correlation is fairly good. However, at the 99% radial station, also shown in figure 37, the correlation is poor because of the 3 dimensional effects. In reference 38, Shenoy, et al, report on a correlation effort utilizing a NASA Ames developed transonic code, ROT 22. The report also documents the methods for intregrating ROT 22 output with DATAMAP such that DATAMAP can be utilized as the tool for making the comparisons.

In addition to providing a massive amount of valuable data on two bladed configurations, the TAAT and OLS were a learning experience relative to future programs involving extensive instrumentation.

Much of the flight test work done during the 70's involved flight research with two bladed rotors as has been discussed in earlier sections; however, the limitation of the use of the readily available two bladed rotor helicopters from Army inventory was recognized in the late sixties, and the development of a generic research aircraft was initiated. The product of this initiation, the **RSRA** or **R**otor **S**ystems **R**esearch **A**ircraft, is discussed in the following section.

RSRA

The idea for a generic research aircraft bore fruit in the early seventies when the NASA and the Army combined to fund the development of the Rotor Systems Research Aircraft (RSRA). After the conduct of a series of pre-design studies, the full scale development of the RSRA began in 1973. The first flights of the completed aircraft occurred in 1977 at NASA's Wallops Station prior to delivery of the aircraft to NASA Ames. These first flights were conducted by the contractor.

The RSRA is one of the most complex aircraft ever constructed. A complete description of the systems and capabilities of the aircraft can be found in references 39 to 44. The aircraft can operate in three different modes, helicopter, compound helicopter (compounded either with engines alone or with engines and wing), and as a fixed wing. These three primary configurations are illustrated in figures 38, 39, and 40. The basic dynamic systems of the aircraft have been adapted from the existing S-61 helicopter, but these systems were packaged in an all new airframe with many unique capabilities. Each of the unique capabilities of the RSRA required the development of unique systems that had to be integrated into the aircraft. This uniqueness was the heart of the RSRA and became the source of many of its problems.

Detailed descriptions of the systems and the requirements for the RSRA are provided in the references so only a cursory discussion is included here. The main capability that sets the RSRA apart from all other aircraft is the rotor system balance system which is described in references 44 and 45. The capability is provided in the RSRA to measure all of the forces and moments transmitted from the rotor to the fuselage. For steady forces and moments this capability works very well and provides the capability to compare predicted rotor performance with measured performance, as well as rotor control capability and force and moment derivatives. The balance system, illustrated in figure 41, does not provide its unique capability without major effort. Not only do the individual load cells of the system require calibration, but the entire system requires calibration. The performance of this calibration has required the development and continued upgrading of a major calibration facility. A photograph of the facility located at NASA Ames is shown in figure 42; a schematic of the facility is shown in figure 43. The facility is described completely in reference 46. As described in the earlier references, there are two different balance systems available for the RSRA. Each of the two systems are installed in one of the two aircraft. The system installed in the compound aircraft, Ames A/C #740, is a conventional balance employing load cells (fig. 41). The RSRA helicopter, Ames A/C #741, uses a unique balance system with vibration isolation capabilty. Both aircraft have been calibrated in the Ames facility. Acree presents the results of these calibrations in references 45 and 47. Hysteresis was a major problem with the balance system as discussed by Acree in reference 48. Figure 44 presents a calibration curve from reference 48 which illustrates this hysteresis effect. The hysteresis effect is one problem that requires further development. A more serious limitation was discovered when a preliminary attempt was made to investigate dynamic calibration of the aircraft.

Dynamic calibration is key to the measurement of vibratory forces and moments. The aircraft was shake tested as shown in figure 45 in order to develop transfer functions for dynamic loads. The aircraft proved to be too non-linear for this methodology to be effective. This non-linearity is illustrated in figure 46 where the transfer function is plotted against applied force and excitation frequency. The transfer function varied both as a function of applied force and frequency thus making it almost an impossibility to develop a calibration matrix that would allow the estimation of vibratory forces and moments in flight. This limitation cuts deeply into the capability of the RSRA to be utilized for vibration research. Alternatives to direct dynamic calibration have been investigated, but to date a fully reliable alternative approach has not been identified that would be worth the considerable investment required. In reference 49 one such alternative is described. In theory, the approach appears feasible, however, the requirement that accelerations of the transmission must be very accurately measured and the transmission system must be accurately modeled may limit its usefulness in the practical world.

Even without dynamic calibration and with hysteresis effects, the RSRA balance system has permitted the acquisition of two unique sets of data. One data set was the acquisition of fuselage download measurements in hover and low speed flight as reported by Flemming and Erickson in reference 51.

Figure 47 from reference 52, illustrates the first ever measurement of rotor hub drag in flight. In the figure, raw hub drag taken on the RSRA in flight in the fixed wing (no rotor) configuration is plotted against airspeed. Acree in reference 52 also makes comparisons with wind tunnel and model scale data.

Like the rotor balance system of the aircraft, the variable incidence wing on the RSRA also provides a unique capability. The wing provides the capability to fly in the fixed wing mode and to fly with rotors that are not capable of carrying the full weight of the aircraft. However, it also provides the capability to vary the amount of load that the rotor carries from a completely unloaded rotor to loaded well beyond the weight of the aircraft by providing negative lift on the wing. These capabilities are extremely valuable in the investigation of rotor performance over a broad range of rotor operating conditions. The wing, like the rotor balance system, falls short of fully acceptable operation. The wing balance system which employs load cells as illustrated in figure 48 has been shown to have redundant load paths. While attempts have been made to rectify the problem, they have not been demonstrated in a calibration. The hydraulic actuation system for the wing has also been a source of problems and requires an expensive modification to rectify the problems.

A third unique system of the RSRA is the emergency escape system which provides both escape capability and the capability to jettison an unstable rotor and fly home as a fixed wing. The installation of the blade severance devices is shown in figure 49. While fortunately never employed in flight, the system has worked well in ground tests. Before the aircraft could be flown in the fixed wing mode, however, a new set of ejection seats had to be installed. In the event of the installation of a new rotor on the RSRA, as is the case for the X-Wing rotor which is discussed in reference 53, a major development effort would required to develop the pyrotechnic blade severance system.

The control system, while not unique among the many variable stability helicopters, is incredibly complex due to the fact that it has: 1) both fly-by-wire and mechanical controls which are implemented through many actuators in each axis; and 2) a requirement to change the coupling and phasing of both full rotary wing controls and full fixed wing controls. The full capability of the RSRA control system has never been fully exploited due to the limitations of the existing flight computer. Further development in also required in the controls area to make the system fully acceptable. However, the combination of the control system and the rotor balance system makes the RSRA an ideal vehicle for exploring rotor/airframe flight dynamics through the use of parameter identification. Considerable work has been done in the parameter identification and math modeling area by DuVal, Wang, Demiroz, and Talbot using the RSRA as a baseline vehicle. These investigations are reported in references 54 through 59. Figure 50 from reference 59 illustrates the comparison of flight data for the RSRA fixed wing configuration with predicted pitch rate response from the math model derived by parameter identification methods. This work was very valuable in the development of models for the RSRA X-Wing configuration.

The RSRA, in 6 years of operation, has proven to have unique capabilities and has provided some unique flight data. The results of these flight operations with the three RSRA configurations, helicopter, compound and fixed wing are reported in two major flight test reports by Erickson, et al (References 60 and 61). In many areas, however, it has fallen short of expectations. It has been plagued by a multitude of development and design problems and is particularly susceptible to mechanical problems. These problems have resulted in a lack of productivity by the aircraft. There has also been a continuing decline in resources and experience to operate and conduct research with the RSRA. These factors combined with the requirement to conduct rotor research on modern 4-bladed rotors, which can not be performed on the RSRA without major modifications, have resulted in a recent decision to indefinitely suspend operations with the aircraft.

The requirement to conduct experiments that will provide extensive data on rotor and airframe dynamics, aerodynamics, and aeroacoustics on a modern rotor system was initially directed at the use of the RSRA. The prohibitive expenditure of resources required to adapt a new rotor to the RSRA and the existing deficiences of the aircraft resulted in a decision not to pursue that direction. It was determined that the UH-60 was the best alternative to the RSRA for the conduct of a broad range of rotor experiments. The next section discusses the status and plans for rotor testing with the UH-60.

UH-60

The UH-60, shown in figure 51, is a modern Army helicopter with a rotor design considerably more modern than those that have previously been utilized for extensive aerodynamic testing. The planned NASA/Army program with the UH-60 will utilize a flight test aircraft located at the Army Engineering Flight Activity at Edwards AFB. The flight research will be conducted over a multi-year period as a combined effort of NASA and the Army. As described in reference 62, the program will involve several phases including both flight and wind tunnel testing of the extensively instrumented rotor system. Research directed at rotor/airframe dynamics, at rotor vibratory airloads, and at rotor airloads and acoustics will be conducted as illustrated in figure 52. Figures 53 and 54 illustrate the two highly instrumented blades under development for the program. The instrumentation includes strain gages, accelerometers, and pressure transducers on the blades. The fuselage instrumentation includes standard aircraft state instrumentation plus extensive airframe and rotor hub vibration measurements. In a certain sense, the UH-60 program will provide a modern extension of the work done of the H-34 in the early sixties; however, the objectives go far beyond those envisioned for the H-34.

A major concern in the planning for the UH-60 problem is the massive amount of data that will be required. One estimate indicates that 1/6 of a second will provide more data than is included in all the tables of the data report on the H-34 (ref. 9). No one was prepared to deal with the data acquired with the highly instrumented blades of the "White Cobra"; therefore, considerable effort is being put forth to prepare for the UH-60 testing, which will begin in 1988, to ensure that the computer tools and techniques are available. A prime objective is to have the capability to get data in the hands of all potential users in a minimum amount of time. One effort receiving considerable support is the implementation of TRENDS, reference 63, for use in the UH-60 program. Advanced versions of DATAMAP are also in the works along with supporting computer hardware.

Extreme care must be exercised to ensure that this program provides the data required for the validation of a number of advanced computer codes and comprehensive analysis programs, and for the development of several new rotor systems for military applications (LHX, ACA, and the advanced Black Hawk rotor).

Other

There are many additional important flight research programs that have not been discussed in this paper since they were outside the scope of the primary subject. Notably among these programs are the many important contributions made in the flight dynamics and guidance and control areas both at Langley and Ames. Equally important is the rotor flight research with the XV-15 tilt rotor which is discussed in a separate paper by Schroers. Finally an important new program that will complement the UH-60 research involves a high speed rotor flight research program with the Army and Boeing on the 360 aircraft.

Summary

Over fifty years of contributions by NASA and the Army through rotor systems flight research have been examined with an emphasis on the last twenty five years. During this time, the helicopter has gone from an abnormality that did a few useful things to a vehicle that is a necessity to life in this country and a major part of all military forces in the world.

Major data acquisition programs like the H-34 and "White Cobra" have been undertaken that have increased our understanding of the aerodynamic behavior of the rotor system. Specialized programs like the Ogee tip on the UH-1 and the flight tests of the hingeless rotor helicopters, the XH-13 and XH-51N, contributed greatly to our understanding of these technologies. The extensive airfoil test program also undertaken on the "White Cobra" provided valuable data on advanced airfoil configurations. Finally the RSRA, while limited by reliability and resource problems, provided unique data and served as a tool to advance the state of the art in parameter identification. As will be described in a separate paper, a major contribution of the RSRA may be through a demonstration of the X-Wing concept.

The highly instrumented UH-60 along with companion programs (High Speed 360, XV-15 ATB, and model scale tests of 360, UH-60, and ATB) will provide the opportunity to explore, over the next several years, a full range of rotor operation and to obtain the data nescessary to fully validate the advanced methodologies being developed.

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TABLE I. REPRESENTATIVE ROTOR TYPES

NUMBER OF BLADES	TEETERING/ GIMBALED	FULLY-ARTICULATED	HINGELESS (PITCH BEARINGS)	BEARINGLESS
2	S	-	-	-
3	S	S,T	S	-
4	S	S,T	S	S
5	-	S	-	-
6	-	S	-	-
7	-	S	-	-

S = SINGLE ROTOR

T = TANDEM ROTOR

TABLE II. HELICOPTER PROBLEMS AND RELATED ROTOR PHENOMENA

PHENOMENON / PROBLEM AREA	TRANSONIC FLOW	DYNAMIC STALL	DYNAMIC BLADE LOADS	BLADE VORTEX INTERACTION	MAIN ROTOR/TAIL ROTOR INTERACTION	ROTOR INFLOW	ROTOR WAKE	GUSTS
VIBRATION	X	X	X	X	X		X	X
NOISE	X			X	X	X	X	X
PERFORMANCE	X	X			X	X	X	
AEROELASTIC STABILITY		X	X			X		
GUST RESPONSE								X

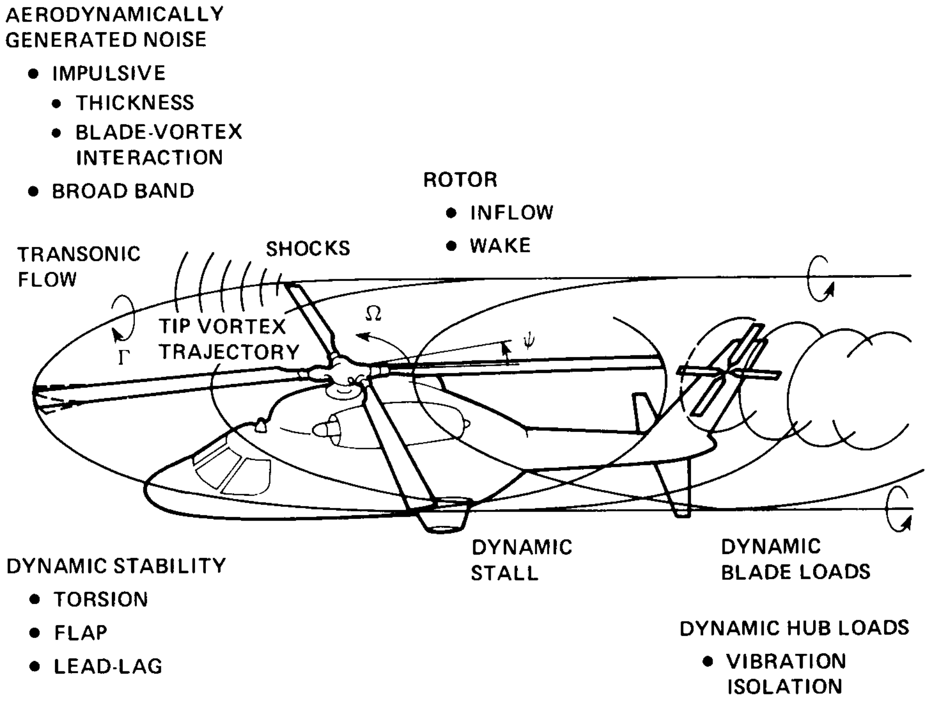


FIGURE 1. Illustration of aerodynamic and dynamic environment of the helicopter rotor.

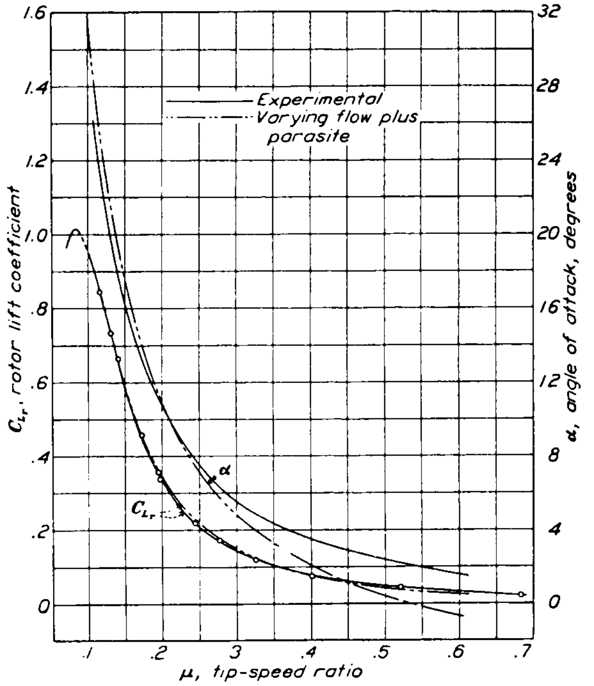


FIGURE 2. Experimental and calculated lift coefficient and angle of attack of PCA-2 autogiro rotor.

FIGURE 3. R-4 test helicopter at Langley Field.

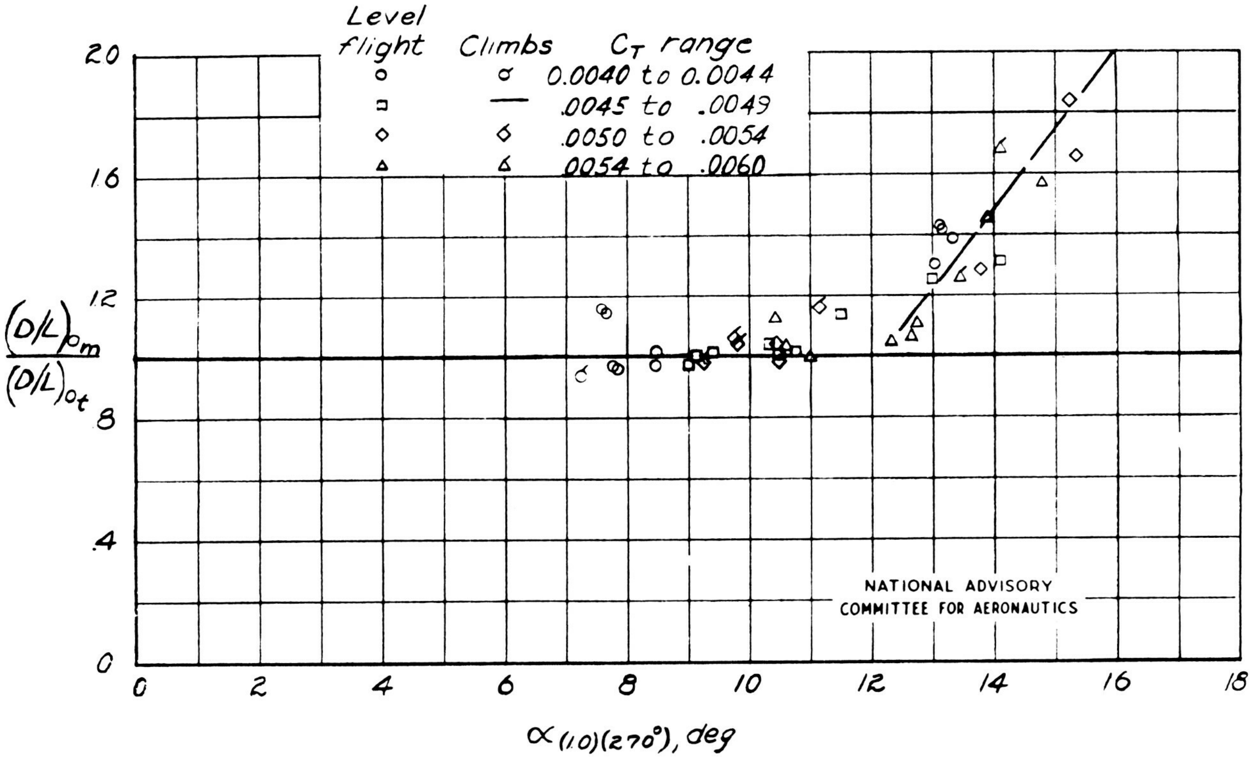


FIGURE 4. Variation of the ratio of measured values of rotor-profile drag-lift ratio to theoretical value with the calculated angle of attack of the retreating blade tip.

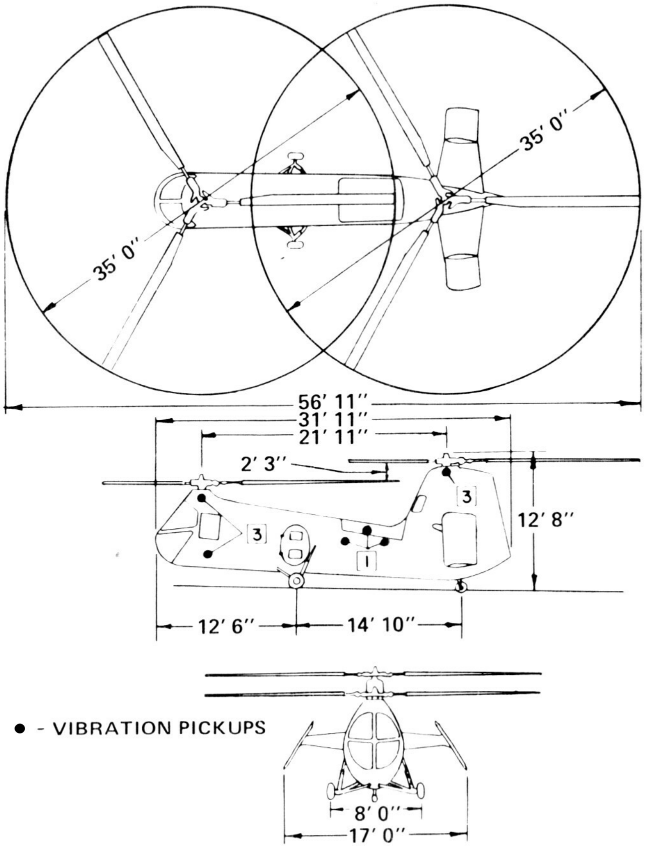


FIGURE 5. Test helicopter showing location of vibration pickups and number of components measured.

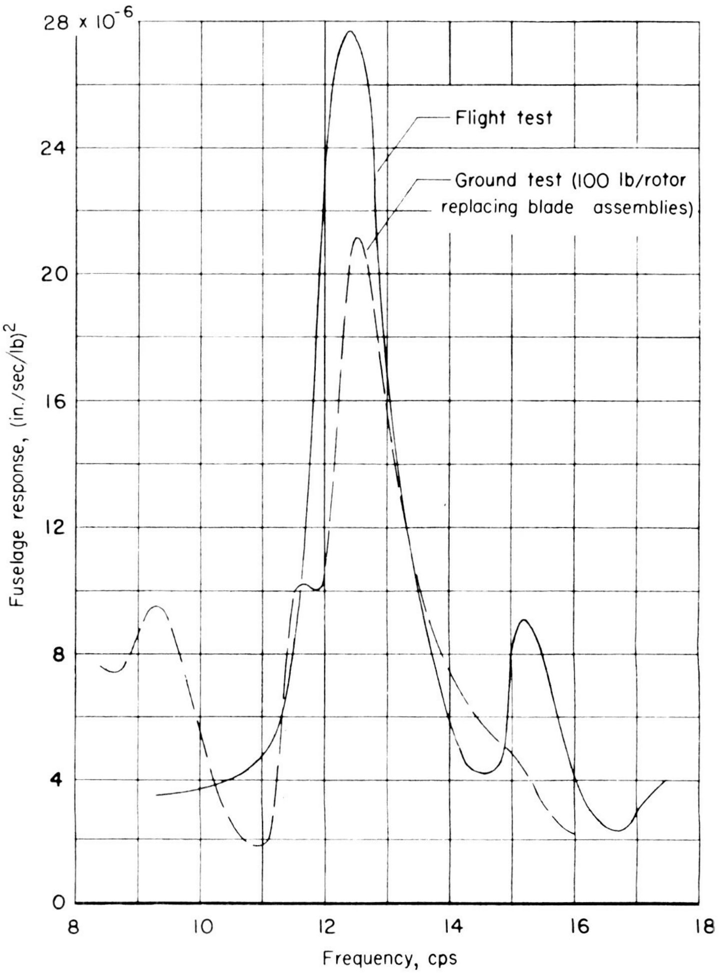


FIGURE 6. Coupled response of helicopter structure measured at the front rotor for wood blade configuration (rotor speed = 273 rpm; forward speed = 55 knots) compared with ground-measured response.

FIGURE` 7. H-19 test helicopter at Langley Field.

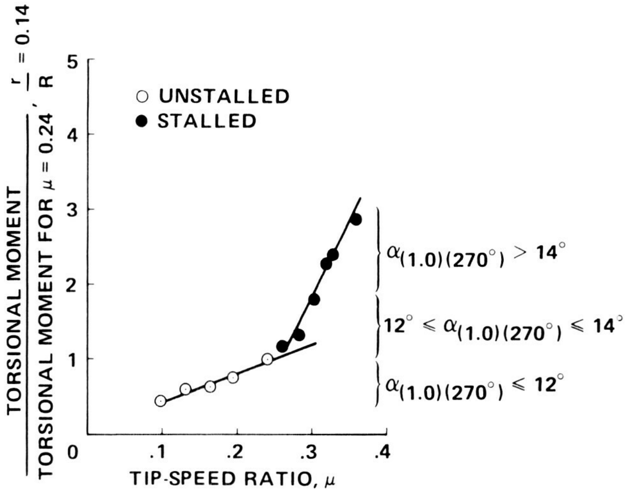


FIGURE 8. Vibratory torsional moments as a function of tip-speed ratio for unstalled and stalled steady forward flight.

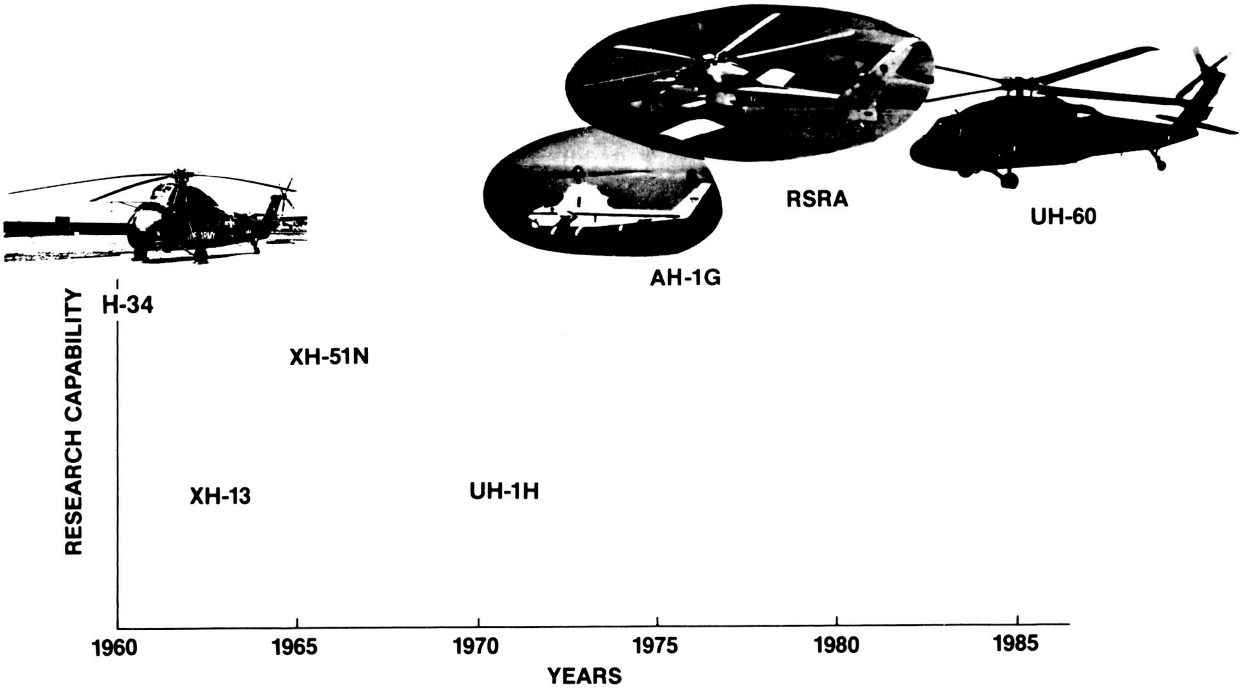


FIGURE 9. Twenty-five years of NASA/Army rotor flight research aircraft.

FIGURE 10. H-34 test helicopter at Langley Research Center.

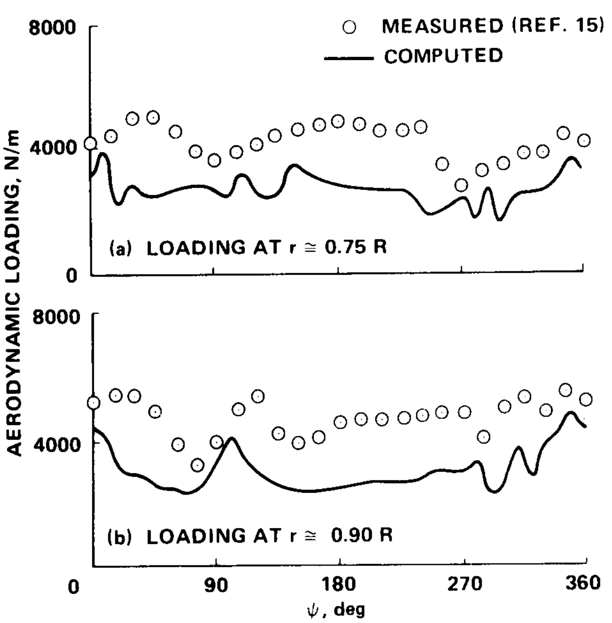


FIGURE 11. Section aerodynamic loading for H-34 in right turn, mu=0.224, f_g =1.5.

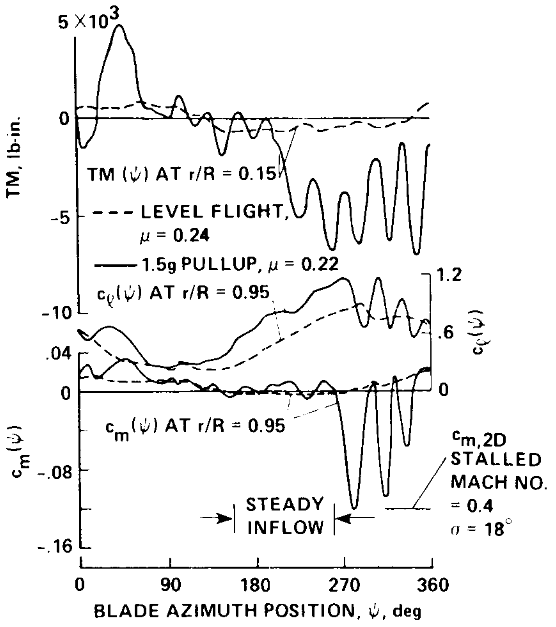


FIGURE 12. Comparison of level flight and 1.5 g pullup time histories of section loading and moment coefficients and blade torsional response.

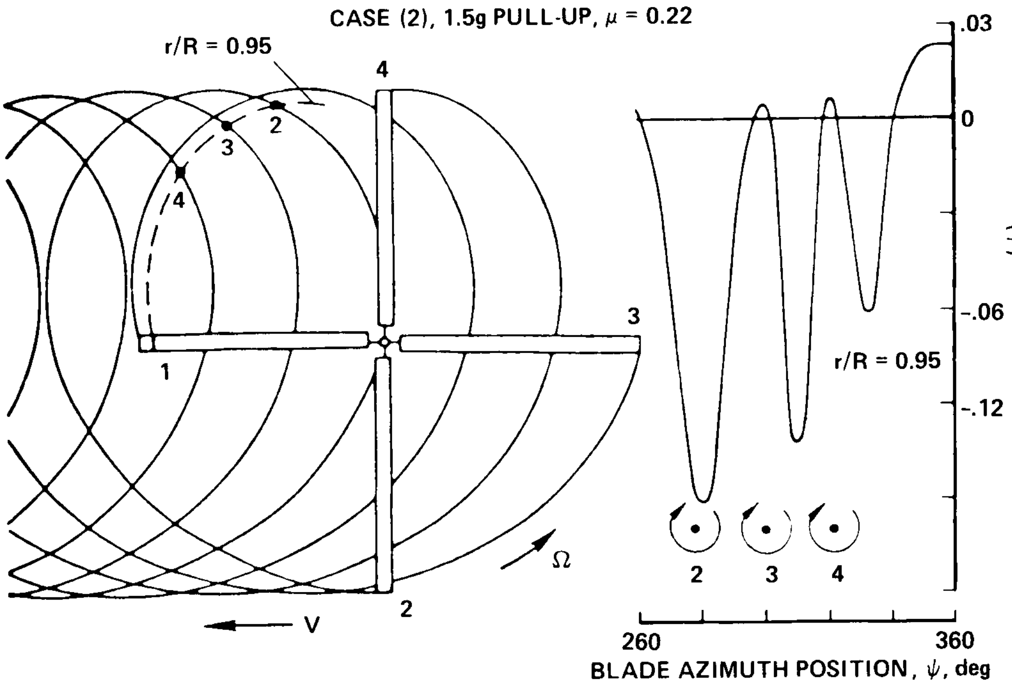


FIGURE 13. Wake helical pattern and correlation of vortex crossings with aerodynamic pitching moment fluctuations for H-34; mu=0.22, 1.5 g maneuver.

FIGURE 14. H-13G hingeless rotor test helicopter at Langley Research Center.

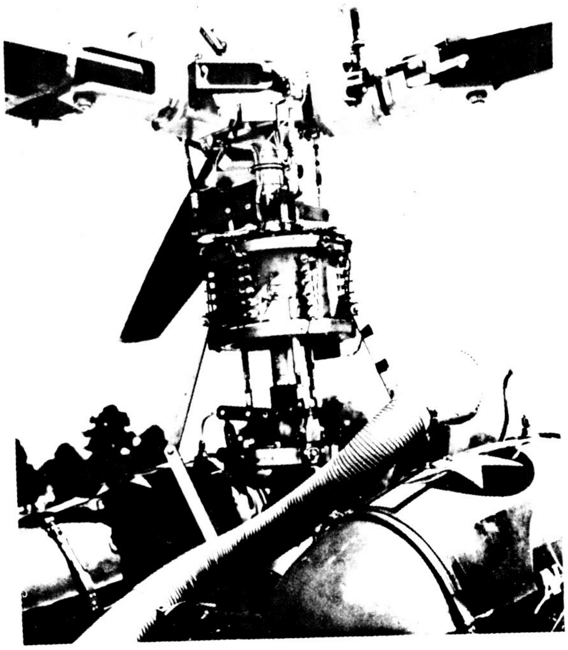


FIGURE 15. H-13G hingeless rotor hub and slipring assembly.

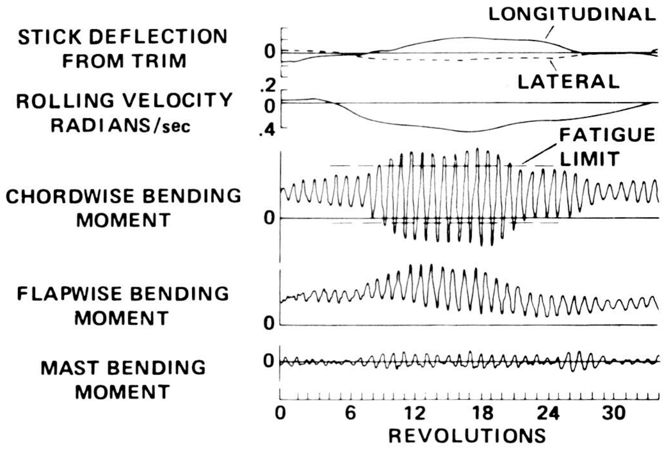


FIGURE 16. Structural loads time history during lateral maneuver with hingeless rotor helicopter in level flight at a forward speed of 80 mph.

FIGURE 17. XH-51N hingeless rotor research helicopter at Langley Research Center.

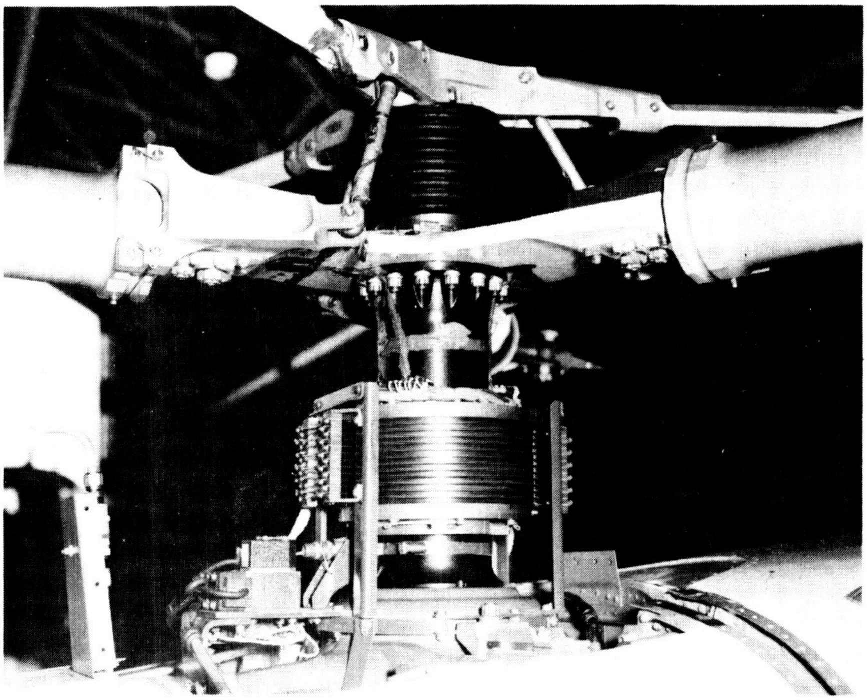


FIGURE 18. XH-51N rotor hub and control gyro.

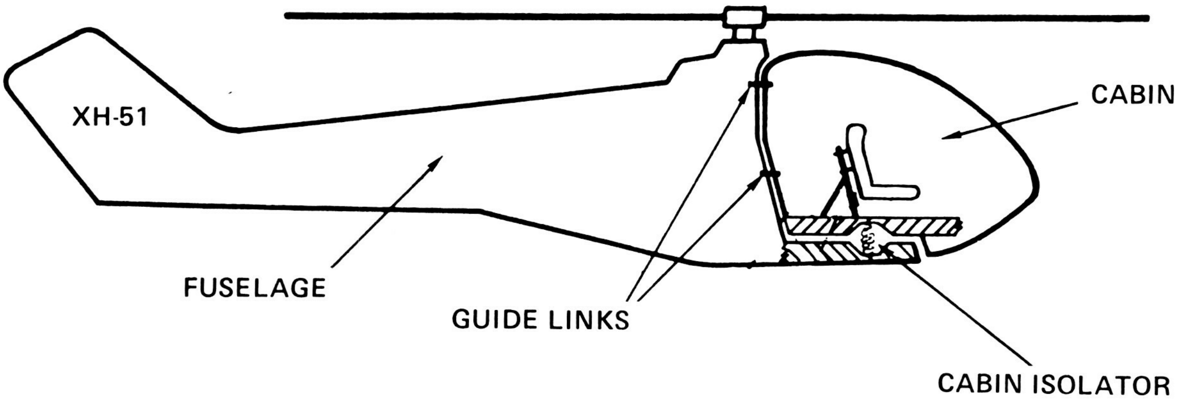


FIGURE 19. Passive cabin isolation system installation on XH-51N helicopter.

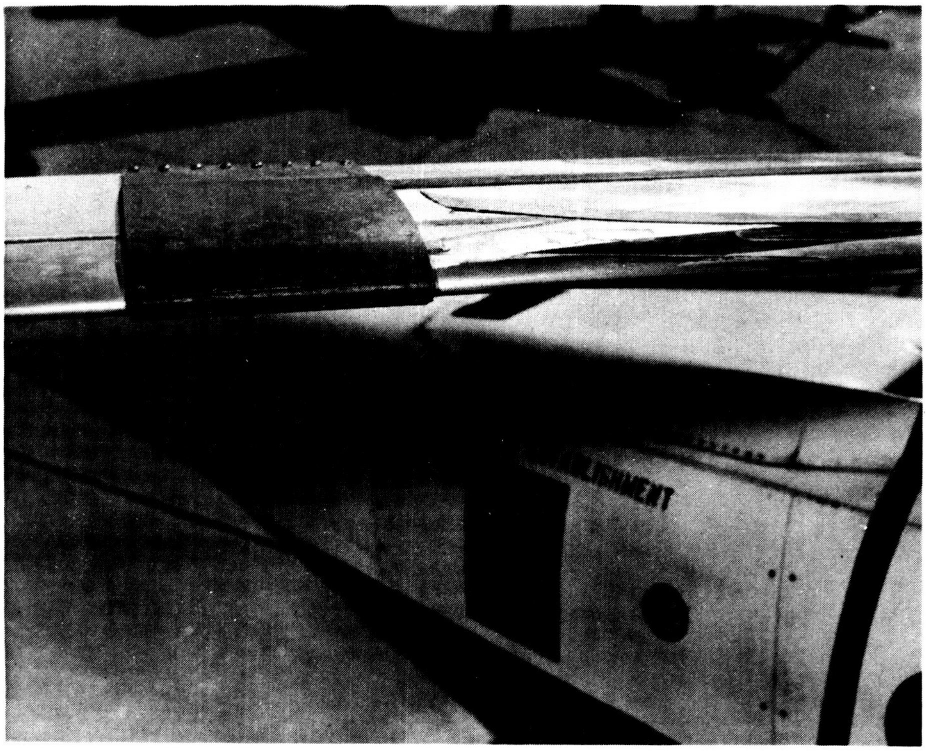


FIGURE 20. Blade tuning mass installed on XH-51N rotor blade.

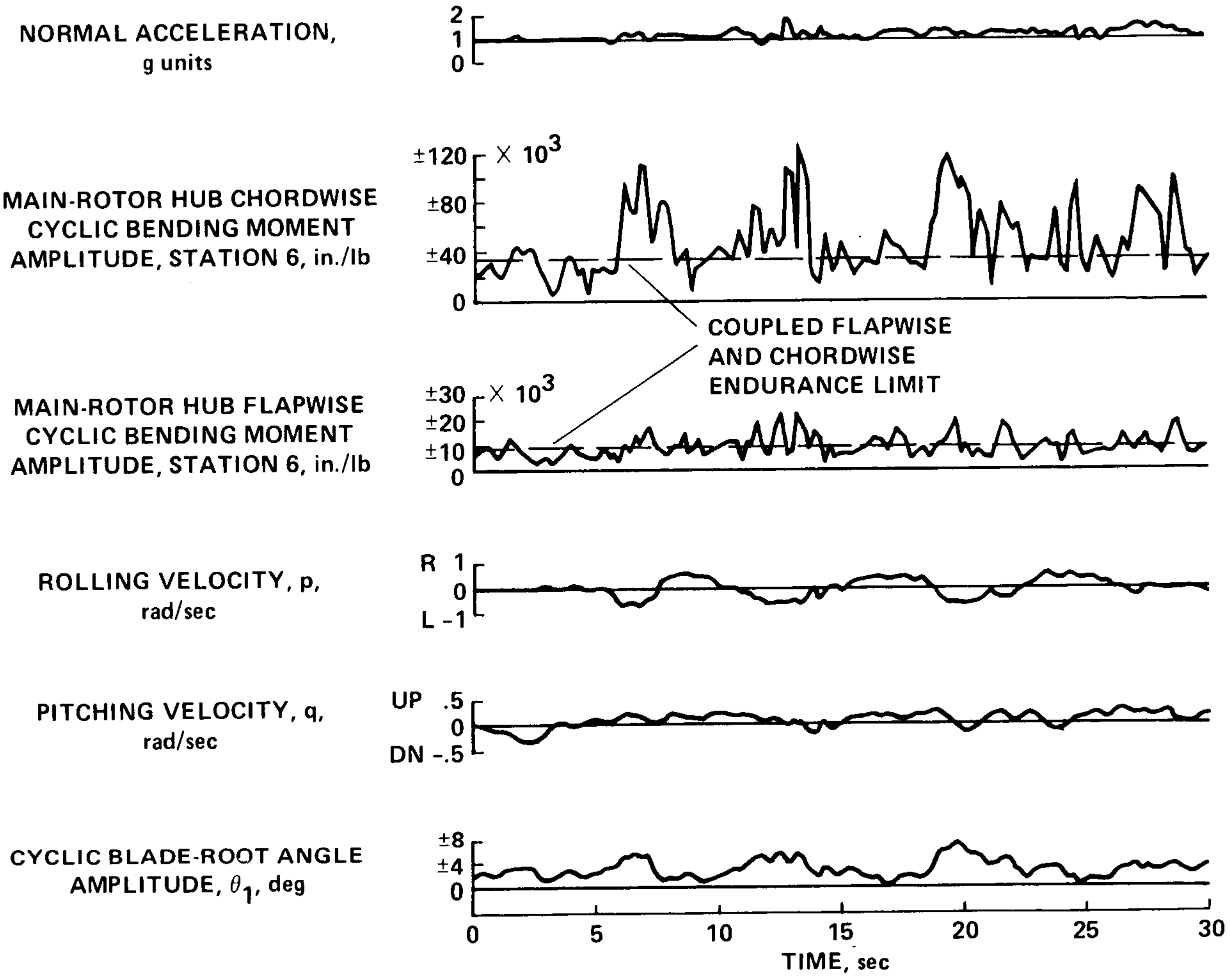


FIGURE 21. Slalom-course maneuver performed at 45 to 50 knots through 200 ft. spaced markers with the XH-51N.

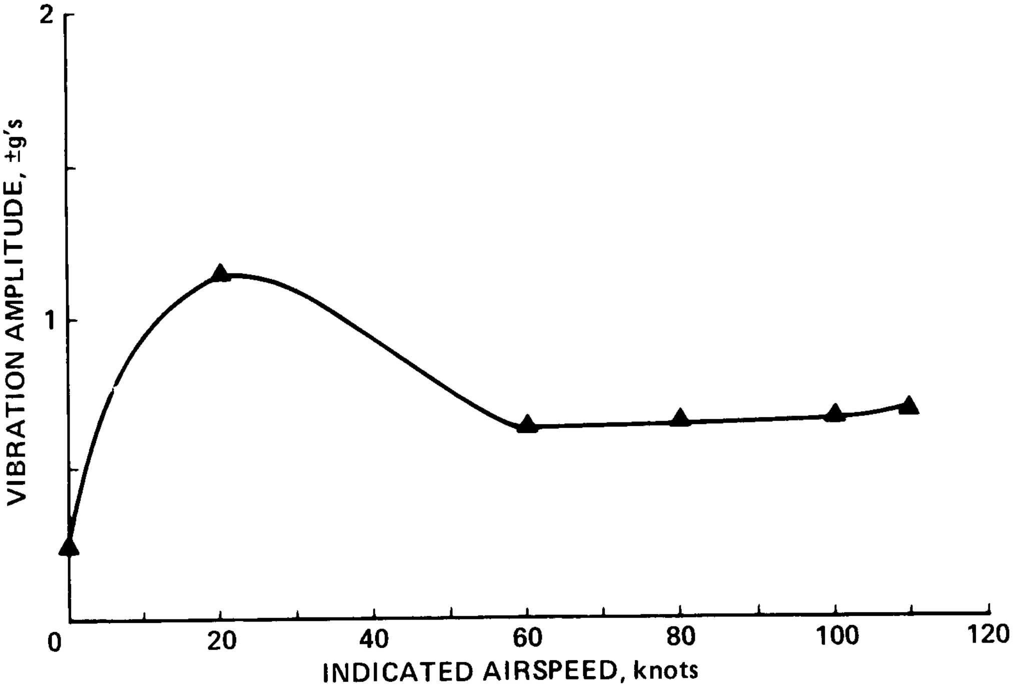


FIGURE 22. XH-51N 18 Hz. vertical vibration at pilot's station in flight with non-isolated cabin.

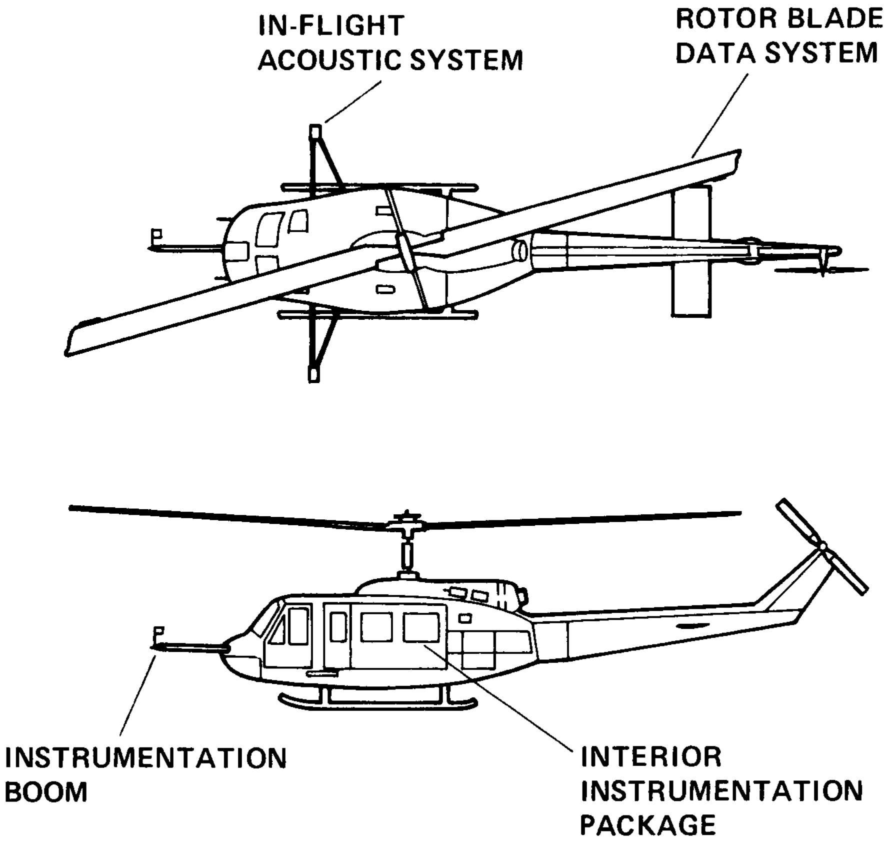


FIGURE 23. UH-1H test helicopter for "ogee" tip test program.

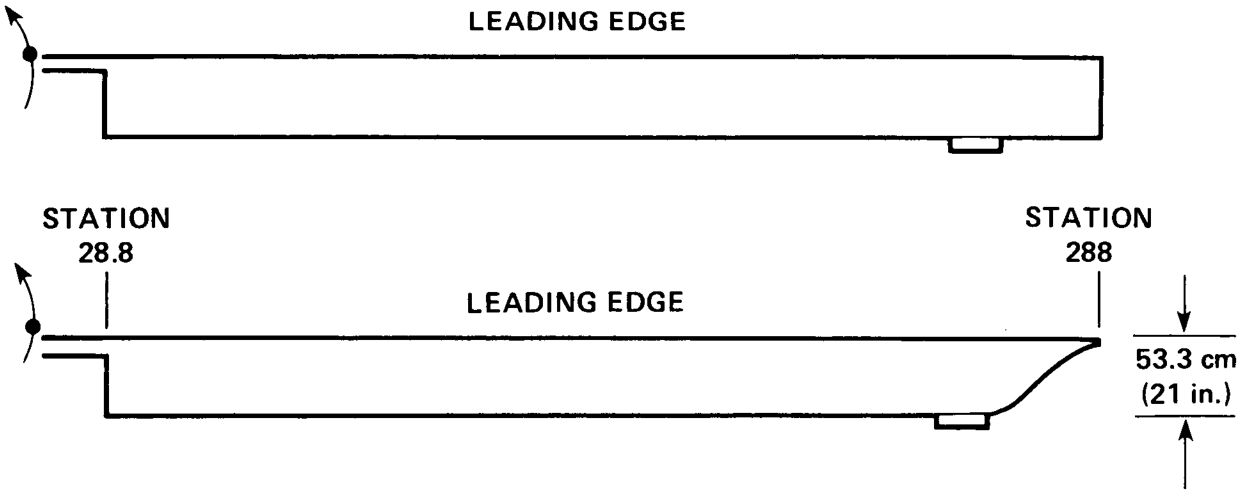
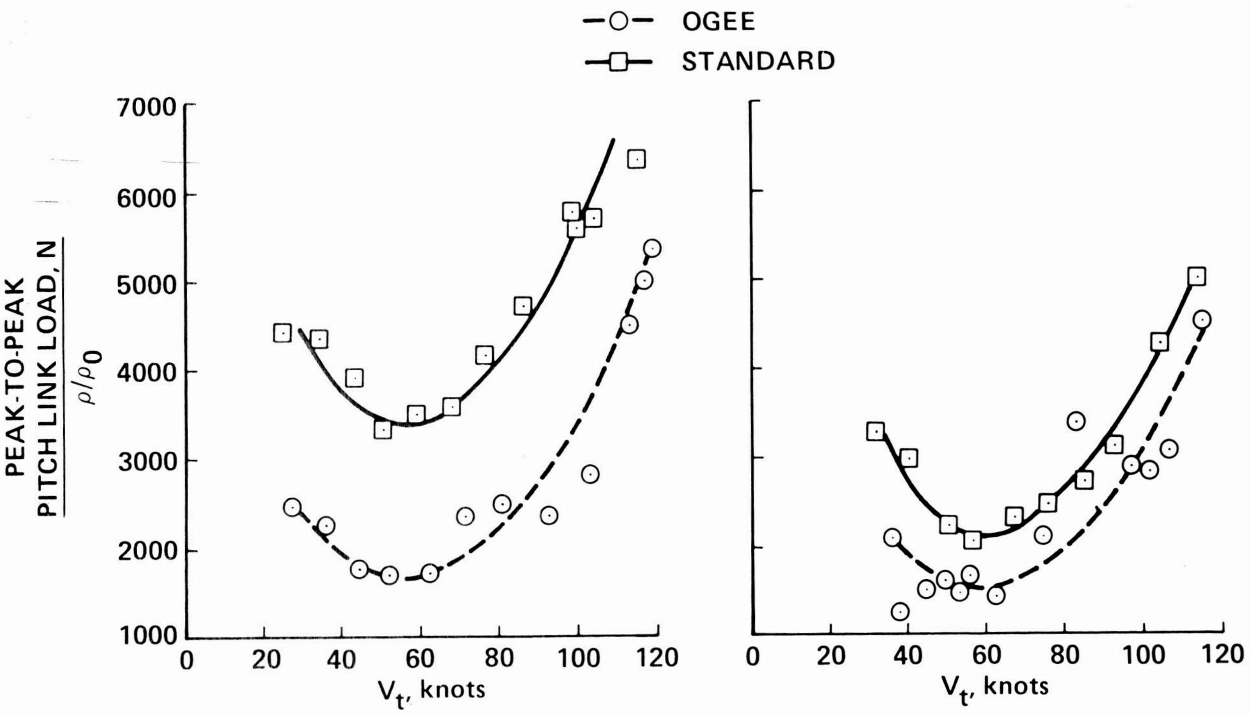


FIGURE 24. "Ogee" and standard test rotor planforms.



(a) $\bar{C}_L = 0.00266$; $\bar{M}_{TIP} = 0.744$

(b) $\bar{C}_L = 0.00323$; $\bar{M}_{TIP} = 0.733$

FIGURE 25. UH-1H oscillatory pitch link loads in level flight for standard and "ogee" tip rotors.

FIGURE 26. AH-1G "White Cobra" test helicopter at Langley and Ames.

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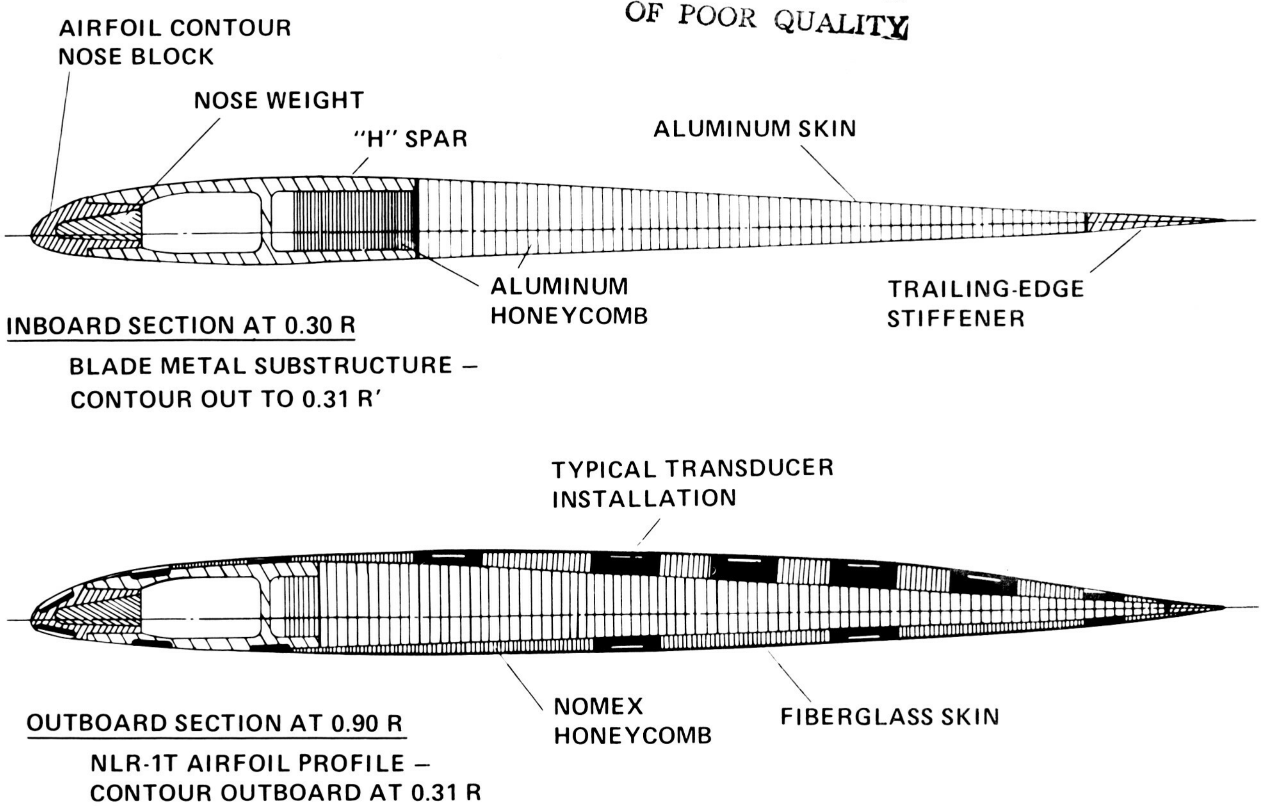


FIGURE 27. Cross section of AH-1G blades modified with NLR-1T airfoil.

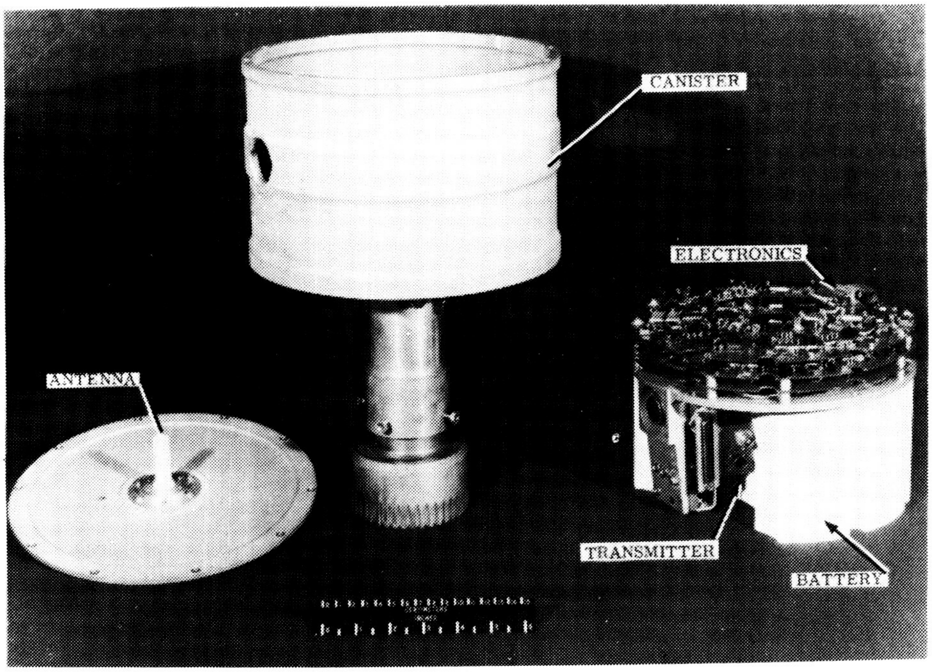


FIGURE 28. Special Rotor Blade Instrumentation system (SRBI) cannister and system for AH-1G airfoil program.

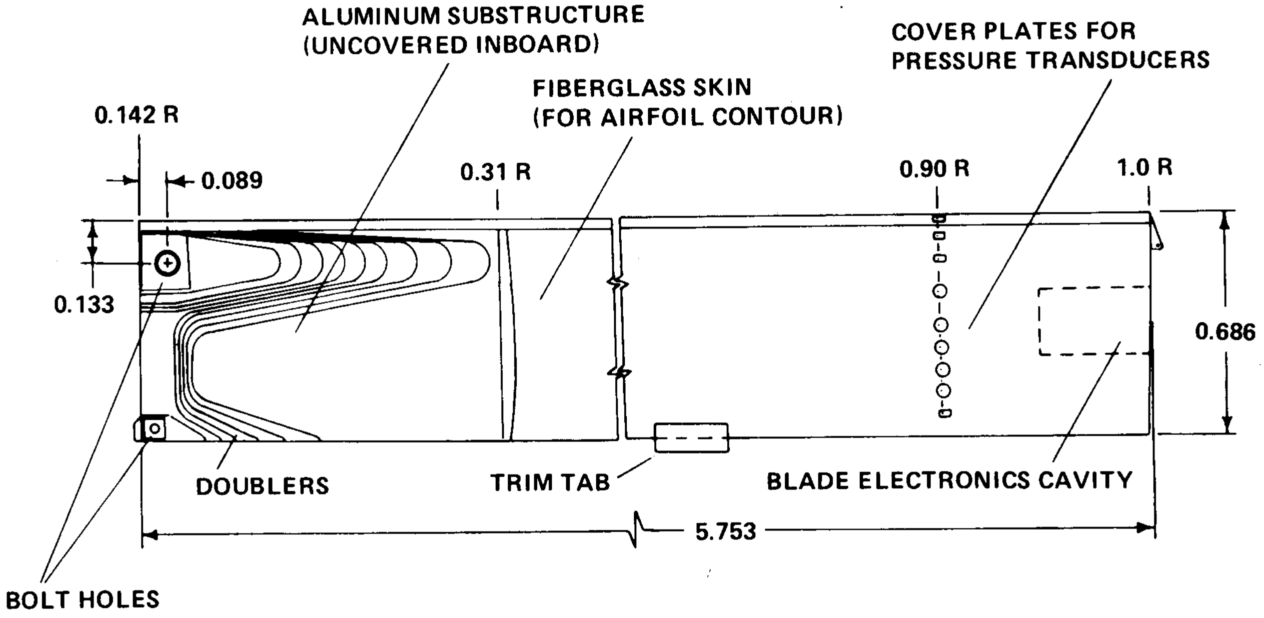


FIGURE 29. Planform of AH-1G main-rotor blade showing pressure transducer locations for airfoil tests. Dimensions in meters.

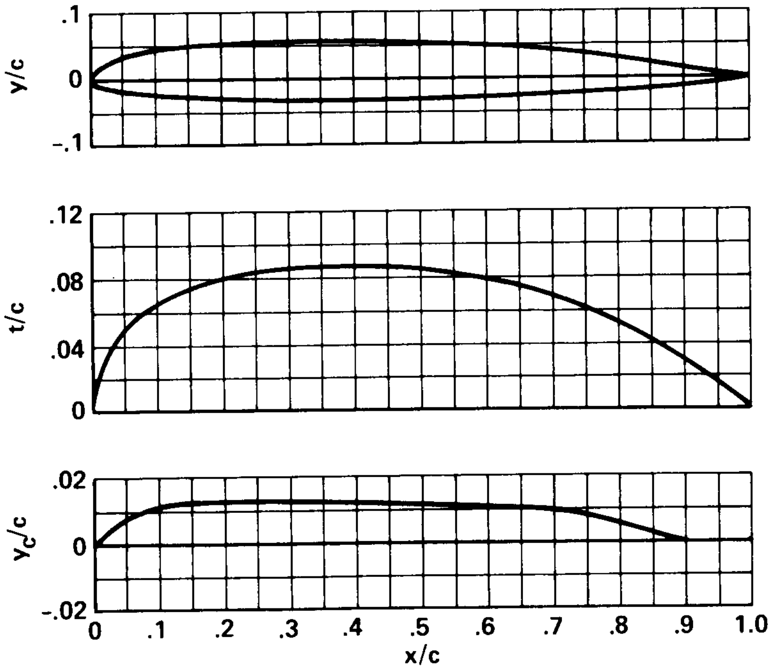


FIGURE 30. Geometric characteristics of NLR-1T airfoil.

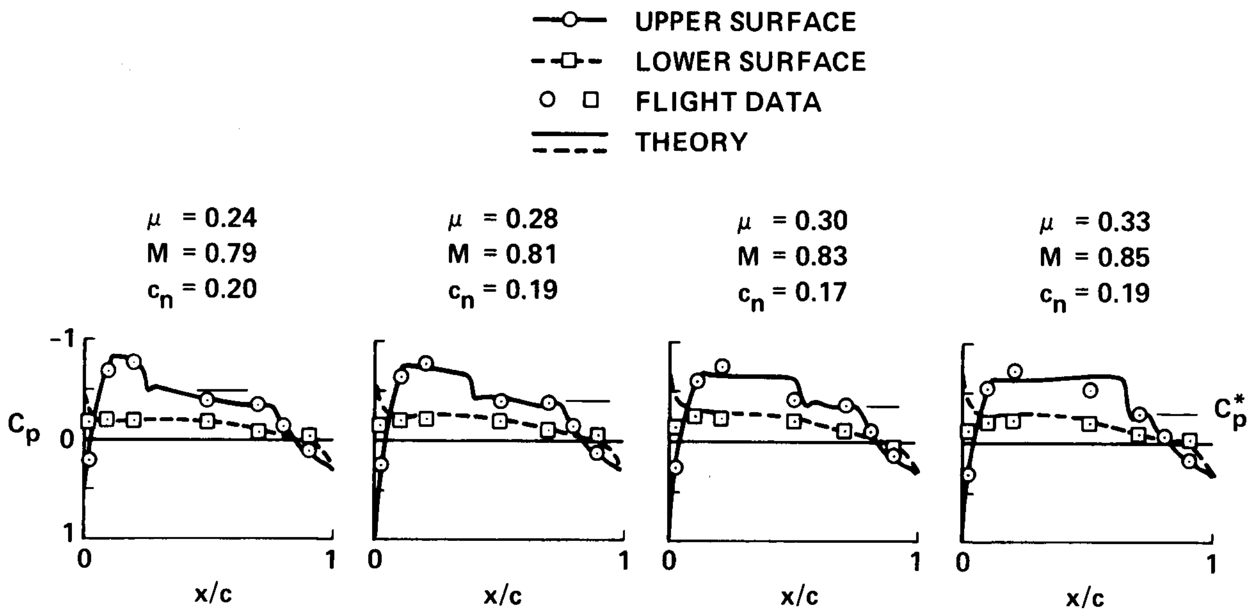


FIGURE 31. Comparison of flight data and theoretical blade-section pressure distribution for an azimuth of 70°; r/R=0.9.

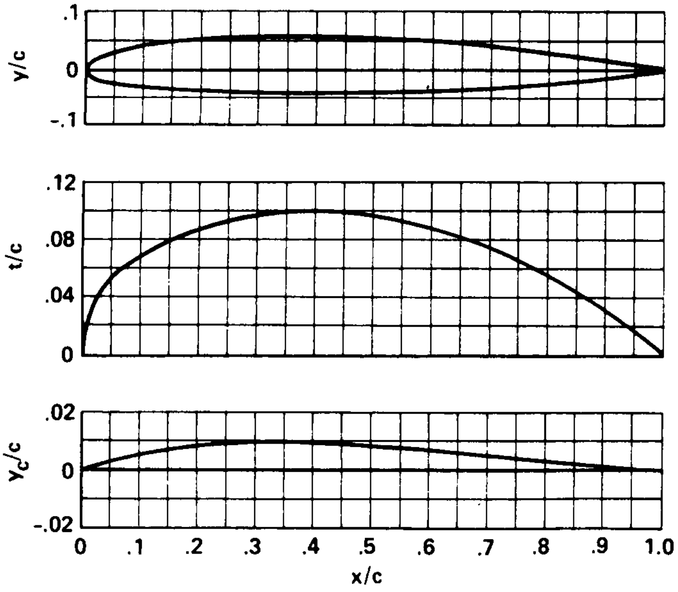


FIGURE 32. Geometric characteristics of 10-64C airfoil.

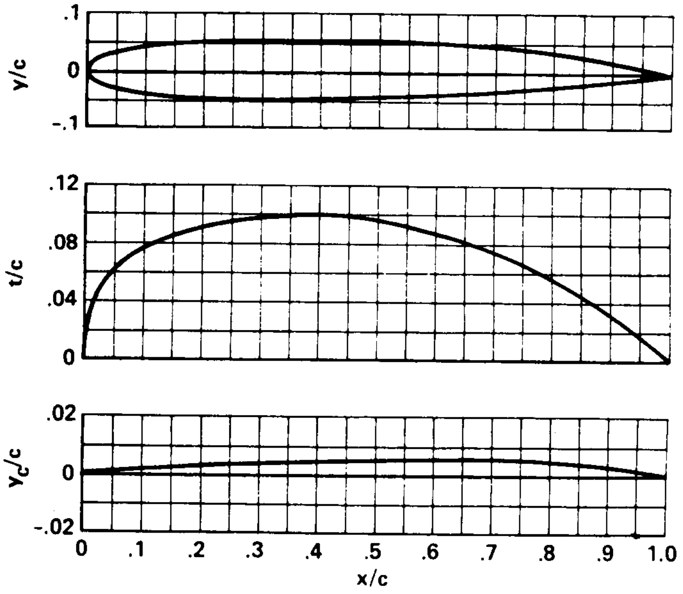


FIGURE 33. Geometric characteristics of RC-SC2 airfoil.

FIGURE 34. Instrumented blade for AH-1G Tip Aero Acoustic Test (TAAT) program.

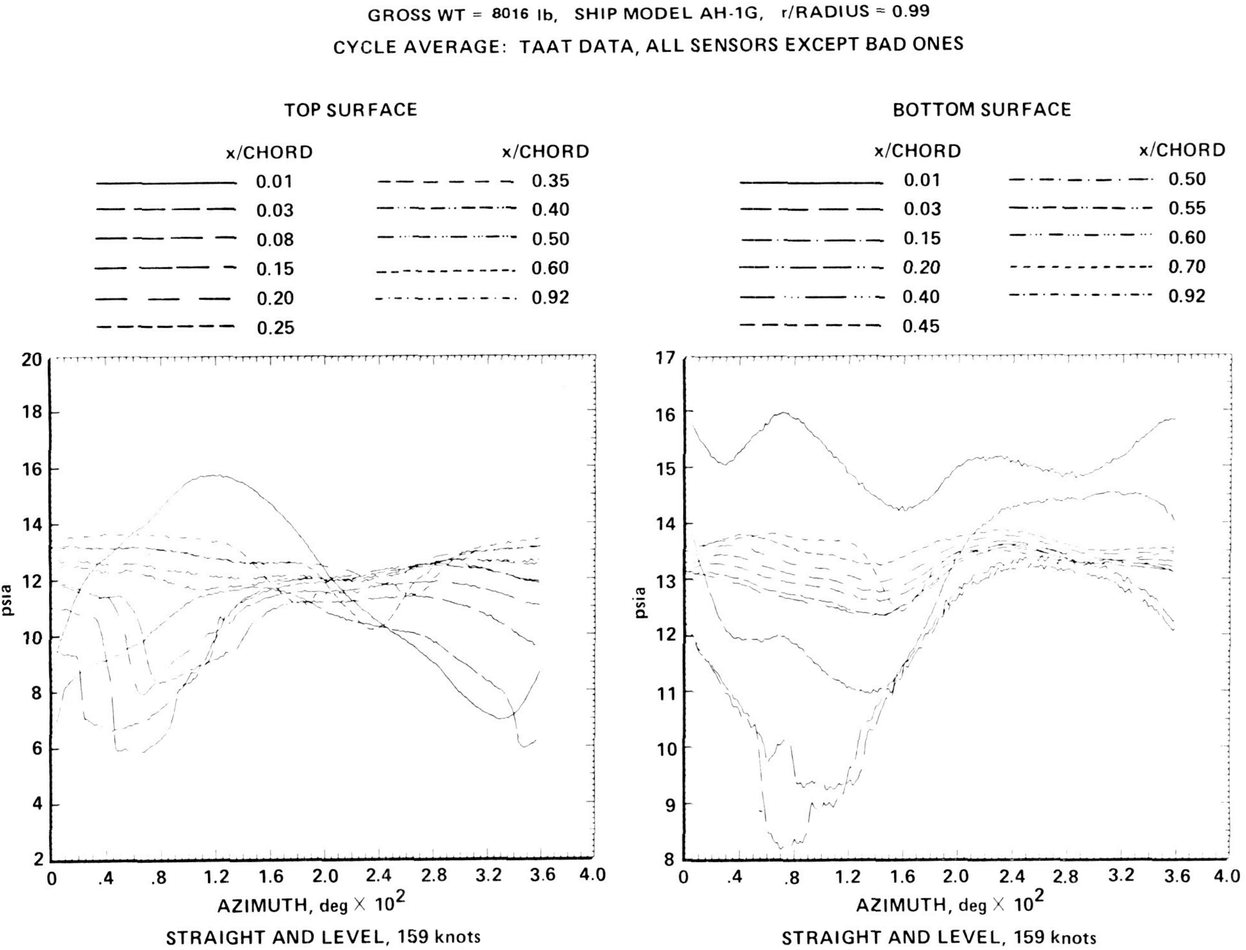
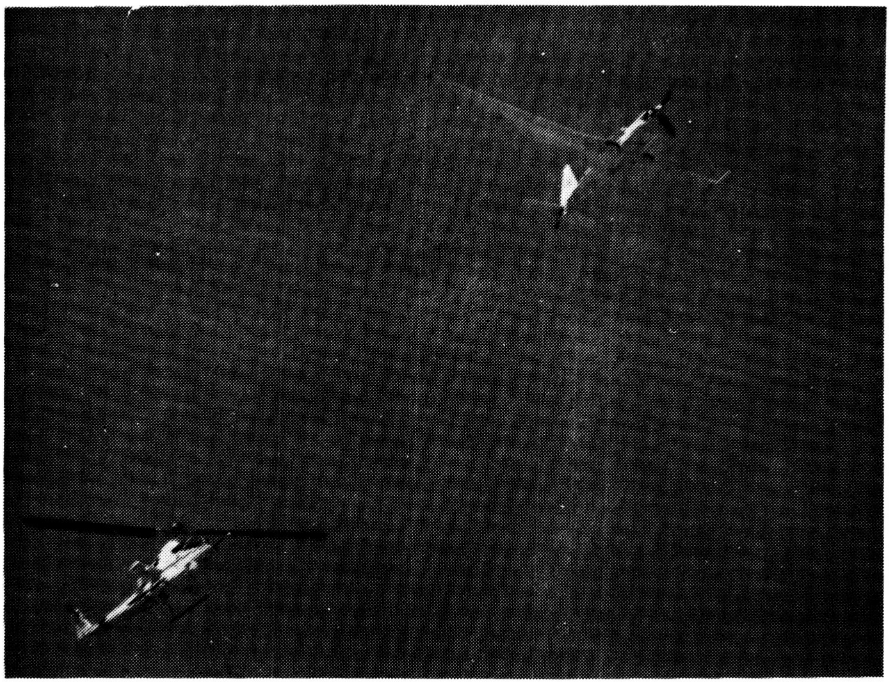


FIGURE 35. Blade pressure measurements (AH-1G) at 99% radius and 159 knots.



\FIGURE 36. YO-3A airborne acoustic platform aircraft in test formation with AH-1G "White Cobra" during TAAT program.

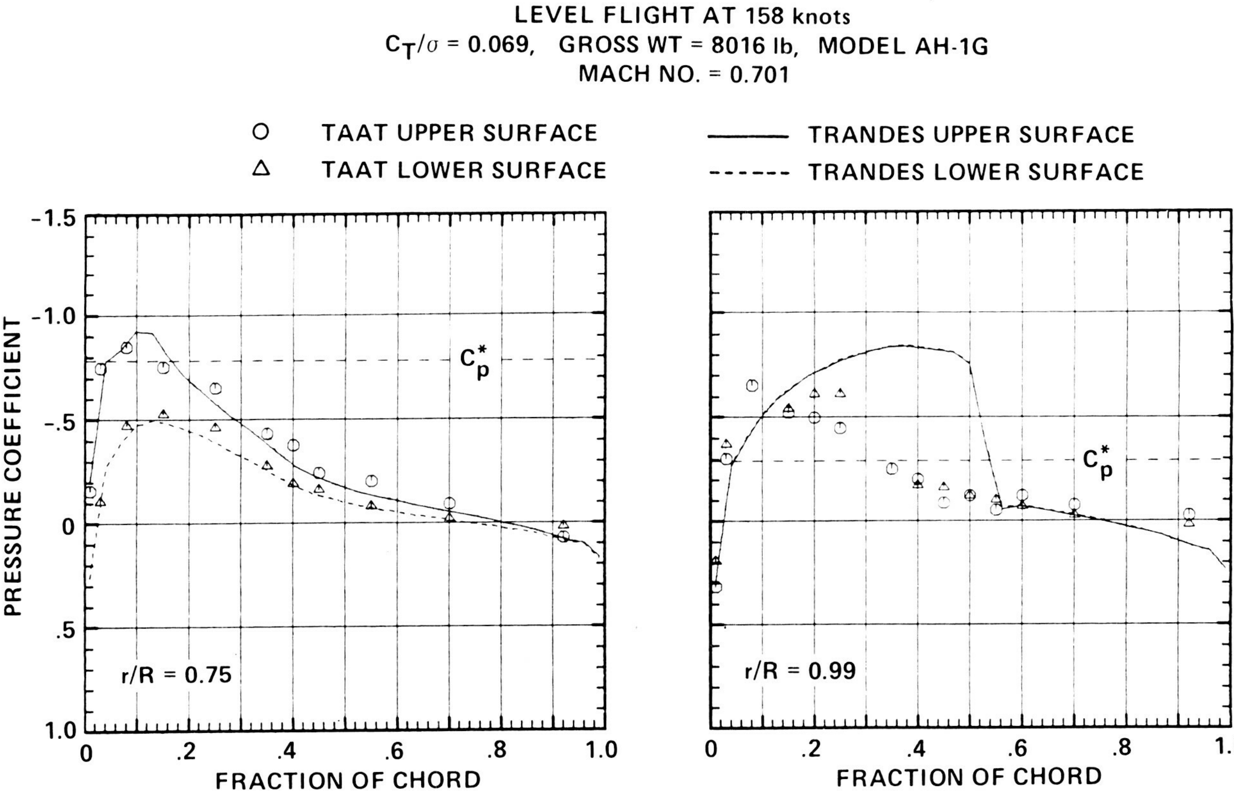


FIGURE 37. Comparison of chordwise pressure distributions for an azimuth angle of 120° and radii of 75% and 99% for AH-1G TAAT program.

FIGURE 38. RSRA helicopter configuration at Ames Moffett.

FIGURE 39. RSRA compound helicopter configuration at Ames-Moffett.

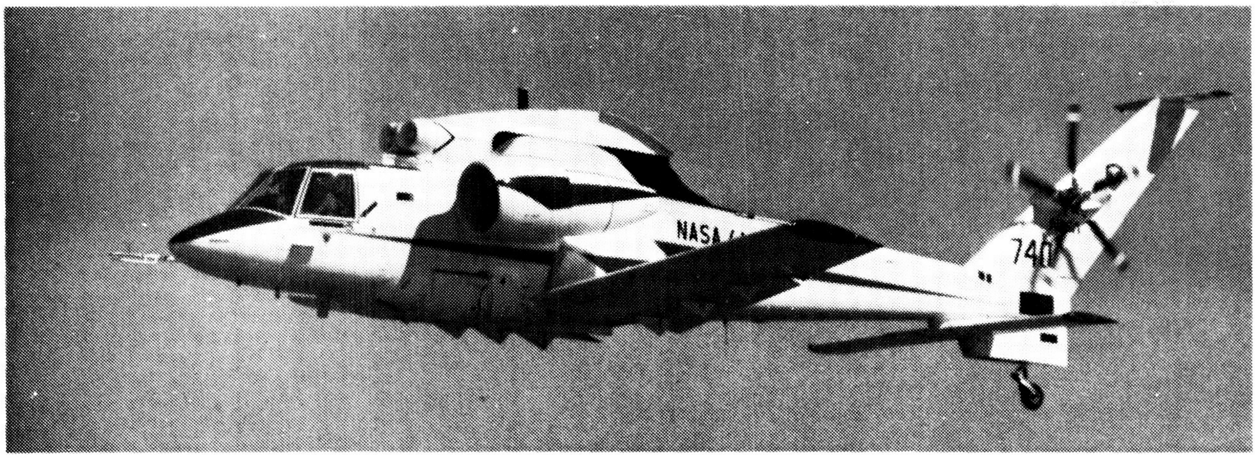


FIGURE 40. RSRA fixed wing configuration at Ames-Dryden.

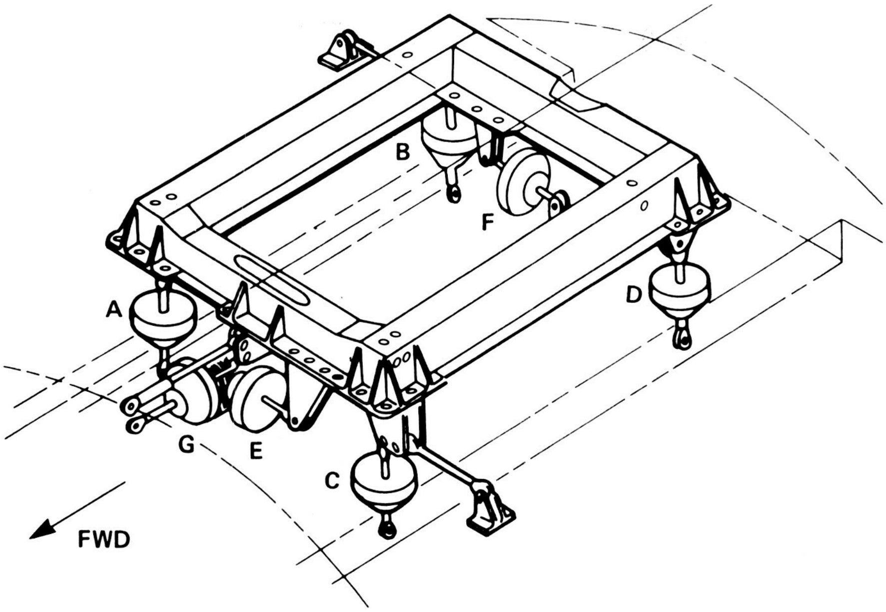


FIGURE 41. RSRA main rotor load measurement system configuration.

FIGURE 42. RSRA load measurement system calibration facility.

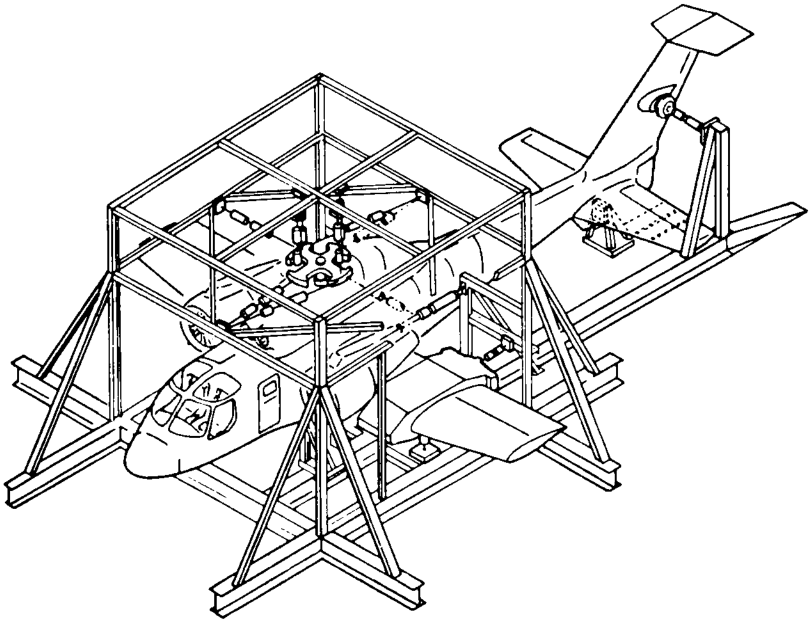


FIGURE 43. Sketch of RSRA load measurement system calibration fixture.

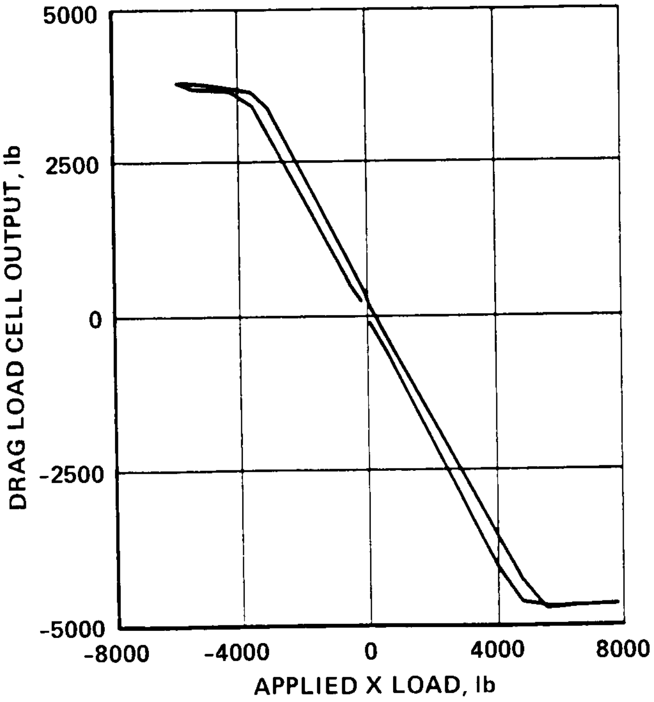


FIGURE 44. RSRA drag load cell output vs. applied longitudinal calibration load illustrating hysteresis.

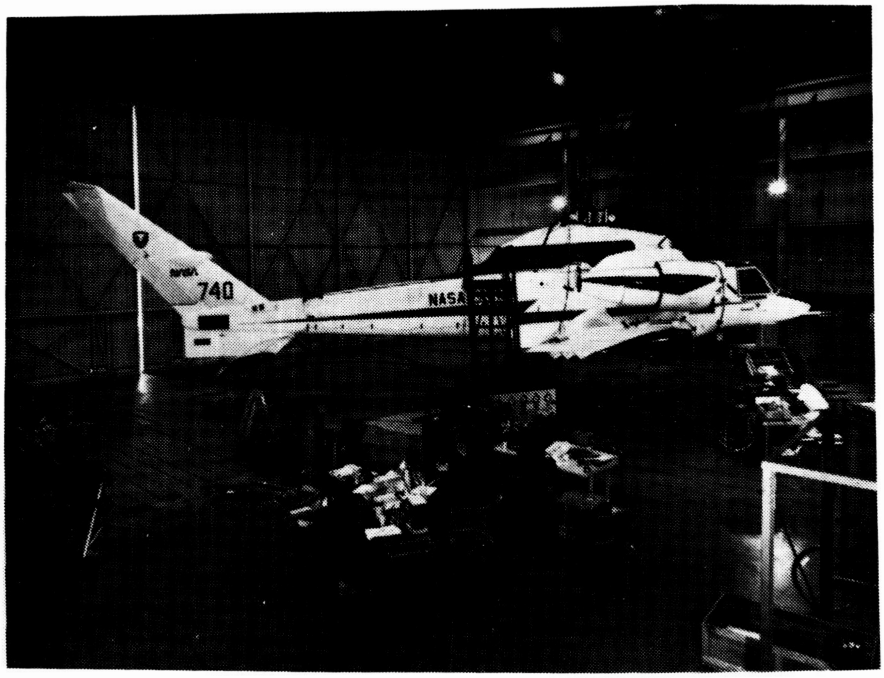


FIGURE 45. RSRA shake test setup.

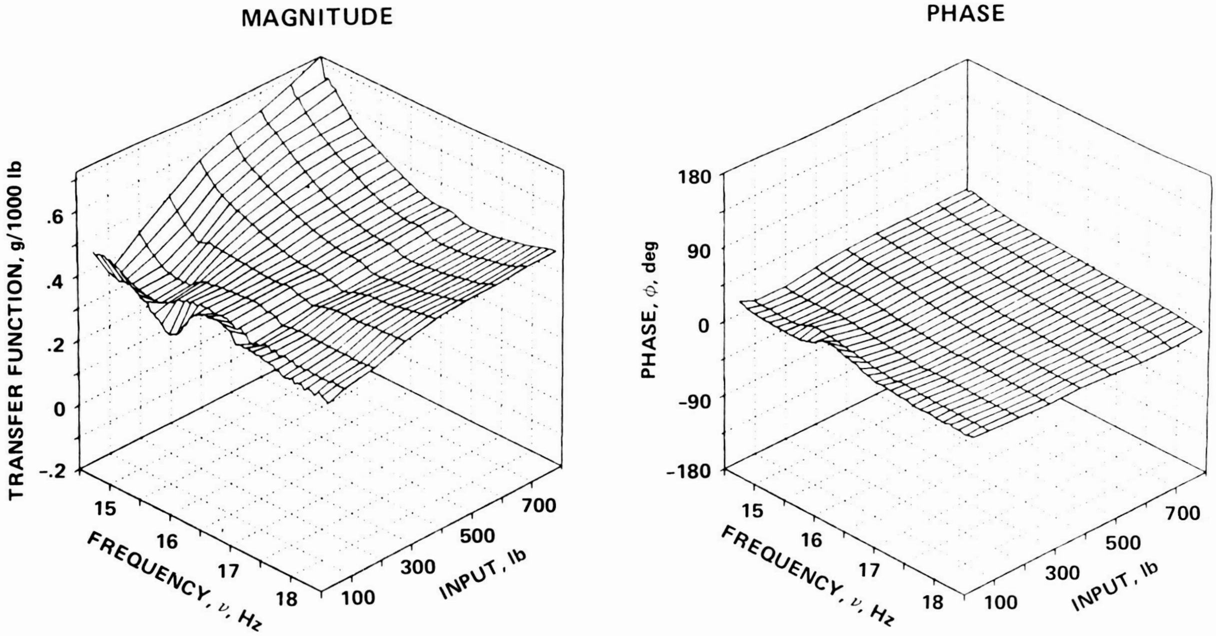


FIGURE 46. Calculated transfer functions for RSRA shake test illustrating non-linearity with force and frequency.

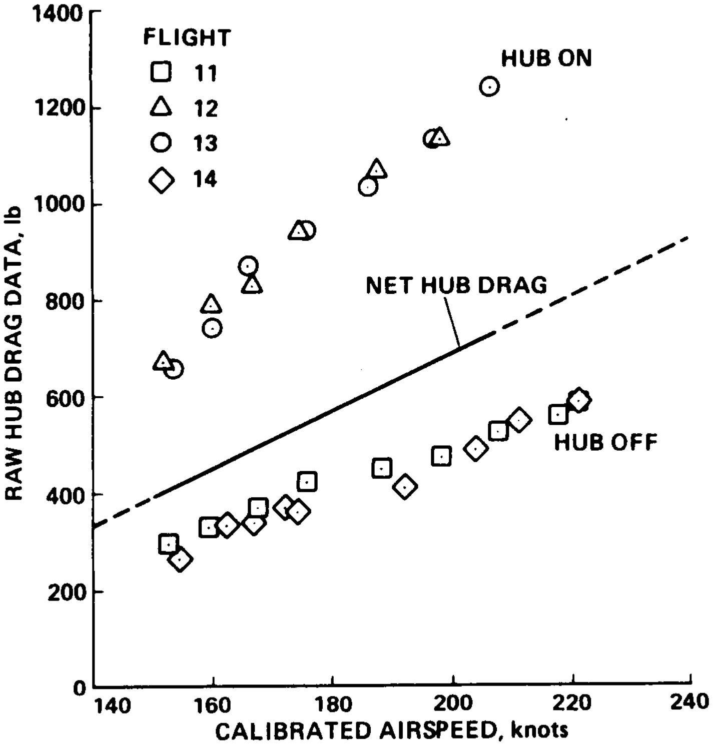


FIGURE 47. Inflight measured hub drag of RSRA versus airspeed.

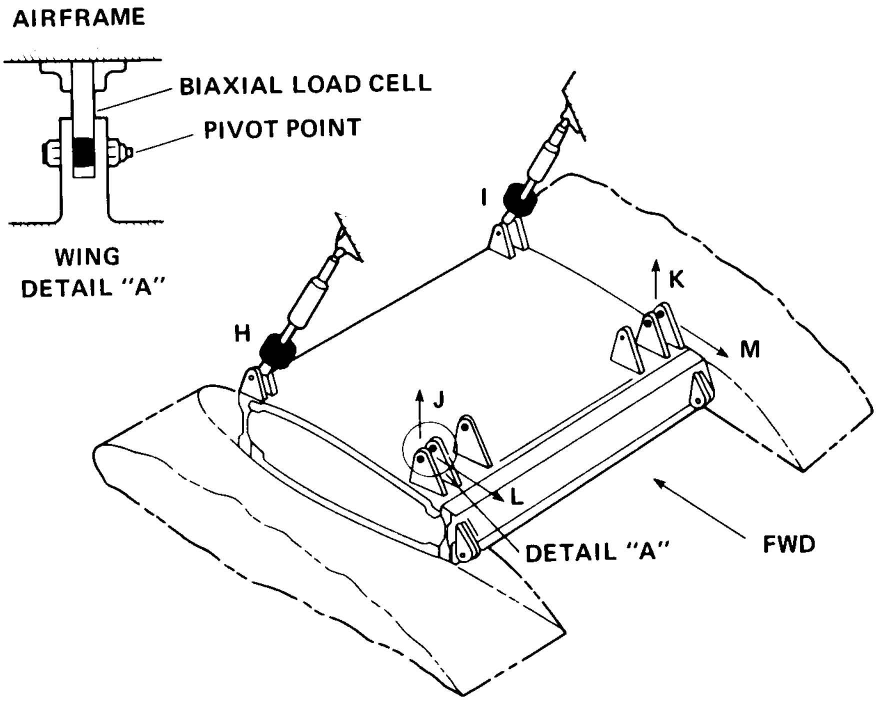


FIGURE 48. RSRA wing flight load measurement system configuration.

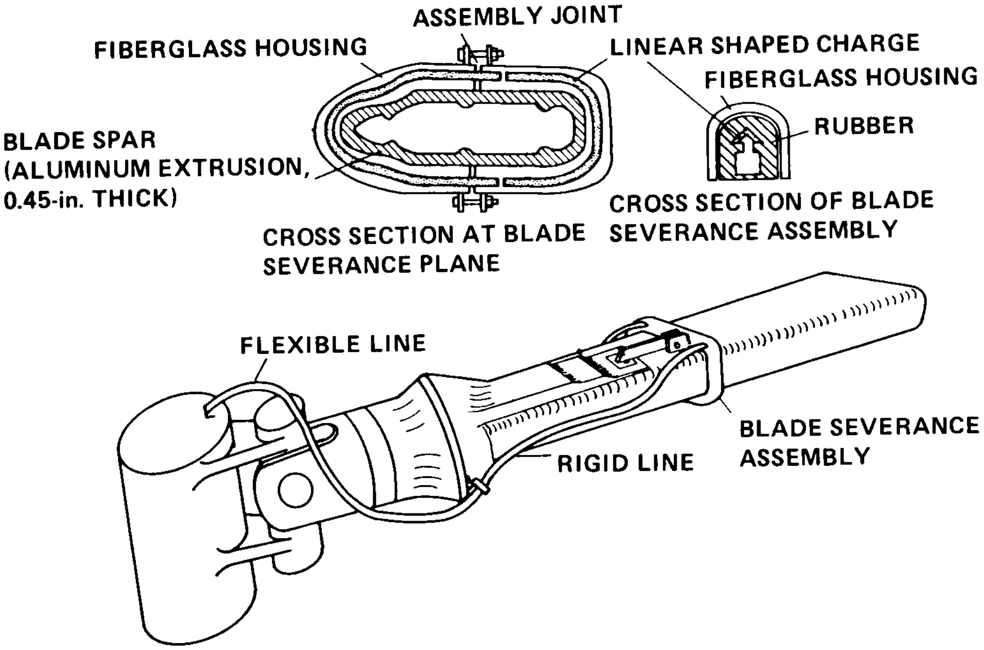


FIGURE 49. RSRA blade severance assembly.

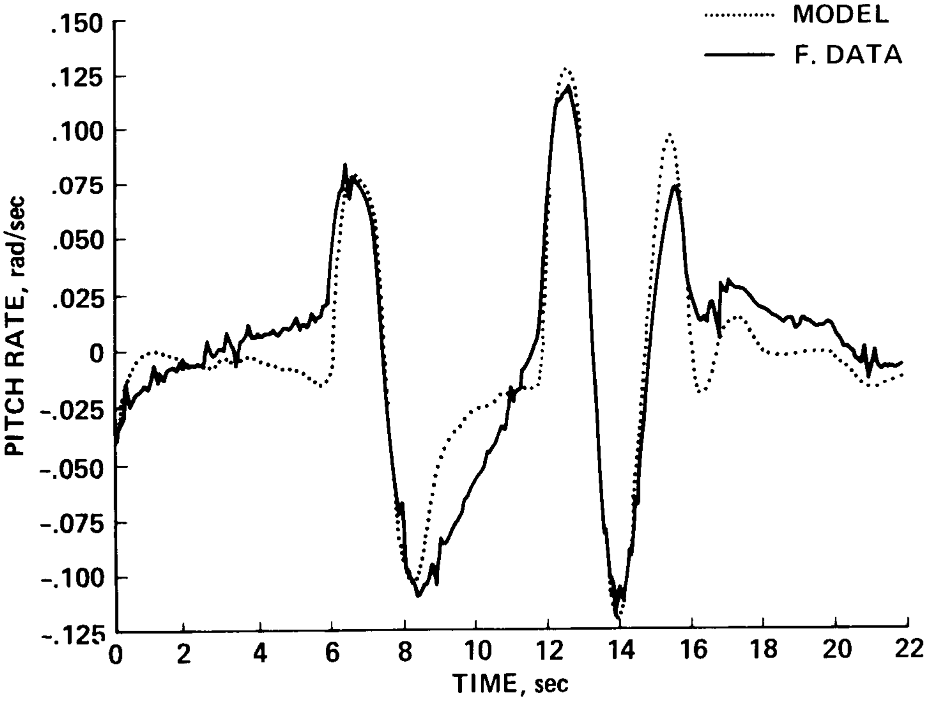


FIGURE 50. RSRA fixed wing flight data versus linear model (obtained from flight data) response for pitch rate.

FIGURE 51. UH-60, modern Army helicopter, at AEFA for NASA/Army comprehensive flight research.

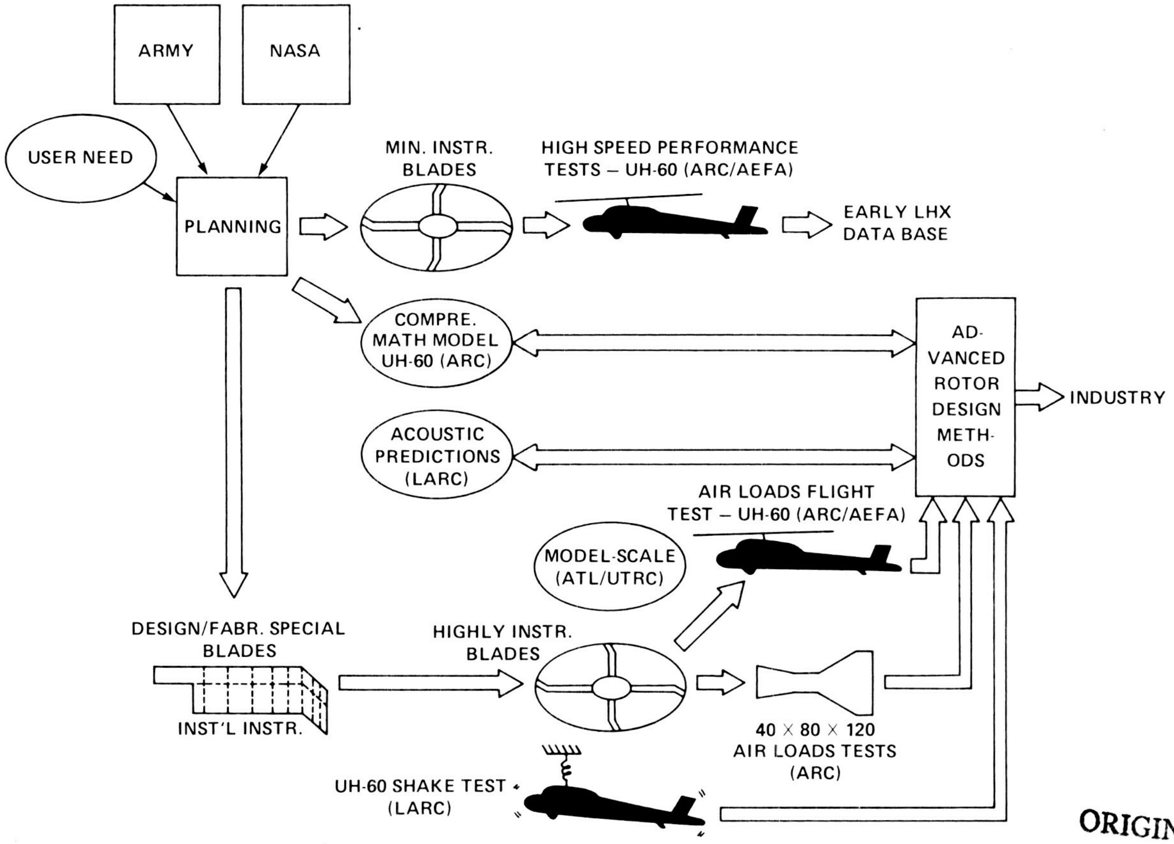
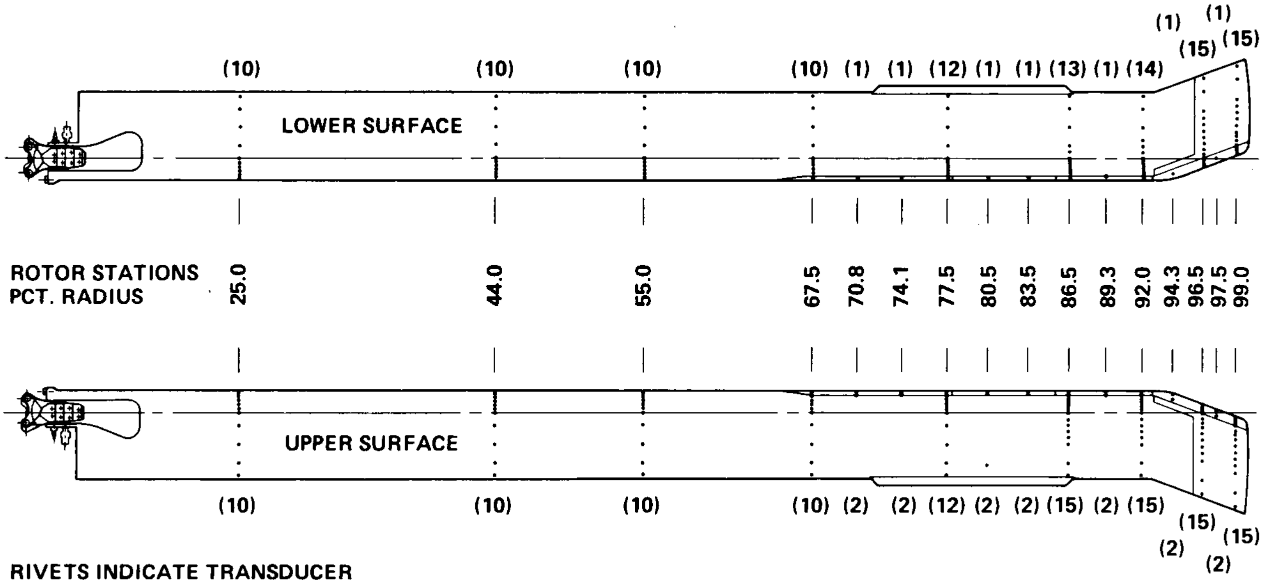
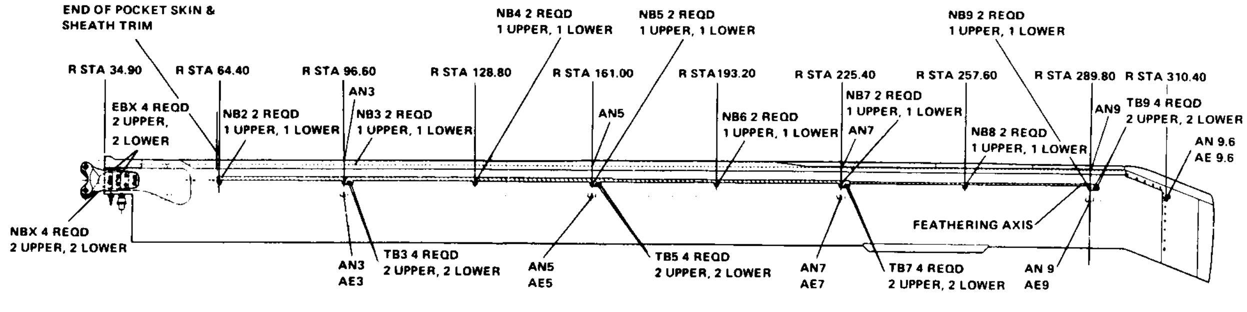


FIGURE 52. NASA/Army UH-60 comprehensive research program.



RIVETS INDICATE TRANSDUCER LOCATIONS. TOTAL OF 126 ON UPPER SURFACE, 116 ON LOWER SURFACE

FIGURE 53. Pressure instrumented blade layout for UH-60 rotor research program.



NOTE: EDGEWISE BENDING GAGES ARE LOCATED AT SIMILAR STATIONS AS NORMAL BENDING GAGES.

FIGURE 54. Strain gage and accelerometer instrumented blade for UH-60 program.