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BLADE LOSS TRANSIENT DYNAMICS ANALYSIS

VOLUME I
TASK 1 - SURVEY AND PERSPECTIVE

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16. Abstract

An analytical technique has been developed to predict the behavior of a rotor system subjected to sudden unbalance. The technique is implemented in the Turbine Engine Transient Rotor Analysis (TETRA) computer program using the component element method. The analysis was particularly aimed toward blade-loss phenomena in gas turbine engines. A dual-rotor, casing, and pylon structure can be modeled by the computer program. Blade tip rubs, Coriolis forces, and mechanical clearances are included. The analytical system was verified by modeling and simulating actual test conditions for a rig test as well as a full-engine, blade-release demonstration.

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1.0 SUMMARY

This document presents the results of Task I of the Blade Loss Transient Dynamic Analysis Program. This task is a survey and perspective of field experience on blade loss in turbine engines and also an evaluation of analytical approaches for the analysis of turbine engine transient dynamic response from unbalance.

The critical problem areas selected from this task, to be analyzed by the method developed in Task II, are:

- Deflection Dominated: Rubs

- High Loads

The component element method, based on modal synthesis, is the analytical approach proposed for and developed in Task II. Task III is the experimental verification of the analytical approach developed in Task II.

2.0 INTRODUCTION

The ultimate goal of this contract is the development of a blade loss transient dynamic analysis for an aircraft turbine gas engine. To achieve this goal, the contract is divided into three main tasks: Task I - Survey and Perspective; Task II - Analysis; and Task III - Experimental Verification. This volume is concerned with the work done under Task I, its results, conclusions, and recommendations.

Because of the many possible modes of engine failure resulting from blade loss, Task I has the main objective to review field experience and place the most pertinent problem areas into perspective. By enumerating the undesirable consequences and their probabilities, it becomes possible to rank the relative importance of each problem area and, therefore, emphasize those that demand immediate attention. This ordering is accomplished by assigning a numerical equivalence to relative damage severity and probability (from 1 to 10). The result is a relative qualitative severity rating which permits a finer gradation of damage than the purely qualitative terms of less good, bad, worse, or worst.

A second objective of Task I is to select the problem area or areas which an analysis and computer program will address and recommend the technical approach which will be developed in Task II. The criteria for selection of a technical approach are predicated upon a goal to calculate the transient loadings and deflections of the turbine engine system and its principal components in the most practical, economical, and technically feasible way. It is not within the scope of this contract to provide a method which predicts local stresses and strains as the result of blade loss but, rather, the loads and deflection from which the stresses can be predicted separately using other available stress-analysis methods. The choice of the technical approach was based primarily on simplicity, flexibility, economy, and accuracy.

Task I was completed in December 1979; following a review and approval by NASA of General Electric's technical approach, work commenced on Task II and Task III in January 1980.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 PROBLEM AREAS

Of the events studied, the loss of a fan blade is the more likely to produce the greatest damage, primarily through rubs in the fan, compressor, and turbine. Thus the problem area of rubs has the greatest probability and was chosen for inclusion in the analysis capabilities.

The other problem area selected is that of high loads in bearings and support structures from blade loss unbalance. The recommendation was made by GE that the method selected and developed in Task II have the capability to analyze these selected problem areas, but the approach selected is capable of handling, in addition, most of the other dynamic problem areas resulting from blade loss. NASA concurred with these recommendations.

3.2 TECHNICAL APPROACH FOR TRANSIENT RESPONSE ANALYSIS

The basic objective of the technical approach is to develop a modular computer code that can calculate the macroscopic dynamic response of an engine structure from a time-dependent load: specifically, suddenly applied unbalance from blade loss.

The recommended method is the component element method; this is essentially a modal synthesis technique. Numerical integration in the time domain is by central difference. Advantages of this approach are:

- Simplicity

- Modular or building block modeling

- No generation or inversion of large stiffness matrices at each time step

- Adaptability to time, displacement, and velocity-dependent loads due to rubs, gyroscopic, and Coriolis effects

- Extendability to include nonlinear connecting elements such as a squeeze film damper

- GE's experience and expertise in the component element method.

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4.0 DISCUSSION AND ANALYSIS

4.1 SURVEY AND PERSPECTIVE OF BLADE LOSS EXPERIENCE IN AIRCRAFT TURBOMACHINERY

From considerable experience in the design and manufacture of aircraft gas turbine engines, General Electric has acquired field data on blade loss and an understanding of the consequences in an operating gas turbine engine. It has been found that, besides the statistical or probabilistic character of the damage, the stage of the location of the blade(s) loss, the operating speed at release and its proximity to engine critical speeds, and the type of aircraft gas turbine engine (high-bypass turbofans, low-bypass turbofans, single spool, twin spool, large, or small) have a considerable bearing on the type and severity of engine damage. For example, small engines are generally much more tolerant to blade loss than larger engines and experience fewer shutdowns. Additional difficulty in identifying the crucial problem areas is also created because assessment is highly qualitative and does not easily permit a quantification of damage described as "seal rubs," blade curling, "corn-cobbing," in-flight shutdown, surge, etc.

4.2 TRANSIENT VERSUS STEADY STATE

One additional fact should be noted here. In the event of engine damage, shutdown, or failure, the damage assessment cannot discriminate which damage was due primarily to transients and which was caused by steady-state operation after the blade loss and before shutdown. Even in instrumented tests, it is difficult to ascertain responsibility for the worst damage to transients because their duration is very short and sometimes masked by acoustic propagation and shell-mode response that accompany a blade release. These include wave propagation due to blades impacting casings, excitation of high frequency shell modes, or the shocks generated when the released blade contacts adjacent blades and other blade rows. It is obvious that damage is inflicted to the engine and its components in various modalities; however, the apportionment of the damage to transients and steady state is sometimes conjecture.

4.3 IMPLICATIONS OF BLADE LOSS

Despite these difficulties, the consequences of some blade-loss incidents are obvious: the loss of power, the economic cost of repair and replacement of inoperable engines or aircraft, and lost earnings. Out of the possible results of lost blade(s) in an aircraft turbine engine, shutdown is one of the more undesirable consequences. An engine shutdown can be the immediate consequence of an irrecoverable stall of the compressor, separation of a turbine shaft, or structural failure of major components such as bearings and frames. Although stalls could be precipitated by several types of malfunctions (other than blade loss) in such items as electronic sensors and fuel controls, as well

as off-scheduled vane setting or mechanical failures, a blade loss at operating speeds is usually the primary initiator of the types of failures that could ultimately lead to engine shutdown.

In a turbofan engine, a lost fan blade is most likely to produce a very large unbalance and could result in damage of varying degrees to structures, bearing supports, and the compressor blading. The possibility of shutdown is therefore great, and the structural repair and replacement can be costly. On the other hand, blades lost in either the high pressure compressor or turbine can also result in compressor stall or other mechanical failures that can induce an engine shutdown, but the extent of structural damage may be smaller than in the case of a lost fan blade. However, from experience, the frequency of lost fan blades is generally small compared to the loss of compressor or turbine blades.

Low-bypass turbofans and small turbine engines appear more tolerant to lost blades. Although these engines also stall and flame out because of lost blades, engine shutdowns from lost blades are fewer. This ruggedness is partly attributed to the smaller blades because of the relatively greater strength related to minimum thickness which is required for practical manufacture.

4.4 AVAILABLE DESCRIPTION OF BLADE LOSS DAMAGE

To show a direct connection between the type of engine damage and its ultimate consequence on operability and maintenance, General Electric's experience in turbine engines has been reviewed for incidents of blade loss. Although the incidents are well documented, the resulting damage, the history of its causation, and its magnitude are perforce qualitative and therefore debatable in the context of this study. To help render some order to the descriptions of blade-loss damage, a list has been compiled that delineates the area of damage, the kind of damage, and the severity. This list is primarily descriptive; however, it provides a basis for a later quantitative ranking.

One should not overlook the fact that the blade loss condition resulting in the worst damage may not necessarily be the most critical because the probability that type of incident may be small. In addition to descriptions of damage and the initial blade release, the relative frequency or probability of occurrence of each category of lost blading is a requisite for a realistic assessment of the most critical conditions of blade loss.

4.5 SUMMARY OF EXPERIENCE DATA

4.5.1 Framework For Experience Data

The initial summary is, by necessity, qualitative. Out of the many types of engines and the numerous types of results, the incidents of blade loss are generalized into various categories. These categories are:

- The location and portion of blade(s) lost. For example, one or more fan blades.

- Relative frequency or probability of an engine type experiencing each category of blade loss.

- The problem area which is described by the primary mechanism of damage and the component that is affected. For example, high pressure (HP) compressor damage from lost fan blades.

- The kind of damage or undesirable results, such as seal wear, "corncobbing," stall, bearing failure, and shutdown.

The problem area has been subdivided into two major classifications according to the dominant mechanism of damage. These are (1) deflection-dominated rotor-to-casing rub and rotor-to-rotor rub, and (2) load- or strain-dominated failures of bearings, frames, and other structures, as well as high-g loads to items such as gearboxes.

Therefore, the blade loss experience in turbomachines is summarized using the foregoing categories as framework. This allows the important problem areas and the severity of consequences of blade loss to be put into perspective.

4.5.2 Experience Summary

With the framework that was discussed in the previous section, the summary of experience of blade loss in gas turbine engines is presented in Table I. The horizontal headings detail the source of unbalance: the engine stage and number of blades lost. The vertical headings on the left-hand side delineate the problem areas between those that are dominated by deflections (such as rubs) and those dominated by high loads or strains. The boxes make up the matrix of the expected structural damage and undesirable consequences.

Because the table is the distillation of blade loss experience encompassing turbofans and turbojets, large and small engines, commercial and military, the specific response of any one class of engines cannot be distinguished. For example, lost fan blades, although sometimes serious, are not relevant to turbojets. And while compressor damage could sometimes result in shutdown, small engines may be more tolerant to this sort of damage than the large engines. It should therefore be understood that this table describes the worst possible consequences of blade loss regardless of engine type and size. To include all the individual characteristics of every engine model and its particular response to blade loss is not feasible. However, it can be inferred from Table I that the problem areas can be easily divided into two categories: rubs and high loads. These are tabulated below and discussed in more detail in the following sections.

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Deflection Dominated

- Rotor-to-Casing Rub

  - Fan Casing Rub

  - HPC Casing Rub

  - HPT Casing Rub

  - LPT Casing Rub

- Rotor-to-Rotor Rub

Load or Stress Dominated

- Structural Loads
- High-g Loads.

4.5.3 Deflection-Dominated Problem Areas: Rubs

4.5.3.1 Rotor-to-Casing Rubs

Any blade lost from a rotor will result in an unbalance which could deflect the rotor from its initial position. A sufficiently large deflection could result in rotor-to-casing contact that might cause seal wear and blade tip damage. The location and severity of this interference are influenced by the engine size, the stage which lost the blade, the local rotor-to-casing clearances, the critical engine modes, and the operating condition when the blade(s) is lost.

In turbofan engines, fan blade loss usually imposes large dynamic loads primarily on the front bearings and the casing. Damage to the rest of the fan blades may cause loss of fan thrust and fan stall. When one or more fan blades are lost, the accompanying large relative deflections in the high pressure compressor can induce heavy rotor-to-casing rubs leading to blade tip and seal wear, performance loss, and unrecoverable stall. Loss of one or more forward HP compressor blades can directly induce large compressor rubs due to vibration response, as well as inducing secondary damage to other airfoils and subsequent performance loss. These conditions usually result in performance deterioration and unrecoverable stall. Multiple loss of HP turbine blades will generally induce moderate HP compressor rubs and performance loss but will usually induce heavy rubs locally in the turbine area, with some performance loss. The degree of rub and damage consequence vary widely and depend on type and size of the engine along with rotor and bearing geometries.

4.5.3.2 Rotor-To-Rotor Rubs

A rotor-to-rotor rub can be encountered in engines with two (low and high pressure) or more spools. An unbalance in the HP rotor may result in an HP-to-LP rub and vice versa when the deflection is sufficiently large. To alleviate this type of interference, some engines are provided with a "bumper"

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bearing, between the HP and LP shafts, whose main function is to limit the relative deflection and increase the stiffness of the combined rotors. While this problem can occur with fan, HPT, or LPT unbalance, actual response varies with engine model and size.

For instance, in turbofan engines, the loss of one or more fan blades can result in rotor-to-rotor rubs if an engine carcass bending mode exists. Rotor-to-rotor rubs of this type are usually benign. Rotor-to-rotor rubs from multiple loss of HP turbine blades can result if local clearances are small. A possible result is an LP shaft rub.

Therefore, the primary effects of rubs are essentially in wear: blade tips, casing liners, seal teeth, and rotor-to-rotor at bumper bearings and at other contact points. Consequences are loss of aerodynamic efficiency, performance, and power, and possible stall or in-flight shutdown; in the most extreme case, shaft decoupling and the necessity and cost of replacement of damaged engine components.

4.5.4 Load- or Stress-Dominated Problem Areas

Failures in this category are the result of overload of bearings or other structural supports such as frames, bolted joints, and conical joints and in other components such as gearboxes and other case-mounted hardware which may experience high-g loads from the blade-loss unbalance. Some of these failures could ultimately result in an engine shutdown.

The loss of one or more fan blades always produces large forces on the rotor, bearings, bearing housing, and support structures in the fan and compressor area. Fretting and fatigue damage may also accumulate in a short time; this may loosen bolts and crack accessories, housings, joints, and other structural components under the "steady state" stimulus of the large unbalances. The damage can be extensive and costly to repair.

Depending on the engine configuration, a lost HPT blade may cause considerable damage and bearing support failure, or it may be benign. Ultimate consequences include engine shutdown. Again, detailed consequences are strongly configuration-dependent.

4.6 RELATIVE DAMAGE SEVERITY

In Table I, the damage in each problem area that may result from the blade loss categories is qualitative and varies from light performance loss to in-flight shutdown (IFSD).

A first and cursory examination would indicate that, according to the number of "stalls" or "IFSD," multiple fan blade loss is the most severe case. Structurally, this is true; however, fan blade loss is very rare. From this observation, the probability of the occurrence of each category of blade loss

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assumes an important and additional facet in the determination of the critical problem areas and their sources of stimulus. In the following sections, a rationale for the quantitative ranking of the relative overall severity of the problem areas is described and applied to Table I.

4.6.1 Ranking of the Problem Areas

To put numerical values where there were only descriptions is difficult. It is impossible to provide a purely analytical assessment, and it must rely, to a considerable extent, on engineering judgment based on experience. However, an attempt is made to convert the descriptions into numerical equivalents.

The assignments of numerical values to the probability of each undesirable consequence from various blade losses is a distillation of the many experiences accumulated by engineers involved in engine design, testing, service, and design analyses, coupled with a summary of statistics collected in previous years. Because these statistics were established for many engine models, sizes, and applications, there is a large disparity in the type and probability of damage and the location and amount of blade loss as well as an apparent lack of consistency in these incidents. Therefore, in this quantification, some conservatism is employed.

4.6.2 Criteria for Damage Assessment: Severity, Damage Areas, and Blade Loss

The ranking of the relative severity of the problem areas under various blade losses is analyzed in this section.

From an examination of Table I, three qualitative categories or criteria are obvious. These are:

- Relative Damage Severity or Degree of Undesirability - Minimal wear, for instance, is assigned a rank of 1, whereas an engine shutdown gets a 10.

- Relative Probability of Damage Occurring in a Problem Area Under Any Condition of Blade Loss - Certainty of occurrence is 1.0; diminishing values indicate less certain encounters.

- The Probability of Occurrence of a Blade Loss Category - This number denotes the probability of a fan blade loss or an HPT blade loss (say, obtained from the operating history of engines). As an example, a fan blade loss may be given as one incident in so many thousand operating hours. In this present task, however, where several models, bypass ratios, and sizes of engines are surveyed, the probability of a type of blade loss must be looked at only in the context of overall engine experience, and probabilities denote only relative values.

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Table I. Summary of Generalized Turbine Engine Blade Loss Experience, Dynamic Response, and Undesirable Results.

Problem Area	Rub. Lock	Blade(s) Loss: Number and Stage Location							
		Partial Fan Blade	One or More Fan Blades	Fwd. HPC Partial	Fwd. HPC One or More	Aft HPC One or More	HPT One Blade	HPT Multiple	LPT One or More
Deflection Mechanism: Rub — Rotor-to-Casing — Fan	Fan	Thrust Loss Tip/Casing-Wear EOD Unbalance	Fan Stall Thrust Loss Tip/Casing Wear. EOD Unbalance						
HPC	HPC	Perf. Loss Possible EOD Wear	Clearance Loss HPT Stall Perf. Loss: EOD Wear IFSD	Unb. FOD Perf. Loss: Wear HPC Stall & IFSD (Slim)	Large Unb. HPC Stall: EOD Perf. Loss Wear: IFSD	Unb. FOD Perf. Loss: Wear HPC Stall & IFSD (Slim)		Clearance Loss HPC Stall IFSD Perf. Loss Wear	
HPT	HPT		Clearance Loss Loss of Drive Power: IFSD Perf. Loss Wear		Clearance Loss Perf. Loss Wear		Clearance Loss Large Unb. Perf. Loss FOD: Wear EOD: Wear	Clearance Loss Large Unb. Perf. Loss: EOD: Wear	
LPT	LPT							Clearance Loss Perf. Loss Wear	Clearance Loss Large Unb. EOD IFSD Perf. Loss Wear
Rotor-to-Rotor			Large Displ. Shaft Rub: Wear					Large Resp. Shaft Rub	
High Load or Over-Stress			High Loads. High G's: Brg-Fretting Loose Bolts: GB-Fail: IFSD					High Loads. Brg Failure Excessive HPT/ Case Wear	

N.B. IFSD – In-Flight Shutdown
SD – Shutdown
EOD – Engine Object Damage – Damage From Debris, Also Blade Debris.

Note: This chart lists the possible undesirable consequences of blade loss in each problem area (engine component(s) and damage mechanism) as a function of number of blades lost and their stage location.

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A simple process of multiplication of the three numbers applicable to each problem area gives a damage severity factor.

4.6.3 Definition of Damage Severity Indices

Ranking of damage severity is naturally relative, and the ultimate implication of any damage also depends partly on the particular engine and aircraft. Table II is an example of how the relative damage severity of typical blade loss consequences has been ranked.

Table II. Relative Damage Severity Ranking.

Undesirable Results	Description of Possible Damage	Rank: Damage Severity Index
Shutdown (SD)	Total Power Loss	10
Rotor Rub - Failure	Midshaft/LP Shaft Failure	10
Bolted-Joint Failure	Casing and Strut Replacement	10
Large Thrust Performance Loss	Power Reduction - 70% Irrepairable Damage	6
Moderate Thrust Performance Loss	Power Reduction - 40% Irrepairable Damage	3
Rotor Rubs - Heavy	Replacement of Shaft	4
Structural Damage	Replacement of Structure	4

4.6.4 Analysis of Blade Loss Experience and Selection of Critical Problem Areas

Before any conclusion can be made with regard to the worst and most critical problem area or blade loss, the actual and immediate causes of mechanical damage must be defined according to the following:

● Transient or steady state

● Primary unbalance mechanism or secondary damage as FOD or clearance loss.

It has been noted earlier that the distinction between transient and steady-state caused failures is very difficult if not impossible from a teardown examination of a damaged engine. For example, a compressor stall is

really a secondary result of blade loss which may or may not have been pro-
duced by vibratory response. There are still cases where the sudden transient
response is not very great but produced sufficient steady (nontransient) exci-
tation to fatigue an engine component minutes or hours after the initial blade
loss. With this distinction, and employing our technical experience and engi-
neering judgment, the probability of each type of blade failure has been com-
bined with the damage severity index and applied to Table I. The resulting
matrix shown in Table III ranks the relative importance of each problem area
and each type of blade loss.

It becomes obvious from examining Table III that the HPC and HPT areas
have the greatest probabilities of being damaged by blade loss from the fan,
compressor, or turbine. These two areas are also both high in severity for
the greatest number of the types of blade loss. By virtue of the very large
unbalance, the fan stage is by far the single worst type of blade loss al-
though the probability of such an incident is very slight. It is for this
reason that fan blade loss must be considered as a critical type of blade
loss as well as a problem area.

With these observations, the following problem areas and blade loss
types are found to be the most critical and are recommended for the analyti-
cal efforts of Task II:

Problem Areas

- Deflection-dominated or rubs:
    - Casing-to-rotor rub
    - Rotor-to-rotor rub

- High Loads and Stresses

Blade Loss Type

- Single fan blade

- Multiple high pressure turbine blades.

4.7 BLADE LOSS IMPLICATIONS OF ADVANCED TURBOFAN ENGINES

Because of their large size and increasing speeds coupled with demands
for fuel economy and greater efficiency, advanced turbofan engines could be
more significantly affected by blade loss than current models. The trends
towards lightweight structures, fewer stages, thinner blading, higher turbine
temperatures, and fewer bearings or frames combine to require increased accu-
racy and creativity in analysis and design as well as in development of more
versatile materials. Table IV summarizes the characteristics inherent in
advanced turbofan engines and the possible consequences of blade loss.

Table III. Quantified Ranking of Problem Area Sensitivity to Blade Loss from 0.0 to 10.0.

Problem Area	Rub	Rub Location	Blade(s) Loss: Number and Stage Location							
			Partial Fan Blade	1/More Fan Blade	Partial Forward HPC	Multi-forward HPC	1/More Aft HPC	One HPT	1/More HPT	1/More LPT
Rub: Deflection Mechanism	Rotor-to-Casing Rub	Fan	0.08	0.16	---	---	---	---	---	---
		HPC	0.06	0.18	3.7	0.8	0.9	---	2.3	---
		HPT	---	0.06	---	---	---	---	3.0	---
		LPT	---	---	---	---	---	---	---	0.34
	Rotor-to-Rotor		---	---	---	---	---	---	0.46	---
	Overstress or High Load		---	0.04	---	---	---	---	0.83	---

Table IV. Summary of Blade Loss Implications of Advanced Turbofan Engines.

Possible Advanced Turbofan Engine Characteristics	Possible Consequences
Lighter weight, more efficient	Higher stress, tight clearance, increased susceptibility to blade loss and rubs
Higher bypass ratio	Large fan means large unbalance and debris or smaller core
Fewer bearings and frames	Larger deflections and loads - more sensitive to unbalance
Higher pressure ratio per stage	Increase possibility of blade loss from surge, and fatigue; less stall tolerance
Higher tip speed	Greater unbalance and debris kinetic energy
Use of improved dampers	Increase unbalance tolerance

4.8 IMPLICATIONS OF TRANSIENTS OTHER THAN BLADE LOSS

The main consideration of the present contract is blade loss transient response; however, a turbojet or turbofan engine is also subject to other types of dynamic loadings. Some examples are:

- Hard Landings

- Gust Loads (Airpocket, Up- and Down-Drafts)

- Exhaust Gas Ingestion

- Bird Ingestion

- Shaft Separation

All of these are considered in the design, testing, and certification of military, commercial, and business aircraft gas turbine engines. Hard landings and gusts introduce g loads as well as gyroscopic loading by way of an induced rigid-body rotation of the gas turbine engine. Rotor steady response to both g loads and gyroscopic forces is calculated as a standard item in the design procedure. However, the engine transients are not considered. The time duration of the input during these events is high compared with the period of the lowest engine mode; therefore, the engine behaves essentially as a rigid body. Of course, this is not true for the aircraft, and a transient analysis of the aircraft structure is essential. The g loads from landings and gusts are obtained from requirements established through experience

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by the aircraft and engine builders as well as by government, commercial, and military customers. Finally, the ultimate verification is by development and certification testing.

The transients from exhaust-gas ingestion that could occur during thrust reverser operation and under strong tailwinds or crosswinds affect primarily the fan blading. Engine response in terms of displacement may be large, but the forces and g loads are small under these conditions.

Bird ingestion is of concern in engine rotor response only as the initiator of blade loss. Although the system transients from the impact loads are negligible, fan or compressor blades broken by the bird impact produce the blade loss unbalance which results in the transients as well as the steady loads studied in the contract.

Shaft separation can be a serious failure caused by rotor-to-rotor rub, bearing failure, and secondary failure. Although rare, shaft separation can result primarily in turbine overspeed or rotor-to-stator interference. High seizure loads may be produced. The consequence of a shaft failure is determined by the specific details of the engine design. Thus, rotor-to-stator engagement occurs, and the extent to which the rotor speed is controlled depends on the particular engine. The resulting impact loads and decel torque are also uniquely functions of the specific design and not easily amenable to generalized analysis.

4.9 BRIEF REVIEW OF METHODS FOR TRANSIENT DYNAMIC ANALYSIS

4.9.1 Finite-Element Methods

In pursuing a practical method for the transient dynamic analysis of turbine engines, the current field was reviewed for relevant computer codes. The results of this review showed that the all-purpose, finite-element, computer programs are much too general to be economically and technically feasible without extensive modification. A finite-element computer code, such as either NASTRAN or SAP IV (Reference 1), is developed for single-body problems that are represented by small, fundamental, building blocks such as brick, beam, plate, tetrahedral, or other geometric shapes. Although the structure modeled by these finite elements may be multiply connected, these connections and their number or location cannot be affected by the structural response. To vary these connections to account for time and displacement dependence, as one can encounter in a rub between engine components, is currently not feasible. Also, most of these finite-element codes do not include gyroscopic and Coriolis forces; where they do, these effects are considered only as static loads such as centrifugal forces.

The direct transient solution algorithm of these large programs is usually by finite-difference techniques applied to the assemblage of finite elements; solutions involve construction and inversion of large, global matrices that require large amounts of computer storage. Because these elements are

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tiny, the necessary time interval could be small, some in the order of 1 micro-
second. There are also finite-element programs still being developed which
utilize a numerical Laplace transform for the time solution; unfortunately,
not enough progress has been published about this approach. Modal superposi-
tion solutions are also employed, as an option (such as in SAP IV), which would
utilize a more reasonable time interval. However, as previously noted, these
are made for single-body problems. Therefore, due to their great generality
and certain shortcomings, they are not recommended for analysis of the tran-
sient dynamics of turbine engines. In summary, the essential characteristics
of the current, general-purpose, finite-element, computer programs which make
them unattractive for the current contract are given below:

- Single-body structure cannot model time and displacement-dependent
  connecting forces.

- Consideration of gyroscopic and Coriolis coupling forces is inade-
  quate.

- In most cases, very small time steps are required for solution con-
  vergence.

- Formation and inversion of large stiffness matrices requires large
  amounts of computer storage.

- Due to large size and complexity, modification is costly and long.

- Potential for extension to accommodate highly nonlinear elements
  (such as rub elements and squeeze film bearings) is very limited.

- There are difficulties with time-varying loads and coupling forces.

4.9.2 Modal Synthesis Method

Beside the general-purpose, finite-element codes are the computer codes
based on simple modal superposition. These codes are simple compared to the
finite-element programs and are fairly old. The modal superposition methods
trace their ancestry to the work of Rayleigh-Ritz (Reference 2) and more
recently to Hurty (Reference 3). At various times and in different discip-
lines, the modal method has emerged in several guises such as: transfer
function, admittance, impedance methods, and component mode, coupled mode,
and (more recently) component element method.

In essence, the modal synthesis method constructs the dynamic response of
a structural system with its normal modes - hence the name. The normal modes
may be for the entire system, such as a turbine engine, or for its major com-
ponents. In the latter, the component modes are coupled through the complete-
system equations of motion. The modal-coupling coefficients are normally
obtained by the principle of virtual work and equilibrium, continuity, and
compatibility conditions at connections.

Because only a finite number of normal modes are used, the modal approach is an approximate method. Simplification may lead to inaccuracies due to inadequate or insufficient normal modes used in the modeling; however, with care these inaccuracies are reduced to acceptable levels.

The temporal solution may be obtained by Laplace transform, finite differences, or other numerical methods. In some of these solutions, however, the formation and inversion of a global stiffness matrix are required. Where the structure has one or two components and few normal modes, the arithmetic is fairly short. However, in the application to a turbine engine where components are numerous and normal modes many, even the modal synthesis approach can be cumbersome. Nevertheless, there are certain advantages. The physical structure can be modeled with a few modular building elements, not unlike the finite-element approach. In this case, the modules would be the normal component modes and the connecting physical elements such as bearings, springs, dampers, etc. For example, the modal element would be adequately described by: geometry (position and extent relative to other components and connectors), modal mass, modal frequency, and mode shape; the connector may be described by its ends (components joined and location), spring rate, or damping rate.

In the general usage of the modal approach, the principal dependent variables are the modal or generalized coordinates which are the amplitude or "participation" of each normal mode. As a consequence, the equations of motion are derived explicitly in terms of these generalized coordinates. This requires that each equation contain two or more generalized coordinates because the connecting elements would introduce coupling terms not only between components but also between normal modes of the same component. (Note that the orthogonality of normal modes applies only to component mass and stiffness and not to elements which are not included in the original component normal mode calculation.) The use of explicit generalized coordinates as dependent variables, therefore, demands also a formation and inversion of a global stiffness matrix. This process can require a large amount of computer storage as well as present some numerical and coding difficulties.

To overcome these obvious limitations, another wrinkle on the modal synthesis approach was developed at General Electric. Named the Component Element Method (Reference 4), it differs from the other modal methods in the formation of the equations of motion and in the temporal or transient solution. Briefly (since this is described in greater detail in the Task II Report), the coupling or connecting forces are derived in terms of physical displacements (or velocities) of the components at the connection points. Each equation of motion is an uncoupled equation (in the left-hand side) in each generalized coordinate with all the coupling terms (in physical coordinates or forces) in the right-hand side. The temporal solution uses a central difference scheme that calculates the present value of each generalized coordinate and each physical force (or displacement) in terms of two past values. After all the coordinates are calculated at each instant, the physical displacement is calculated (being the sum of the normal mode shapes at connecting points times the generalized coordinates) with which the physical force is updated. By

this quasi-uncoupling of the equations of motion and the central difference scheme, the component element method obtains the transient solution with neither matrix formation nor matrix inversion.

4.9.3 Recommendations

What the modal approach lacks in detailed definition it compensates in great simplicity, economy, flexibility, and a general and clearer understanding of the basic transient dynamics of the whole structure. The end product is transient response of the turbine engine in terms of reactions and bearing loads, deflections, and rotations. To obtain the localized stresses and strains, a highly detailed finite-element analysis may be made with the loadings obtained in the transient dynamics superposition calculation.

It is obvious from this brief review that there is a duality in the determination of turbine engine transient reponse. This duality lies in the generation of the component normal modes by a finite-element program and in the calculation of transient response by the modal approach. In calculating the detailed stresses, we run full circle: back to the finite-element analysis.

In this task, the modal approach was recommended for the transient dynamic analysis of a turbine engine under a blade-loss excitation. In particular, the component element method was recommended for the following reasons:

- Simplicity

- Modular or building block modeling

- No generation or inversion of large stiffness matrices

- Adaptability for time, displacement, and velocity-dependent loads such as rubs, gyroscopic loads, and Coriolis forces

- Extendability to include nonlinear connecting elements (squeeze films)

- GE's experience and expertise in the component element method.

Finally, a facet of the component element method is the relative ease in checking the computer coding. The modular approach permits checking the transient calculation for each component and each mode or for two components at a time. This reduction to simpler or degenerate cases will provide checks of analysis and program coding against previously known solutions, simpler experimental models, or both.

The GE-recommended approach was accepted by NASA and has been pursued and developed for Task II and Task III.

5.0 REFERENCES

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