Normal Modes Vibration Analysis of the JT9D/747 Propulsion System

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The results of an exploratory research program on structural integration of aircraft propulsion systems are reported. The need for cooperative analysis by the engine and airframe manufacturers is discussed. The procedures for executing a multicompany, integrated vibration analysis are described. An 11,000-degree-of-freedom, finite-element model of the JT9D/747 installation was assembled and reduced to 388 freedoms from which 388 natural frequencies and 50 mode shapes were calculated. The model was evaluated by correlation with available test data.

Introduction

MAJOR structural components of aircraft propulsion systems are provided by both the engine manufacturer and the airframe manufacturer. The development of the propulsion structure therefore requires a close working relationship between the engine and airframe companies to define system interfaces, exchange structural data, and carry out the required analyses and tests to ensure safe and economical operation.

Powerful analytical tools[1-3] have been developed in recent years which now permit detailed and accurate mathematical simulation of complex structures such as aircraft propulsion systems. Utilization of these tools at the proper time in the design/development cycle can improve structural integrity, and reduce the cost while improving the effectiveness of development tests. These same analytical tools can also improve understanding of engine performance degradation by predicting clearance changes under operating loads.

Compressed development schedules and economics have in the past precluded a detailed system simulation of airplane propulsion systems. The time required and the cost of system simulation have been reduced now to the point where development philosophy can include total system simulation within the development cycle.

To develop the methodology of multicompany integration analysis, the Boeing Commercial Airplane Company and Pratt and Whitney Aircraft embarked on a joint research program related to the JT9D-7 propulsion system on the 747 commercial airplane. The objective was to carry out a normal-modes vibration analysis using the NASTRAN program.[1] Earlier work[4-6] utilized NASTRAN in propulsion-system static and dynamic analyses. This paper describes the execution of a joint integration analysis, which included interface requirements, data exchange, modeling, and correlation of analytical results with test data.

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Propulsion System Modeling and Substructures

A detailed flexible-body simulation of the propulsion system is not generally used in structural simulation of the airframe. This is because the attachment of the engine is usually statically determinate, and the flexible propulsion system vibration frequencies, which are considerably higher than the wing frequencies for wing mounted engines, do not appreciably affect airframe flutter characteristics.

The aircraft flutter model typically utilizes a semirigid or simple beam idealization of the nacelle. The engine manufacturer is, however, concerned with engine strength, durability, and running clearances – the analysis of which requires a detailed flexible-body simulation of the propulsion system. The airframe manufacturer's role is to provide simulations of structure, such as strut, inlet, reversers, etc., to be attached to the engine. The manufacturer also provides mission profiles, usage, and detailed flight loads to permit analyses of engine strength, durability, and running clearances.

A multicompany integration analysis requires careful attention to interface definition and data exchange. The task was simplified for this joint study, since a common analysis tool (i.e., NASTRAN) was available to both participants in the program. Therefore, data tapes could be exchanged directly and used without transformation to some other structural analysis program.

The mathematical model was jointly developed by the two companies and began with an identification of below-the-wing propulsion system substructures, which were provided by each party. Since, primary emphasis in the study was on flexible, dynamic behavior of the engine, the wing was not included. By excluding the wing, the nacelle/strut combination could reasonably be assumed to be symmetric about a vertical plane through the engine centerline. Symmetric and antisymmetric behavior could then be calculated with a half model for much less cost than a full model.

Substructure interfaces were chosen where subassemblies were mechanically joined (i.e., mount points, flanges, etc.). Detailed finite-element models of the engine static structure (cases and bearing support frames), rotors, and thrust yoke were provided by Pratt & Whitney. Rotors were modeled as beams with discrete masses input directly. Boeing provided the inlet, strut, and tailcone models.

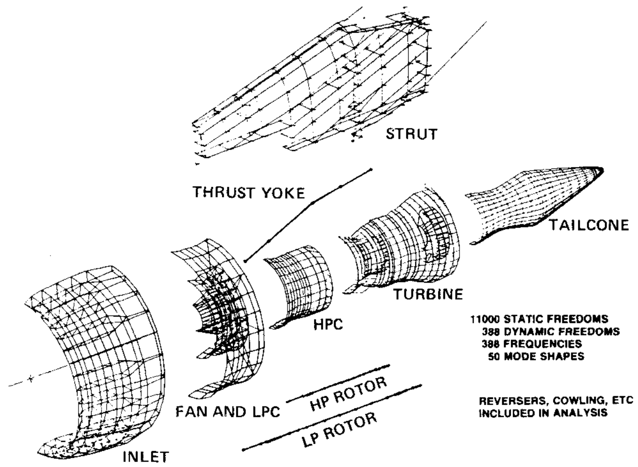

Fig. 1 JT9D/747 propulsion system substructures.

Secondary structural components (fan and core cowls, fan and turbine reversers, stator assemblies), accessories, and plumbing were included as discrete or distributed masses as appropriate to bring the mass properties of the model to within 5% of the actual hardware. Gyroscopic stiffening terms for the rotor mass points were set to correspond to engine steady-state cruise operating conditions. The final static model consisted of eight substructures with approximately 11,000 freedoms as shown in Fig. 1 and summarized in Table 1.

Substructure Analysis Flow

The substructure analysis is carried out in three phases as illustrated in Fig. 2. In Phase I the individual substructure stiffness and mass matrices are formed and reduced to the boundary, retained mass, and interface freedoms. By carrying all boundary conditions into Phase II, both the symmetric and antisymmetric boundary conditions can be applied without repeating a Phase I analysis. The output of Phase I is a restart tape for each substructure which is copied and sent to the other participants in the joint analysis effort. At this point each participant can proceed independently if desired.

Phase II uses the Phase I restart tapes to generate partition vectors that prescribe the connectivity between the substructure interface freedoms. Boundary conditions and any additional required data such as multipoint constraints or additional stiffness elements are added, further reduction is carried out, and the analysis run, giving solutions associated with the Phase II retained mass freedoms.

Phase III requires back-substitution from Phase II into each individual substructure to obtain the solutions over the detailed Phase I mesh.

Dynamic Model

The dynamic model is shown in Fig. 3. This model was formed by reducing the freedoms of each individual substructure to mass, interface, and boundary freedoms, and then merging the reduced substructures at the interfaces. Symmetric or antisymmetric boundary conditions could then be applied and further reduction of the nonretained mass freedoms at interfaces and boundaries carried out. In this study, the analysis was confined to symmetric-mode shapes. The final number of dynamic degrees of freedom was 388. Nonstructural plot elements were connected between the retained grid points for visibility of the mode shapes.

Analytical Results and Correlation

A total of 388 natural frequencies for symmetric boundary conditions were computed by Given's tridiagonalization and the modified Q-R procedure. The first few were recomputed by the inverse power method to provide a check on computational precision. The first 50 mode shapes were computed. Frequencies and mode shapes were examined in detail and compared with available test data and independent analytical results. These tests and analyses are now briefly reviewed.

Available Test Data

The test data used in this study came from design development and verification type tests, which generally were conducted to demonstrate safe operating ranges. Some were component tests, others were full-scale engine tests with and without flight hardware and with and without the engine running. None of the test configurations exactly duplicated the NASTRAN math model. Much of the test data provided frequency but not modal data. The specific tests utilized and a brief description follows:

Structural Development Laboratory (SDL) Tests

Two component tests fall in this category: a test of the tailcone attached to the turbine exhaust case and a test of the fan on a bare engine. The tailcone was excited by a hand-held shaker with mode shapes observed using strobe lights. The fan case test used stinger excitation and strobe lights. The fan exit guide vanes were not present and an early design of the JT9D inlet was used.

Live Engine Tests

The live engine tests were conducted on an engine test stand without certain flight hardware including inlet and tailcone. These tests were accel-decel runs using generally four accelerometers at selected points on the engine flanges to detect significant vibration. The forcing function was normal as-built unbalance of the installed rotor. Mode shapes were inferred by visual observation, accelerometer readings, and rotor frequency calculations.

Table 1 Summary of substructures

		Elements				
Substructure	Grid points	Spring[a]	Rod	Beam	Membrane	Plate
Inlet	236		76	249	98	204
Fan and LPC	363			283		319
HPC	267	65		86		183
Turbine	587	2	1	343		495
Tailcone	362	16		165		314
Strut	185			166	124	
Rotors	171	345		168		
Thrust yoke	5			4		
Totals	2176	428	77	1464	222	1515
	Total freedoms ≈ 11,000			Total elements ≈ 3706		

[a] Scalar spring elements used for modeling bolt flanges and gyroscopic stiffness.

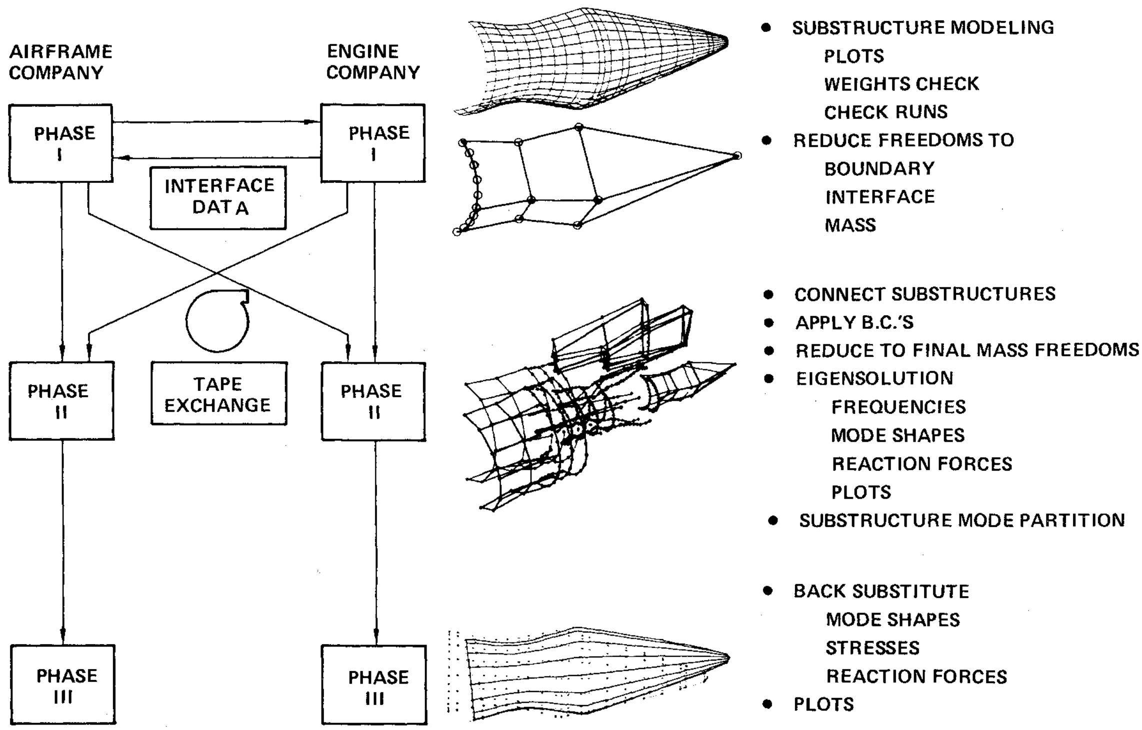

Fig. 2 Substructure analysis flow.

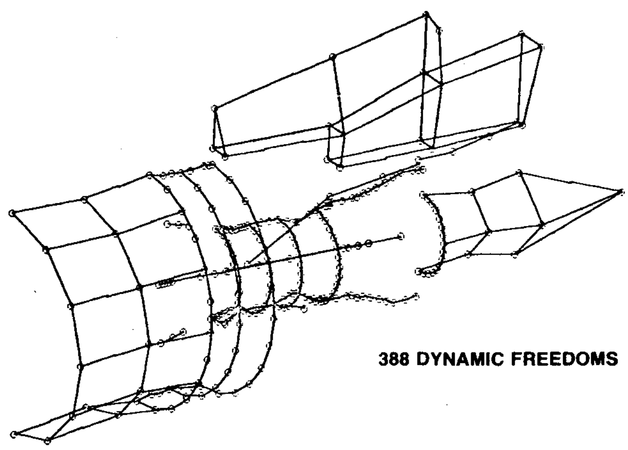

Fig. 3 Integrated propulsion system dynamic model.

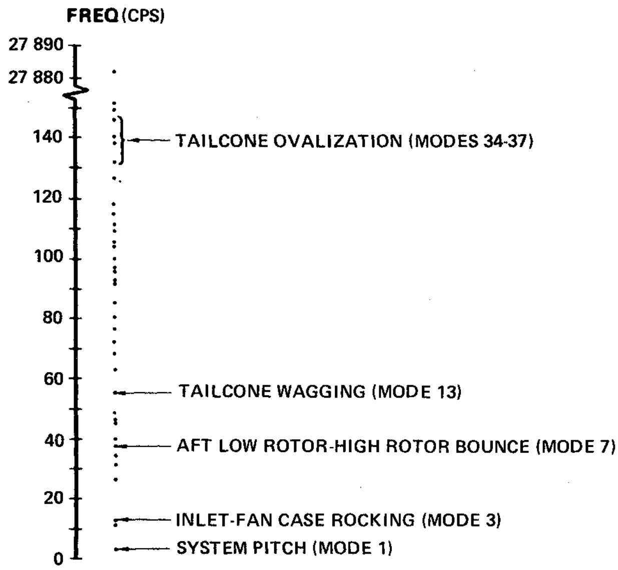

Fig. 4 Relative positions of modes evaluated.

Flight-Dressed Engine Tests

These tests were conducted by Boeing on the fully flight-dressed propulsion system including the strut. The strut was attached to a stiff frame at the strut-to-wing interface points. The purpose was to verify the three important flutter-type modes – pitch, side bending, and yaw torque of the nacelle – used in airplane flutter calculations, the fundamental rigid-body modes of the nacelle. The engine was static, i.e., rotors stationery. The gyro stiffening of the rotors has neglible effect on airplane flutter speeds.

Independent Analytical Results

Three independent analyses were used for correlation of the NASTRAN results in this study. They were as follows:

Rotor-Frame Analysis

This analysis treats the propulsion system as a system of beams and lumped masses interconnected by discrete springs. Its primary use is for calculating rotor critical speeds based on the classical Myklested-Prohl method.

Shell of Revolution Analysis

This procedure treats segments of the engine case as surfaces of revolution for calculating shell-type vibration modes. Engineering judgment determines what boundary conditions to apply.

BCAC Analysis

This analysis is companion to the flight-dressed engine tests used for airplane flutter characterization described above. The strut stiffness simulation is crucial and is modeled in detail by finite elements as shown in Fig. 1. The nacelle is treated essentially as a very stiff beam sprung from the strut by appropriate spring representations.

Correlation

For most of the 50 calculated modes, no information could be found to substantiate or refute the existence of particular modes. Some for which a basis for evaluation could be established are identified in Fig. 4. The dots in Fig. 4 represent the lowest 50 calculated frequencies. The first mode (Fig. 5) involved pitch of the entire assembly against restoration by the wing and correlated satisfactorily with Boeing test and

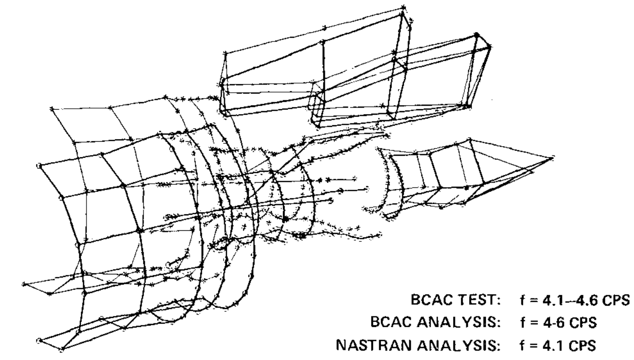

Fig. 5 System pitch (mode 1).

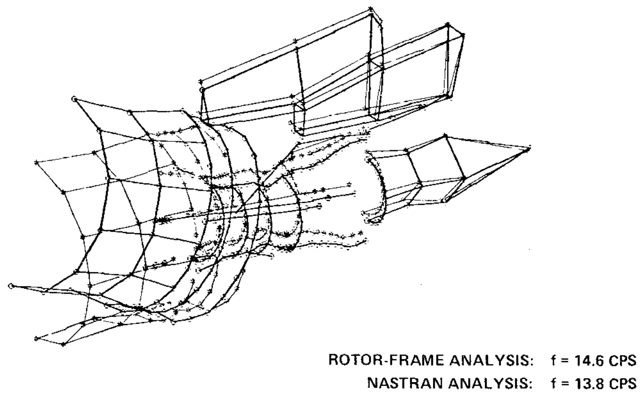

Fig. 6 Inlet-fan case rocking (mode 3).

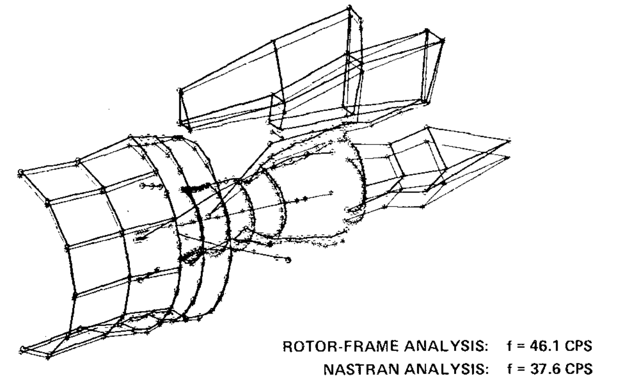

Fig. 7 Aft low-rotor/high-rotor bounce (mode 7).

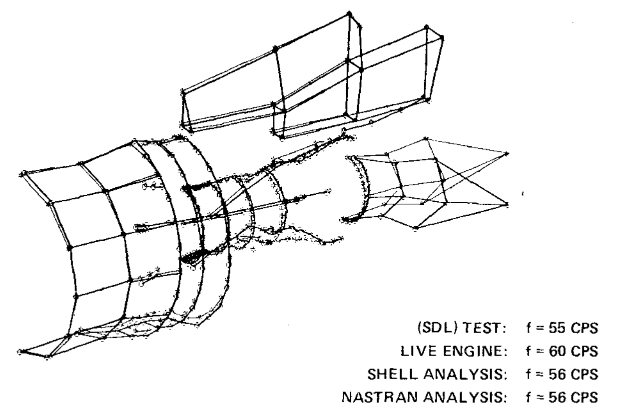

Fig. 8 Tailcone wagging (mode 13).

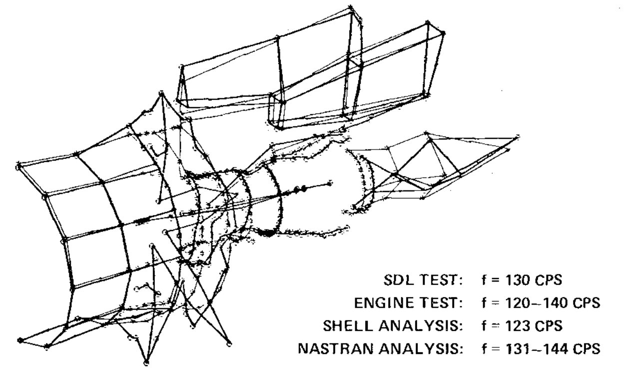

Fig. 9 Fan case and tailcone shell deformation (mode 36, $f = 140$ cps).

analysis. The third mode (Fig. 6) was dominated by rocking of the inlet and fan cases upon the front frame struts and agreed fairly well with results from the conventional rotor-frame analysis. Mode 7 (Fig. 7) exhibited strong rotor participation but showed only fair agreement with previous analyses. Subsequent re-examination of the finite-element model revealed several areas in which improved modeling for description of rotor-frame behavior could be fruitfully pursued. For example, the connection of the rotor-to-bearing housing was simulated by a single-point connection to the bearing housing, which proved too flexible. This can be adjusted by rigid-body constraints on the bearing housing or by using multiple springs from the rotor to the bearing housing, thus distributing the load.

The model was found to be fully adequate for capturing beam and shell characteristics of the tailcone (modes 13 and 36; Figs. 8 and 9, respectively). Interesting shell modes were also seen to develop in the fan case (Fig. 9), but could not be evaluated due to differences between tested and analyzed hardware. The fan exit guide vanes were omitted in the test and an early inlet design was used.

Summary and Conclusions

The main objectives of this cooperative airframe/engine structural integration study were accomplished. A comprehensive finite-element model for vibration analysis of the JT9D/747 propulsion system was jointly assembled and successfully executed. Correlation of results from the model with available independent experimental and analytical data was in most cases acceptable but indicated some areas in which modeling practices could be improved. Additional data from flight-dressed engine tests would be required for satisfactory calibration of the complete model.

An area that needs further study is propulsion-system modeling requirements. Finite-element technology originated in the airframe industry where extensive convergence studies and correlation with airframe tests were carried out. Similar studies are needed for propulsion-system-type structure to establish requirements on mesh size versus accuracy and the best representation of complex features such as flanges, bearing frames, and variable guide-vane holes in the compressor case for a particular level of analysis, i.e., preliminary design, design development, or final system design verification.

It was confirmed that propulsion system major components such as the inlet cowl, engine cases, and tailcone, which are directly attached, develop strong dynamic structural interactions that can be accurately described by integrated structural models. The NASTRAN computer program was found to be adequate for predicting large-scale interdependence of propulsion system structural components but could not compete with specialized in-house programs for defining less global behavior such as engine rotor-frame vibration (critical speeds).

The use of similarly detailed, general purpose models for treating more complex dynamic behavior, such as the sharp transient response associated with fan blade loss, would be prohibitively expensive compared to more efficient, special purpose models. However, application of general purpose models to prediction of deflection-related behavior, such as short-term engine performance deterioration caused by seal wear from flight loads, promises to have a significant impact on the design process during the evolution of next-generation aircraft.

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