Comprehensive Aeromechanics Analysis of Complex Rotorcraft Using 2GCHAS

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Abstract

2GCHAS is a comprehensive, multi-disciplinary, computer software system for predicting rotorcraft aeromechanics characteristics. It is a finite element based system with a variety of aerodynamic modeling options and provides modeling and analysis flexibility, prediction accuracy, and user-friendly input and output. The software is maintainable, expandable, and transportable to various computer platforms. The paper briefly describes the development of the system and key features for modeling complex rotorcraft. A series of rotorcraft analysis problems is presented to illustrate the range of capabilities available, including single and tandem rotor helicopters with engine/drive trains and feedback flight control systems. Various aerodynamic airloads, rotor wake, and component interference models are used in calculating performance, flight dynamic response, rotor loads and vibrations, and aeroelastic stability.

Introduction

The Second Generation Comprehensive Helicopter Analysis System (2GCHAS) is a comprehensive multi-disciplinary, computer software system for predicting the performance, stability and control, aeroelastic stability, loads and vibration, aerodynamics, and acoustics characteristics of rotorcraft. Comprehensive rotorcraft analysis capability is an important, integral part of the broad-scale aeromechanics research and development (R&D) program aimed at developing and improving rotary wing aircraft.

Furthermore, it has been developed to provide a common interdisciplinary analysis and data base which can insure communication between engineering disciplines in the design, development, test, manufacturing, and support process, while providing a common analysis environment to enhance technical communication between the developer and the government. The requirement for this capability is even more important as the world is driven by new ways of doing business, such as Integrated Product and Process Development.

Since existing rotorcraft analysis capabilities cannot adequately satisfy many application requirements, 2GCHAS was developed by the Aeroflightdynamics Directorate of the U.S. Army Aviation and Troop Command (ATCOM) to overcome the limitations of first generation systems arising from both the inherent complexity of rotorcraft aeromechanics and from inadequate software development methodology. The key objectives of the 2GCHAS Project were to develop a comprehensive, interdisciplinary rotorcraft analysis system to support rotorcraft R&D, design development, test, and evaluation activities, and to significantly improve modeling and analysis

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flexibility, prediction accuracy, user-friendly input and output, transportability, maintainability, and expandability.

2GCHAS was developed by the government for several reasons. It brings to bear the substantial resources in the field of aeromechanics R&D to address a large interdisciplinary problem. It can provide a uniform and unbiased basis for analytical prediction technology available to the rotorcraft industry, and it provides a direct technology transfer medium for the products of government research. At the same time a government-developed comprehensive analysis provides an important mechanism for controlling technology transfer in the interest of US competitiveness. Finally it provides a natural focus for much of the aeromechanics research performed by government researchers.

Reference 1, an overview of 2GCHAS through late 1991, provided a technical description of 2GCHAS, and described the program objectives, the project management approach, the methodology used in the development of the system, and the system integration and engineering validation phases of the 2GCHAS Project. Several other papers have also addressed 2GCHAS Project development (Refs. 2-7). Refs. 8 and 9 described the project management approach, 2GCHAS engineering capabilities, documentation, user interface, and representative test results through the completion of the First Level Release of the System in December 1990. This paper is intended to describe the current capabilities of 2GCHAS and to present results for typical helicopter engineering problems. A companion paper, Ref. 10, presents some of the correlation of 2GCHAS analysis results with experimental data.

Role of Comprehensive Analysis

The need for comprehensive rotorcraft analysis arises from the fundamental interdisciplinary nature of rotary wing aircraft: the structure, controls, and the fluid flow are interactive; success thus requires integrated treatment of aerodynamics, dynamics, propulsion, and control systems.

Analytical prediction methods and codes of all types are central to build and apply the technology base that serves to meet Army needs for research, vehicle design, flight test, and operational support. Prediction codes form the basis for design methodology, aid the invention of new concepts, and help generate new fundamental knowledge about rotorcraft phenomena. Many times, these functions may be satisfied with specialized codes of limited scope. Other applications require the more extensive capability of a fully integrated comprehensive analysis. Such an analysis also provides an interdisciplinary system to support development, testing, and evaluation of research codes. The key role comprehensive rotorcraft analysis plays within this spectrum is illustrated in Fig. 1.

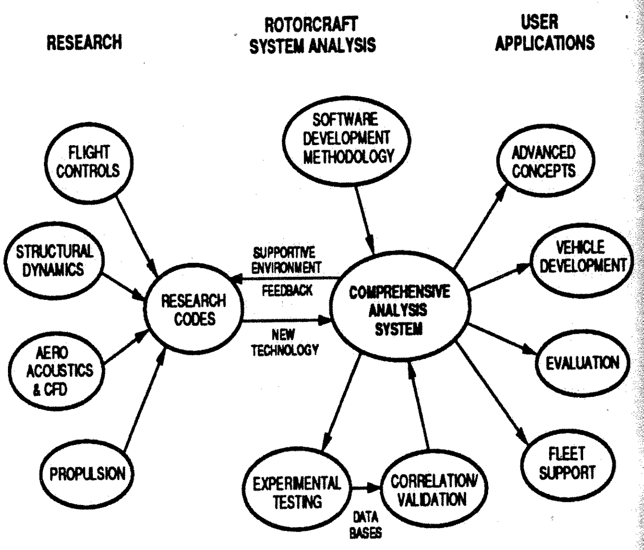

Fig.1 Role of comprehensive analysis is essential for development and application of rotorcraft technology.

Development of comprehensive rotorcraft analysis capability involves significant challenge for the researcher. These challenges arise partly from an incomplete knowledge of the fundamental physics of rotorcraft. Other scientific barriers occur at the system level, where the narrow discipline math models are integrated into practical comprehensive analyses for the entire vehicle.

Comprehensive analysis represents the heart of the ongoing rotorcraft aeromechanics prediction development effort. It provides the basic framework for addressing system level and/or interdisciplinary scientific barriers to accurate prediction. Comprehensive analysis is a distinct and central discipline of rotorcraft aeromechanics technology. It is the single interdisciplinary element essential to unify and leverage analytical research in diverse rotorcraft disciplines. It is integrally tied to the discovery of fundamental knowledge, the evolution of computer power, the acquisition of experimental data for code validation, and the prediction needs of new rotorcraft configurations.

Development Background

The history of the 2GCHAS development effort from 1977 until late 1991 was described in Ref. 1, 8, and 9. The development of 2GCHAS was a team effort which included representatives from Kaman Aerospace Corporation, Advanced Rotorcraft Technology, Inc., McDonnell Douglas Helicopter Corporation, Sterling Federal Systems, Boeing Helicopter Company, United Technologies Research Center, Sikorsky Aircraft Company, Computer Sciences Corporation, University of Maryland, Georgia Tech Research Institute, and Rensselaer Polytechnic Institute.

2GCHAS was designed with two major complexes; the Executive Complex and the Technology Complex. The Executive Complex enables efficient execution of the Technology Complex and provides a user-friendly environment within the host computer. The Executive also facilitates the System development and includes a set of integrated software tools that provide utility and auxiliary System functions. The Technology Complex provides the capability for all trim, maneuver, stability, and aerodynamic analyses of the finite element-based system.

The first integration of the Technology and Executive Complexes software was completed in December, 1989 and released to the 2GCHAS contracting community and the Government for an extensive test period. The first public release was Release 1.9 in December 1990. Subsequent releases included Release 2.0 in December 1991, Release 2.1 in July 1992, and Release 2.2 in June 1993. Each new release of 2GCHAS includes updated software and documentation.

2GCHAS was developed, and will continue to be enhanced, using modern software development methodology and a rigorous product assurance discipline. The 2GCHAS software development methodology is discussed in Ref. 1. This methodology requires that for each system enhancement the developer derive the mathematical basis, perform an analysis of the requirements, carry out preliminary and detailed designs, and then implement and acceptance test the software. The extensive 2GCHAS documentation produced during development was a direct result of the 2GCHAS software development methodology: the timely publication of supporting design and user documentation throughout the software development cycle. The final phase of each enhancement is the delivery of the documentation which includes updates to the final Software Design (Type C5) Specification, and the primary 2GCHAS documentation that includes the Theory Manual, User's Manual, Programmer's Manual, Applications Manual, and Installation Manual (Refs. 11--15).

The Government is continuing to maintain, enhance, and validate 2GCHAS through the combined efforts of its inhouse staff and two companion contracts -- the System Maintenance contract and the System Enhancement contract. The 2GCHAS Project Office provides maintenance and configuration management of the publicly released versions of 2GCHAS. This includes periodic upgrades to the software and documentation, regression testing of the upgrades, responding to user System Trouble Reports (STRs), and generally improving the functionality and performance of 2GCHAS. The Project Office is currently maintaining VAX VMS and SUN and HP UNIX versions.

The paper will include an overview description of the 2GCHAS structural and aerodynamic modeling features, the available analysis options, the user interface, and portability characteristics. A principal part of the paper will cover the application of 2GCHAS to typical problems involving complex rotorcraft to illustrate by example some of the capabilities of the System. The paper concludes with a discussion of some of the technical issues of large comprehensive analyses and plans for future evolution of the System. For an extensive preliminary comparison of 2GCHAS with experimental data, the reader is referred a companion paper, Ref. 10. That paper treats correlation and engineering validation of the System and presents results for nonlinear beam structural response, hingeless rotor aeroelastic stability, rotor performance, and blade loads and airloads, using experimental data from model and full scale rotors in wind tunnel and flight test conditions.

System Description

This section describes the system from the standpoint of engineering analysis capabilities available to the rotorcraft specialist. 2GCHAS provides thorough and consistent treatment of all important rotorcraft features, including rotor systems, fuselage, auxiliary lifting surfaces, automatic flight control systems, propulsion and drive systems, aerodynamics of rotor blades, wings, bodies, and interference effects. To perform an analysis with 2GCHAS, the analyst must supply two sets of input data to the system: the mathematical model (structural and aerodynamic) and the analysis data. These data sets will be described. This section will also describe analysis options and user interface of the System.

Structural Model

The 2GCHAS finite element structural model is the key to modeling diverse rotor and rotorcraft configurations, such as articulated, semi-articulated, tandem, coaxial, hingeless, bearingless, teetering, and tiltrotors.

The structural model of 2GCHAS, illustrated schematically in Fig. 2, consists of a user-specified hierarchy of subsystems, primitives, and elements. *Subsystems* are a fuselage, rotor(s), and control system(s). Each subsystem is composed of an arbitrary number of primitives. A *primitive* is a collection of finite elements, the fundamental building block of the structural model. Element or system degrees of freedom may be constrained using *single point* and/or *multipoint constraints*. The ability to couple elements to form structural models of arbitrary topology is a major strength of 2GCHAS.

The fuselage subsystem can include an engine/drive train model by using transfer function elements model engine torque generator dynamics and structural elements to model the driveshafts, engine inertias, etc. The mechanical couplings between the fuselage thrustblock, engine driveshaft, and rotorshaft are modeled using "transmission constraints."

Control subsystems are used to model the physical control system of the vehicle which consists of up to eight aircraft controls and five pilot inputs. Second order transfer function elements can be connected in an arbitrary fashion to model actuators, filters, etc. The control subsystem is coupled to the rotorcraft using a "control constraint."

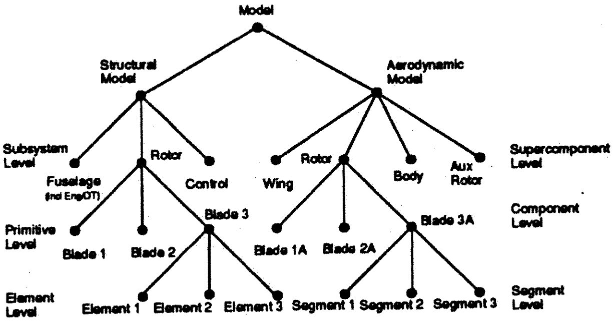

Fig. 2 2GCHAS hierarchical system model.

The element library accommodates various types of structural behavior that allow the analyst to define a complete structural model. The 2GCHAS library of elements includes: nonlinear beam, rigid body mass, nonlinear spring, nonlinear damper, linear beam, rigid blade, transfer function, mechanical applied loads, and direct matrix input/user defined element

The *nonlinear beam* element is primarily intended for the modeling of rotor blades. This element has two end nodes with six degrees of freedom and three or more interior nodes having one degree of freedom each. The element can model small strains and moderate rotations, with second order nonlinear terms included. The *rigid body mass* element is a single node, six-degree-of-freedom element and is used to model a rigid fuselage or wherever point masses are appropriate, such as a blade tip weight, a hub, or fuselage stores. The *spring* and *damper* elements, which can be linear or nonlinear, are used to model hinge and ground springs and elastomeric bearings and snubbers, respectively. The *linear beam* element is used primarily for nonrotating isotropic parts of the structure, such as the fuselage. The *rigid blade* element represents a rotor blade as a rigid flapping mass that is coupled via a rigid offset to the hub. It contains only seven degrees of freedom: the six hub degrees of freedom and the blade flapping angle. All rotations (i.e., hub rotations and flap angle) are treated exactly. The rigid blade element has many fewer degrees of freedom than the nonlinear beam element, and it will therefore result in a significantly smaller structural model that will have a faster execution time. This element is used when a very simple blade model is sufficient for an analysis.

The *transfer function* element uses the ratio of two second-order polynomials to relate input and output quantities in the Laplace transform domain. Transforming this relationship into the time domain results in coupled, linear second-order differential equations for the inputs and outputs, and these lead to conventional mass, damping, and stiffness matrices that may be assembled into a finite element model. The transfer function element may be used to model acutator, sensor, or control dynamics in the control subsystem and in an engine/drive train model. The *mechanical applied loads* element converts fixed external loads to nodal loads in the finite element model. The loads can be discrete or distributed. This element is typically used to represent external forces such as the tail rotor force in a simplified rotorcraft model. The *direct matrix input* element allows the user to input mass, stiffness, and damping matrices and force vectors from other codes such as NASTRAN directly into 2GCHAS.

To describe a subsystem of the structural model the user defines the subsystem frame motion, the nodes that bear the subsystem degrees of freedom, the element connectivities, the properties of the materials in the elements, and the constraints. Frames are used to impart prescribed, rigid body motion to structural components, and are essential for modeling inertial effects that result from rotor spin. The prescribed frames used in 2GCHAS are the *Inertial* frame, the *Global* frame, which moves with the steady-state motion of the fuselage, and the *Rotor* frame, which is attached to the global frame and moves with the steady-state spin of the rotor.

Constraints model the coupling of the elements and rotorcraft components, and special constraints are available to represent the unique attributes of rotorcraft. Constraints between subsystems include the rotating-nonrotating constraints, a control subsystem-to-rotor constraint, and an engine/drive train-to-rotor constraint.

Aerodynamic Model

Modeling aerodynamics in 2GCHAS involves specifying the aerodynamic model and the airloads, inflow, and interference models. The aerodynamic model can consist of lifting (wings, rotor blades, auxiliary rotors) and nonlifting (aerobodies) entities. Like the structural model, the aerodynamic model is arranged hierarchically as shown in Fig. 2. The top level is the full aerodynamic model, which is subdivided into *supercomponents*. A supercomponent may be a wing, rotor, or aerobody. A supercomponent is further divided into *components*, which may be lifting surfaces, or bodies. An aerobody supercomponent cannot contain lifting surface components; i.e., components that generate vortex flows. Examples of components are the left and right portions of an airplane wing, and the individual blades of a rotor. Components are subdivided into *aerosegments*, which are the basic elements that generate aerodynamic forces from the air flow. The System computes aerodynamic forces at discrete points on the aerosegments called *Aerodynamic Computation Points* (ACPs), which are at the lowest level of the model. Linkage between the structural and aerodynamic models is accomplished by the user specifying the correspondence between aerodynamic components and structural primitives, and the locations of ACPs relative to the structural elements.

Airloads. -- Airloads for lifting surfaces, such as rotor blades, wings and bodies, are computed using a two-step process. Basic airloads are based on a two-dimensional, steady model and are obtained from user-supplied tables that relate airloads to angle-of-attack for specified Mach numbers. Basic airloads are corrected for radial flow, unsteady flow, and tip loss.

A dynamic stall unsteady aerodynamic model is based on a model by Leishman. The model uses an indicial response function that consists of a noncirculatory part obtained from piston theory, and a circulatory part which is a semi-analytical, exponential decay function similar to the Wagner function. To account for dynamic stall, the indicial response function is extended into the stall regime by introduction of empirical parameters. Simple, quadratic functions for lift, moment, and drag versus angle-of-attack are provided for lifting bodies that do not generate vortex wakes. A model of linear unsteady aerodynamic coefficients is provided to account for the effect of unsteady flow on linear aerodynamic coefficients.

For simple wing, body, and tail surfaces, a linear aerodynamic coefficient model provides an alternative to conventional table look-up. The linear aerodynamic coefficients may be input using either a simple airloads model or a linear unsteady aerodynamic coefficients. The simple airloads model uses elementary analytical equations for the section aerodynamic characteristics. This simple model is also valid in the reverse flow region.

Inflow. – Inflow may be modeled using momentum theory, a generalized dynamic wake, a vortex wake, or a free wake (Fig. 3). Momentum theory inflow is based on classical actuator disk theory assuming uniform inflow over the rotor disk. The generalized dynamic wake is the Peters-He finite state dynamic inflow model (Ref. 16).

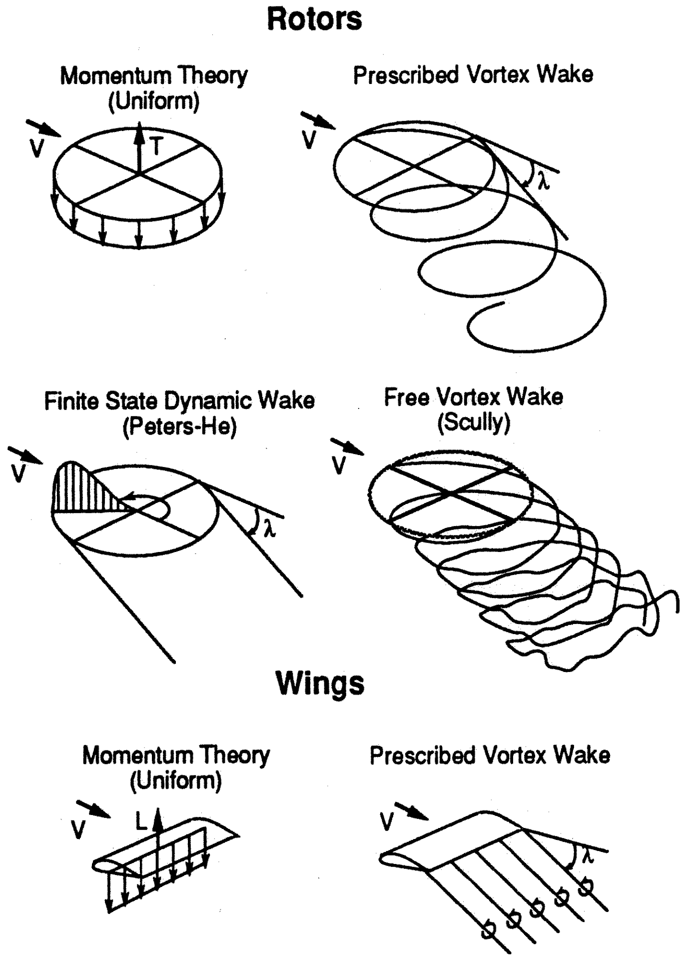

Fig. 3 2GCHAS inflow models.

There are two prescribed vortex wake models implemented in 2GCHAS: a prescribed vortex wake and an alternate prescribed vortex wake. The prescribed vortex wake uses so-called classical wake geometry. The vortex wake model assumes that 2GCHAS is in a constant time step interval, and that tip speed and flight speed are constant. The wake is defined by a finite number of straight trailing filaments that are functions of the lifting line positions, the blade azimuth, the wake age, and the transport velocity based on momentum velocity. The alternate prescribed vortex wake model uses semi-empirical envelope functions to distort the axial coordinate of the tip vortex, while the inboard wake retains its classical geometry. A maneuver wake model is also being implemented in which the wake is dropped off in space behind the rotor blade path and the trailing vortices move with induced velocity based on momentum theory and prescribed wind gusts.

The free wake is based on the Scully model (Ref. 17) for calculating the free-wake geometry of a single rotor in steady state flight in the absence of ground effect. The model for the free wake calculation consists of line segments for the tip vortices and rectangular sheets or line segments for the inboard shed and trailed wake vortices.

The wake model for nonrotating wing surfaces is assumed to be a subset of the rotor wake, and is modeled analogous to the maneuver wake.

Interference. – The six types of interference models in 2GCHAS (Fig. 4) are simple rotor-to-rotor, blockage/ground effect, body (source/sink), simple horseshoe vortex, cylindrical vortex sheet, and discrete vortex wake (prescribed, free). Simple rotor-to-rotor interference can be used when a rotor is in the wake of another rotor. Blockage/ground effect is used when the vehicle is close to the ground or wall. Simple body interference is used for the wake generated by a body supercomponent. The aerodynamic body is represented by a set of six sources and sinks placed symmetrically about the three axes of the body. A simple horseshoe vortex is used for the wake generated by a rotor or a wing supercomponent. The horseshoe is formed by the bound vortex line perpendicular to the flow and the two trailing vortices originating from the ends of the bound vortex line extending to infinity parallel to the flow. Cylindrical vortex sheet interference can be used for the wake generated by a rotor. The interference of this model is calculated form a continuous cylindrical vortex sheet generated by an equivalent rotor with an infinite number of blades and constant vorticity along the radius and azimuth. A discrete vortex wake can be used for the wake generated by a rotor or a wing supercomponent when the interfering rotor or wing is modeled by a vortex wake. The interference of this model is calculated from a discrete vortex wake model by summing the induced velocity of all the vortex sheets or segment lines.

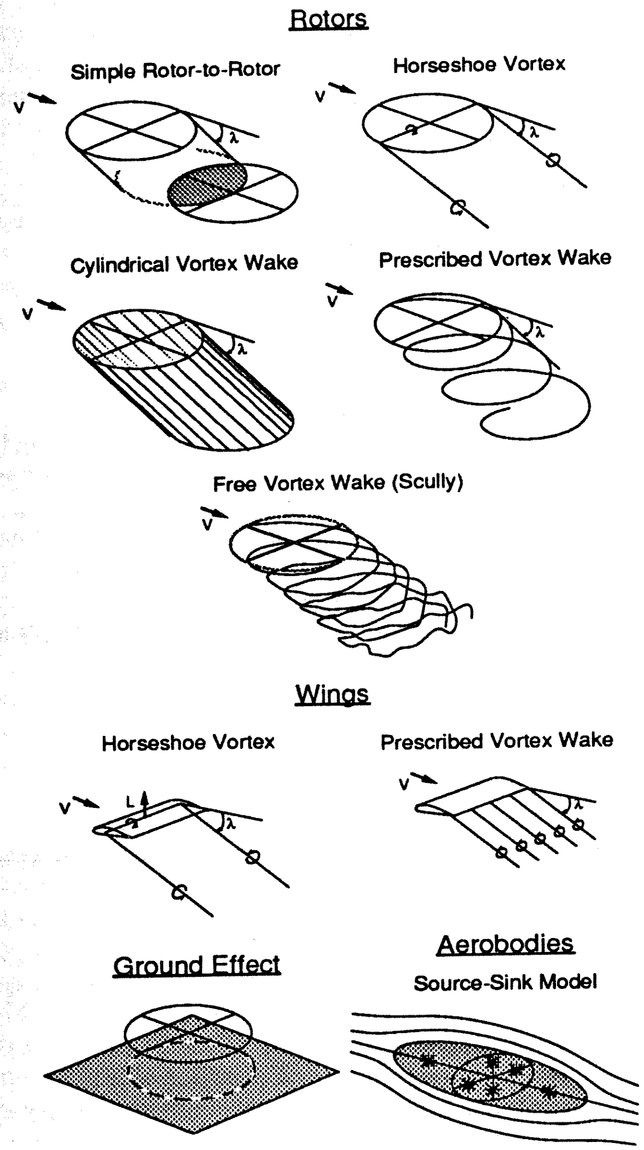

Fig. 4 2GCHAS interference models.

Analysis Options

Analysis options determine the analysis that the system performs and how the results are postprocessed and presented. The analysis and postprocessing options available to the user are summarized in Fig. 5.

The basic analyses available to the user comprise comprehensive rotorcraft analysis; i.e., trim, stability, nonlinear transient response, and linearized response. The trim options include free flight and wind tunnel trim. In free flight, the options include straight and level flight (hover, forward, rearward or sideward flight). The wind tunnel conditions assume the shaft angles are fixed. There are several wind tunnel options to determine the pilot controls δ_0, δ_c, and δ_s for given thrust, side, and drag forces, and cyclic flap angles. Both the free flight and wind tunnel trim conditions can be applied to either a rotor or a complete aircraft model.

An initial trim estimate analysis (ITE) is available in 2GCHAS to provide a good initial estimate of the trim variables for free flight and wind tunnel trim analyses. In the initial trim estimate analysis the rotor blade is modeled as a rigid flapping blade (articulated and hingeless) with a hinge and flapping spring. Simple 2-D quasi-steady strip theory is used for aerodynamics with blade root cutout, tip loss, and compressibility effects included. The wake modeling includes uniform and linear inflow models.

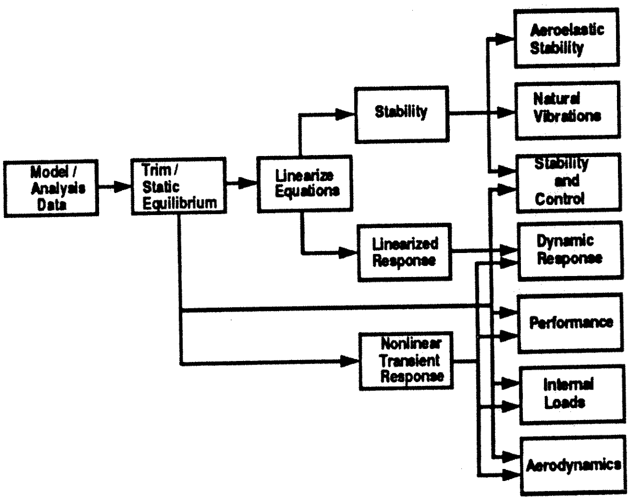

Fig. 5 2GCHAS analysis options.

The trim analyses are currently done in the time domain, and the determination of the trim state is a two step process. First, a given set of trim input controls is assumed, and a periodic solution is determined by direct integration using the Newmark-Beta method coupled with Hilber-Hughes-Taylor; i.e., the equations of motion are integrated until the transients die out and a periodic steady state is reached. If the periodic solution is not an equilibrium solution for the model, a sensitivity matrix is generated that relates changes in the applied forces to the trim controls, and new values of trim controls are obtained using the Newton-Raphson method. The iteration process stops when equilibrium is achieved to within a specified tolerance.

A static equilbium solution (*in vacuo* trim) option is also available. This approximate solution to the system dynamic equations assumes that velocity and acceleration are zero and that there is no aerodynamics. Mechanical loads, however, are allowed.

The nonlinear transient response analysis is generally used for vehicle maneuvers. Typically, the maneuver analysis calculates response to specified pilot control inputs for the full (generally nonlinear) physical model starting from a trim state. Transient response is computed using the Newmark-Beta method, which can be made unconditionally stable (i.e., stable for all integration step sizes) for linear systems. In general, the method is only conditionally stable for nonlinear systems, but experience has shown that the method generally remains stable for time steps that are of practical interest.

Linear systems analysis is undertaken in two parts: first, the equations must be linearized numerically about some trim state, and then the linearized equations are processed either with an eigenanalysis (stability) or a transient response analysis. The linearization is done numerically, and may be followed with model order reduction involving state space reduction or Guyan reduction. The equations may be left in periodic coefficient form, or the states in the rotating system may be transformed to the fixed system using the multiblade coordinate transformation. If the equations are in constant coefficient form, an eigenanalysis may be applied directly, but if the equations are periodic, the eigenanalysis must follow generation of the Floquet transition matrix. Linearized response analysis (transient) may be carried out using the linearized system equations.

The postprocessor serves two functions. It directly prints or plots computed results, but it also postprocesses these results so that they may be presented in forms that meet the special needs of rotorcraft engineers. The basic output categories are listed in Fig. 5. Outputs for the stability functions (aeroelastic stability and stability and control) include tabular reports of eigenvalues and eigenvectors, vector plots, and root locus plots. Natural vibration outputs include tabular reports of dominant degrees of freedom, eigenvalues, eigenvectors, and plots of dominant degree-of-freedom mode shapes. Performance outputs include reports and plots of loads and load harmonics, and tabular reports of trimmed state parameters and aerodynamic performance parameters. The internal loads outputs consist of reports and plots of time histories of element nodal reactions and element force response. The aerodynamics outputs includes reports and plots time histories of aerodynamic forces and moments at ACPs, induced velocities at ACPs, bound circulations, aerosegment loads, and Mach numbers. Dynamic response outputs include maneuver response and linearized transient response for the case of unsteady response, and includes plots of time histories of modal and nodal degrees of freedom. Steady-state response outputs also include reports of harmonic response (Cartesian and polar forms) and histogram plots of harmonics.

User Interface

2GCHAS was designed for ease of use. The 2GCHAS user interface is fully interactive and menu driven. The user interacts with the system using *menus* and *screens*. The menus guide the user through a selection of analyses and data input on *screens*. Menus are hierarchical and menu selections can bring up other menus, screens for data entry, or tutor sessions to provide process parameters. Menu options include *global operations* such as printing data, saving and restoring portions of input data, or supplying actual input data. Screens display data with legends and titles. Each data input screen has on-line HELP screens with information about the type of data needed, its form, and how the data is used in the 2GCHAS solution algorithm. The user is not restricted to input the data in a specified order as long as the input data set is complete. Data is validated and checked for consistency. Defaults are provided for many values and parameters. Although the user interface is interactive, the order for entry of input data is arbitrary.

The Run Data Base (RDB) allows the user options to save data runs and to save/restart analyses. An alternate data input mode is also available using *script files*. Script files, which are generated by the System for existing input data, enable the user to easily edit the input data files to create a new version of the input to run a similar problem. The optional script files are text files which can be modified with any text editor. Input files for the 2GCHAS

In a typical problem set up, the structural model is defined by selecting the menus and screens to identify a rotor subsystem and a fuselage subsystem and to define their orientation relative to a global frame. Then the components (primitive structures) such as the blades and the hub are defined for one of these subsystems. Each primitive is then defined in detail. For a blade, for example, the orientation, beam element type, node location, connectivity constraints and material properties are defined. The systematic ordering of the menus and screens is designed to automatically lead the user down through each level. The aerodynamic model is then defined similarly. An aerodynamic supercomponent is identified and its components defined. For example, the orientation, aerodynamic node location, and aerodynamic section definition are defined for the aerodynamic component of each blade. The analytical attributes of the supercomponent such as the inflow and vortex wake models are then defined.

Next, the analysis data can be defined by first selecting the type of analysis desired and then accessing a set of related input screens to define the input necessary for the analysis. Finally, the user specifies the kind of 2GCHAS output desired, e.g., plots and reports of the steady state response at specified nodes on a blade, or of the segment airloads at specified aerodynamic computation points on a blade.

Size of System

The over 2000 units of the System contain over 220,000 lines of source code. The majority of the source code, including all of the technology code is FORTRAN 77. The remaining code consists of C source code, 2GCHAS User Language code, assembly language code, and VMS DCL procedures. Over 400 auxiliary units, with almost 50,000 lines, contain menus, screens, and help information. The source code and auxiliary units are supplemented by almost 170,000 comment lines.

On computers with the VMS operating system, a minimal installation of 2GCHAS requires about 90 Mb of storage, for executables, source code, auxiliary files, and working space. A complete installation, which includes test files, and documentation, requires an additional 50 Mb.

Portability

2GCHAS is currently operational on a VAX with the VMS 5.5 operating system, on a SUN SPARCstation with OS 4.1.3 or Solaris 2.2, and on a HP 9000 workstation with OS 9.0.1 Additional future ports to other UNIX workstations such as DEC, SGI, and IBM are anticipated. 2GCHAS was designed with features to enhance its portability. Platform independence means that 2GCHAS will look the same way, will accept the same commands, and will operate the same way whether the host is a VAX, a SUN, or any other platform. The user will be able to move between different 2GCHAS implementations with a minimum of "dead time".

Standard languages are used throughout. FORTRAN 77 is used primarily for the technology code while the Executive is primarily written in the C language. "Standards checking" processes were in use throughout the development. Unit level software units are the same in all versions of 2GCHAS. More than 95% of 2GCHAS units are host independent. TAE, a NASA developed, portable user interface, is the core of 2GCHAS's User Interface. TAE is available for virtually all workstations, most mini-computers, and some mainframes.

System Testing Results

To aid in system testing, a comprehensive set of test problems was selected to thoroughly test the system capabilities. A sampling of test results is presented to demonstrate many of the modeling and analysis capabilities of 2GCHAS. Configurations include a single and tandem rotor helicopters, engine/drive trains, flight control systems, and a bearingless rotor helicopter

Single Rotor Helicopter Model

A substantial portion of the results will treat a single main and tail rotor helicopter. This configuration consists of an articulated rotor, flexible fuselage, tail rotor, auxiliary wings, horizontal tail, engine/drive train, and flight control system. The structural and aerodynamic models are shown in Fig. 6. The rotor subsystem consists of four identical blades (primitives) with coincident flap and lead-lag hinges (4.66% offset) and lead-lag dampers. Each blade consists of two nonlinear beam elements, one inboard and one outboard of the hinges. The bending stiffnesses of the outboard element are representative of typical elastic blades (e.g., UH-60). Property values are provided in Ref. 14. For simplicity, the torsion degrees of freedom are constrained out.

The fuselage subsystem consists of three primitives. The first primitive contains two rigid body mass elements for the fuselage and tail rotor masses, and two linear beam elements for the tail boom and rotor mast. The wing primitive comprises two linear beam elements for the left and right wings. The third primitive comprises a single linear beam element for the horizontal tail. Figure 6 also shows the springs and dampers used for the trim solution.

The engine/drive train subsystem consists of one primitive with rigid body mass elements, spring elements, a damper element, transfer function elements, and multipoint constraints. This model is illustrated in Fig. 6. The rigid body mass elements represent the transmission inertia, the engine inertia, and the tail rotor inertia. The spring elements represent drive shaft flexibility. The transmission gear ratios between the rotor, engine, and tail rotor shaft speeds are modeled by multipoint constraints. The engine torque generator transfer function elements model the engine torque response to engine throttle control and a mechanical damper element represents the engine internal aerodynamic damping. Finally, transfer function elements are used to model a simple governor feedback system. More details are given in Ref. 14.

Single Rotor Helicopter Structural Dynamics

The modal frequencies and damping of the single rotor helicopter *in vacuo* will illustrate the basic structural dynamic modeling capabilities of the System. The finite element model for this problem was described above, and has 105 degrees of freedom. Since the rotor degrees of freedom are referred to the rotating frame and the analysis is done *in vacuo*, the equilibrium solution is treated as a static equilibrium problem and analyzed by using the 2GCHAS static analysis procedure. The equations are then linearized about the equilibrium state and the multi-blade coordinate transformation is applied. The eigenanalysis solution of the resulting constant coefficient equations yields the modal frequencies, damping, and mode shapes.

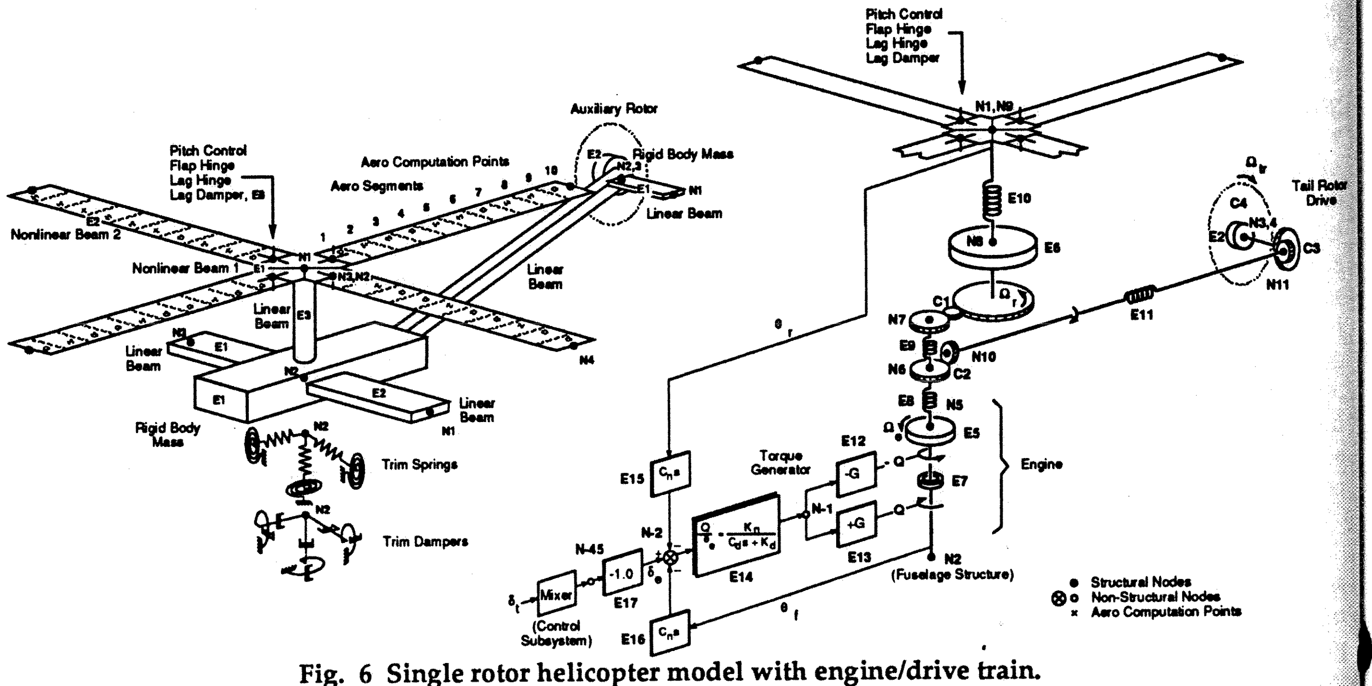

Fig. 6 Single rotor helicopter model with engine/drive train.

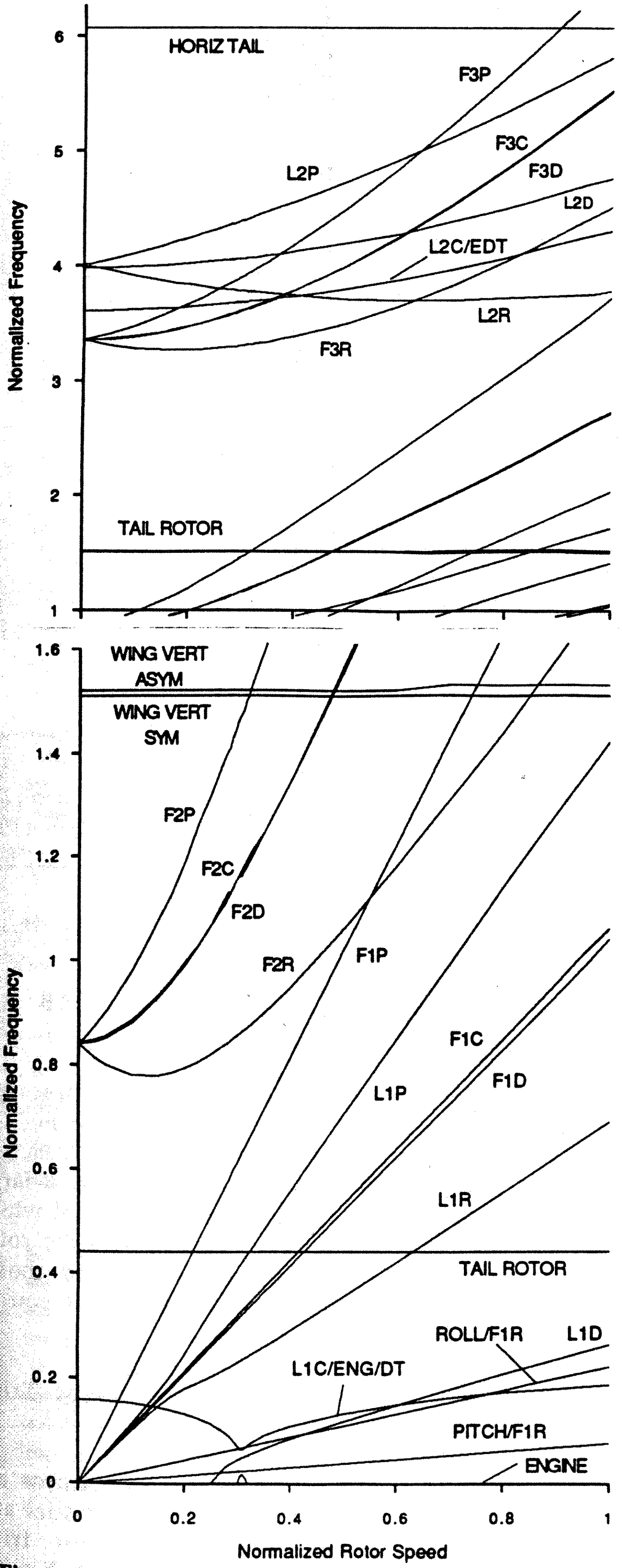

Fig. 7 Single rotor helicopter frequency fan plot *in vacuo*.

The results in Fig. 7 and 8 show frequencies *in vacuo* and damping normalized by the nominal rotor speed. The multiblade coordinates of the four-bladed rotor are denoted by L1R, L1C, L1D, and L1P, for example, for the first lag regressing, collective, differential collective, and progressive modes, respectively. The isolated blade structural dynamics are conveniently illustrated by the differential collective flap and lead-lag modes (F1D, F2D, L1D) of the four-blade rotor which do not couple with the fuselage degrees of freedom. Rigid body pitch and roll motions coupling with flap regressing, vertical motion with flap collective, and lateral translations coupling with lead-lag regressing mode. The lead-lag collective mode couples with the drive train and fuselage yaw degrees of freedom.

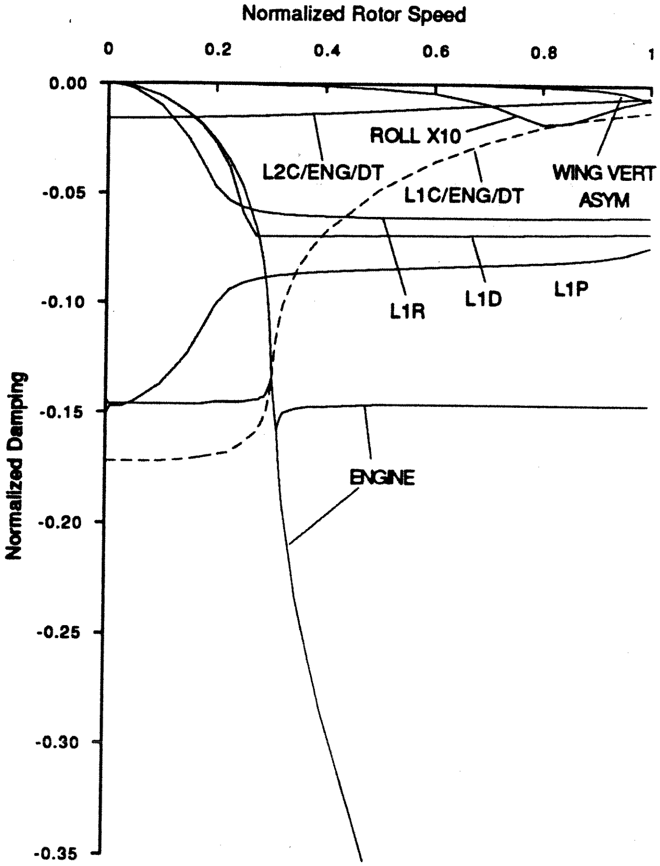

Fig. 8 Single rotor helicopter damping plot.

The elastic flap and lead-lag bending modes are only slightly coupled with the fuselage degrees of freedom. The fuselage, wing, and tail elastic modes are evident, although they are not strongly coupled with other degrees of freedom.

The drive train modes are strongly coupled with the rotor lag collective modes and the effect of the blade lead-lag dampers is significant, especially at lower rotor speeds. Other drive train modes such as the tail rotor, transmission, and engine torque generator are either lightly damped or critically damped.

The damping in Fig. 8 shows the effect of the engine damping and blade lead-lag dampers coupling with the rotor, fuselage, and engijne drive train modes. At low rotor speeds the differential collective blade lead-lag mode (L1D) becomes critically damped. The lag collective/engine/ drive train mode (L1C/Eng/DT) frequency and damping vary substantially with rotor speed.

Structural Dynamics with NASTRAN Fuselage Model

A more practical configuration illustrates the capability of 2GCHAS to couple a complex fuselage model with a finite element rotor through Direct Matrix Input (DMI). This provides a means of combining the powerful 2GCHAS rotorcraft modeling capabilities with a detailed NASTRAN model. Here, a DMI element comprising the mass, damping, and stiffness matrices for the 16 lowest frequency modes of ~5000 degrees of freedom NASTRAN UH-60 fuselage model is used as the 2GCHAS fuselage subsystem (Fig. 9). The rotor and fuselage subsystems are coupled with a rotating-nonrotating constraint to yield a complete system with 76 degrees of freedom.

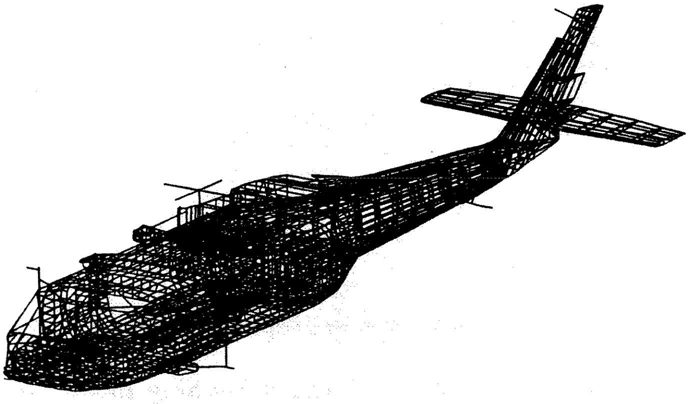

Fig. 9 UH-60 NASTRAN model.

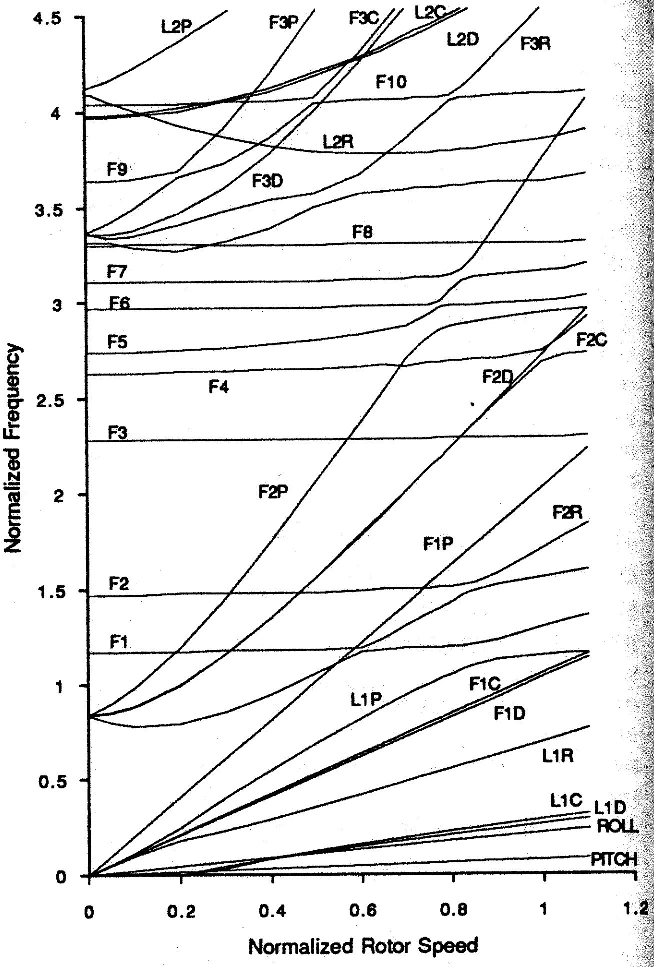

Fig. 10 UH-60 NASTRAN fuselage/2GCHAS rotor fan plot.

The equilibrium solution and eigenanalysis proceed as before to produce the results shown in Fig. 10. The fuselage modes are denoted as F1, F2, etc., in Fig. 10. The NASTRAN model produces a large number of flexible fuselage modes, some of which are more or less strongly coupled with the rotor blade flap and lead-lag modes. As noted above, the differential collective modes do not couple with the fuselage modes.

Single Rotor Helicopter -- Free Flight Trim, Performance, Loads, and Vibration

A range of aerodynamic modeling features are applied to the single rotor helicopter model and used to generate typical results for trim, performance, loads, and vibrations of a helicopter in trimmed free flight. The aerodynamic model for the single rotor helicopter consists of five super-

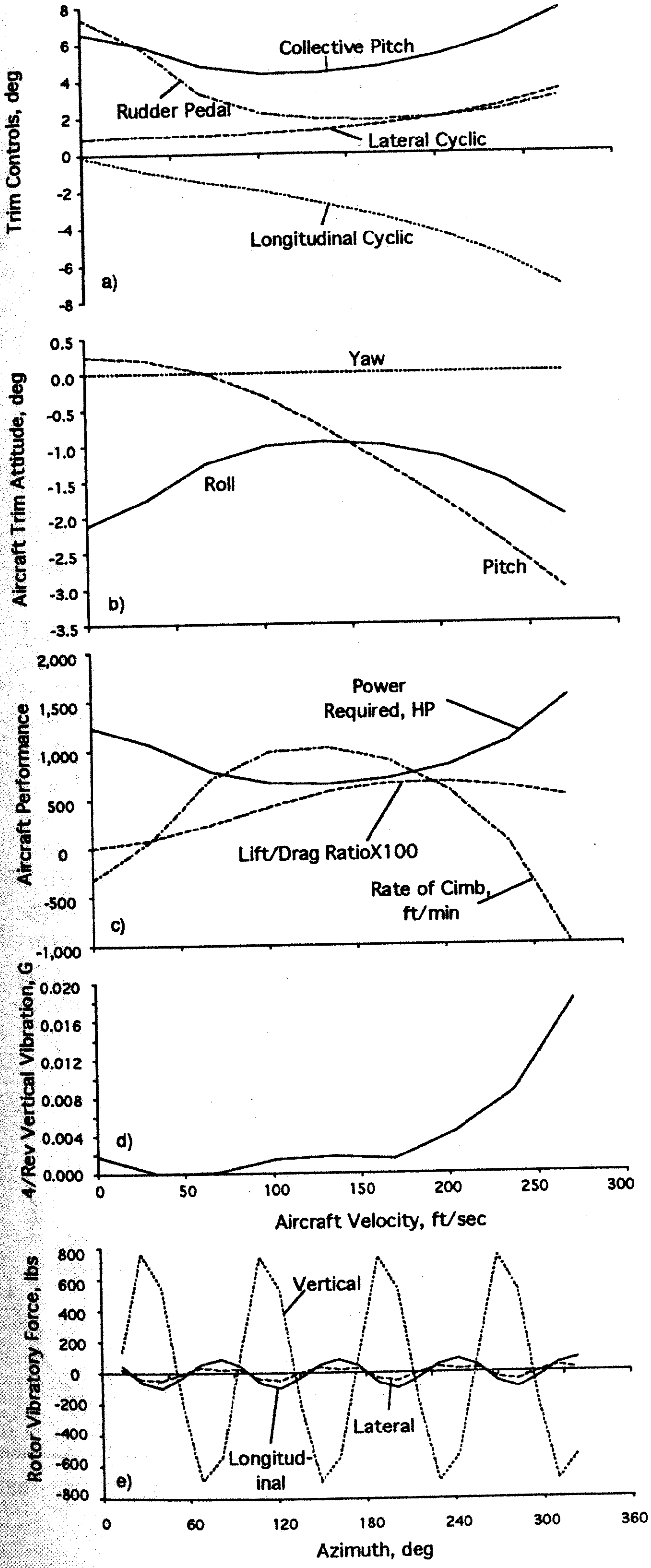

Fig. 11 Single rotor helicopter coupled rotor/body free flight trim.

A range of aerodynamic modeling features are applied to the single rotor helicopter model and used to generate typical results for trim, performance, loads, and vibrations of a helicopter in trimmed free flight. The aerodynamic model for the single rotor helicopter consists of five supercomponents: rotor, wing, horizontal tail, tail rotor, and fuselage. The rotor supercomponent consists of four components, one for each blade; the other supercomponents each consist of a single component. Each blade component consists of ten aero segments, the wing component consists of six aero segments, and the horizontal tail component consists of two segments. The tail rotor is modeled with the auxiliary rotor element and fuselage component is modeled with the simple airloads model.

For the results to be presented herein, the rotor blade airloads are based on the Leishman airload option with the rotor uniform inflow option. The principal objective is to illustrate the six-degree-of-freedom free-flight trim analysis for a complete rotor and fuselage configuration, including aerodynamic force and moment contributions from the tail rotor, horizontal tail, and wing. At the same time, the trim and dynamic response address the full dynamic coupling of the rotor-fuselage system.

Typical results are shown in Fig. 11a-c for vehicle trim controls, fuselage orientation, and vehicle performance variables over a speed range from 0 to 160 kts for the level flight condition. A trim solution with fully coupled rotor-fuselage dynamics naturally produces the internal vibratory forces at the rotor-fuselage interface and the resulting fuselage vibration. The coupled rotor-fuselage 4P vertical vibration at the fuselage center is shown in Fig. 11d. The three force components as a function of azimuth are shown in Fig. 11e and display the expected 4P harmonic content.

Rotor Blade Airloads

A more detailed look at the aerodynamic modeling capabilities and options of 2GCHAS will be presented for a rotor with fixed hub and prescribed controls at the 60 kts velocity. Here, the analysis option is the periodic solution, physically analogous to a wind-tunnel operating condition with specified control inputs for collective, lateral, and longitudinal cyclic of 10°, 2°, -7°. The rotor is the same described above for the single rotor helicopter except that the blade is stiff in bending and the lead-lag hinge and chordwise bending degrees of freedom are constrained out. Each blade contains ten aerosegments with an Aerodynamic Computation Point (ACP) located in the midpoint of each aerosegment. In the case of the vortex wake and Peters-He generalized dynamic wake analyses, only five segments are used to economize computation time. The results show the azimuthal variation of blade section airloads at the 75.5% radius locations, first comparing the effects of various airload options (Fig. 12) with uniform inflow and then comparing the effects of various inflow options (Fig. 13).

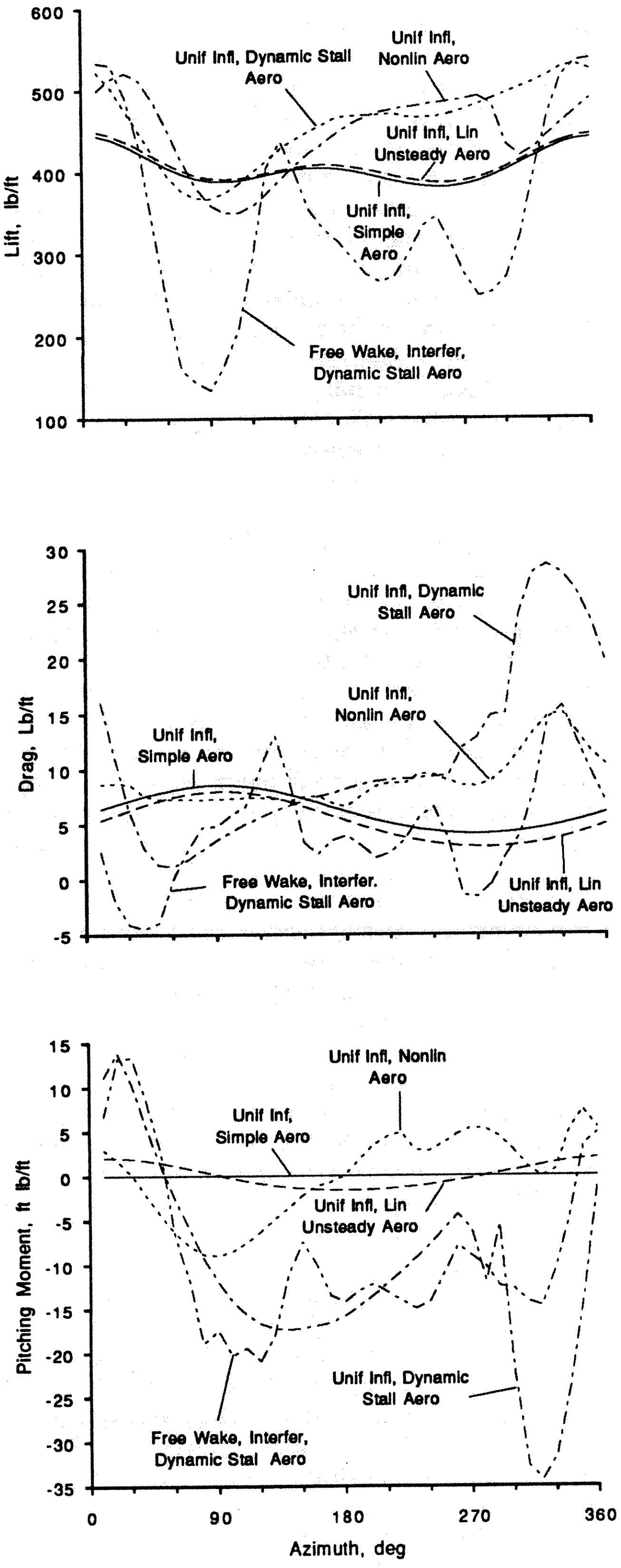

Fig. 12 Single rotor helicopter rotor blade airloads, effect of airfoil airload options.

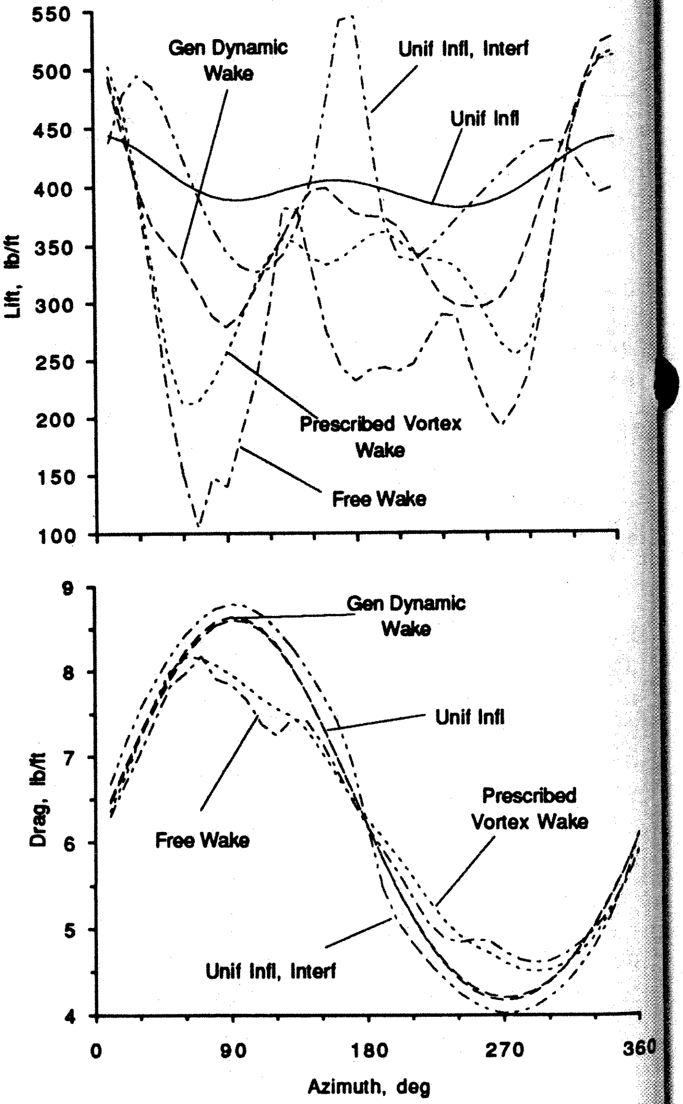

Fig. 13 Single rotor helicopter rotor blade airloads, effect of inflow options.

Figure 12 shows lift, drag, and pitching moment airloads respectively, using the simple airloads model ($c_l = 6.28\alpha$, $c_d = 0.01$, $c_m = 0$; see Ref. 14 for reverse flow region), linear unsteady airloads model (Theodorsen theory c(k)=1.0), nonlinear airloads model (SC-1095 airfoil table lookup but no unsteady aerodynamics), and the nonlinear unsteady airloads model (SC-1095 airfoil table lookup plus Leishman-Beddoes dynamic stall). For ACPs in the reverse flow region, the nonlinear airloads model is used. Each of these four airloads models is used with uniform inflow to more clearly compare the airloads models. To compare a full-up blade airloads and inflow calculation with these similar models, a fifth set of results is also included in Fig. 12 that uses the nonlinear unsteady airloads model in conjunction with a full free wake inflow model plus the fuselage source-sink interference flowfield.

Figure 13 shows blade lift and drag airloads, respectively, using the five different inflow options. In each case, the simple airfoil section airloads option is used. The uniform inflow model is the baseline. Next is uniform inflow with the fuselage source-sink flowfield model, the Peters-He generalized dynamic wake, the alternate prescribed vortex wake, and the free wake. To directly observe the effects of the various inflow options, Figure 14 shows the vertical component of rotor inflow versus azimuth at 0.75.5% radius for the five inflows. And for completeness, the tip vortex trajectory of the free wake model is shown in Fig. 15.

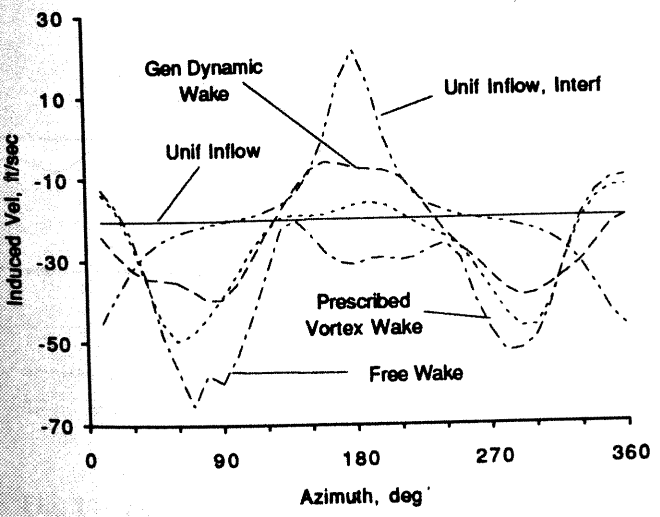

Fig. 14 Single rotor helicopter inflow for five interference options.

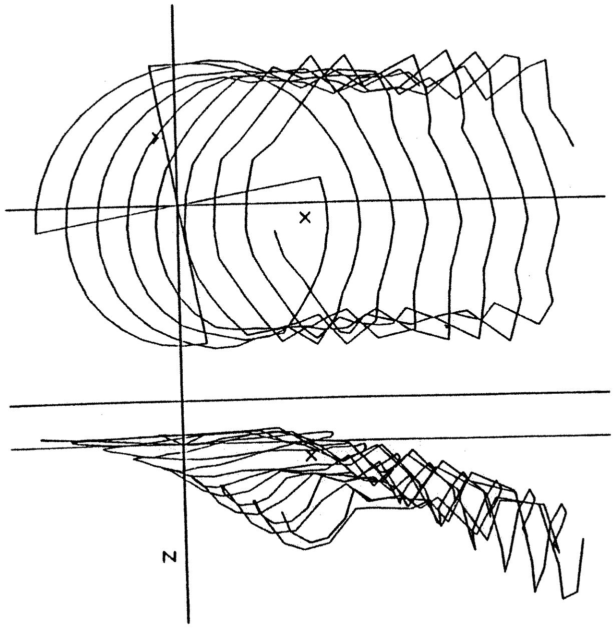

Fig. 15 Free wake vortex trajectory.

Single Rotor Helicopter Flight Dynamics with Control System Feedback

Modern digital hi-bandwidth flight control systems have the capability to strongly couple with the high frequency dynamic characteristics of the rotor system. 2GCHAS provides the capability to study such problems. In the present example, the Linearized Transient Response analysis option is used to illustrate the control response and feedback control modeling capabilities of 2GCHAS for the single rotor helicopter. The feedback flight control system model shown in Fig. 16 consists of transfer function elements and multi-point constraints. Altitude (vertical velocity) and roll rate are fed back to collective and lateral control inputs via feedback channel transfer function elements chosen to improve the stability of the rigid body motion. The problem contains 109 degrees of freedom.

The analysis begins with a six-degree-of-freedom free flight (ITE) trim solution before the equations are linearized and reduced to a system of constant coefficient equations. These equations are then integrated in the time domain to produce the dynamic response to specified pilot control inputs.

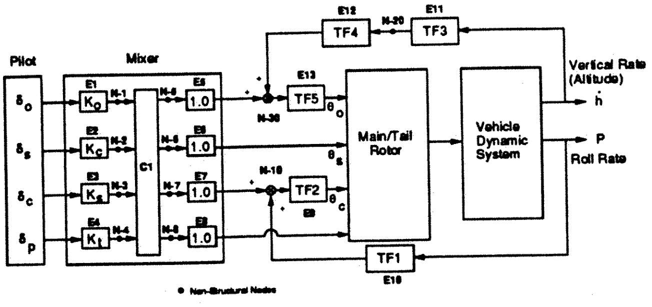

Fig. 16 Single rotor helicopter flight control system.

Before the dynamic response is presented, a locus of roots plot as a function of control system roll rate feedback gain from eigenanalysis of the constant coefficient equations is shown in Fig. 17. Of interest is the reduction in the roll mode damping and the coupling of the rotor lead-lag regressing mode with the flight control system. For the highest gain, K=0.2, the lead-lag stability begins to decrease. Except for the high lead-lag damping, this mode could be driven unstable.

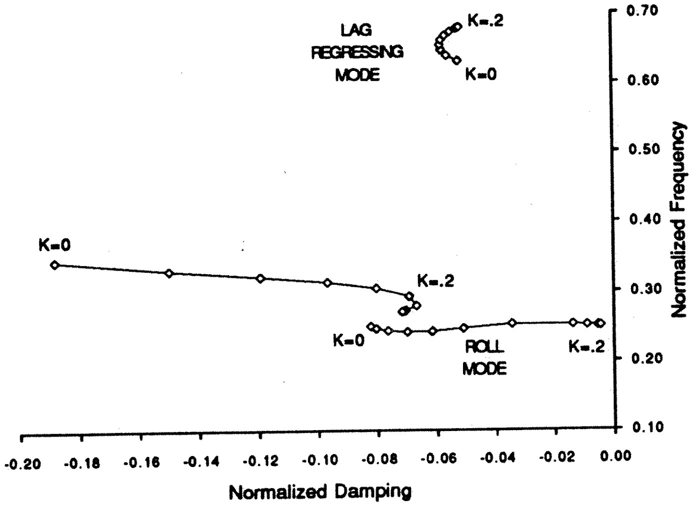

Fig. 17 Single rotor helicopter locus of roots versus roll rate feedback.

Selected transient responses to a collective doublet input at 100 kts are shown in Fig. 18 both with and without feedback control. Fuselage vertical, roll, and pitch response, as well as rotor blade flap and lead-lag angle responses are shown. The effects of the control feedback were chosen to stabilize the transient responses.

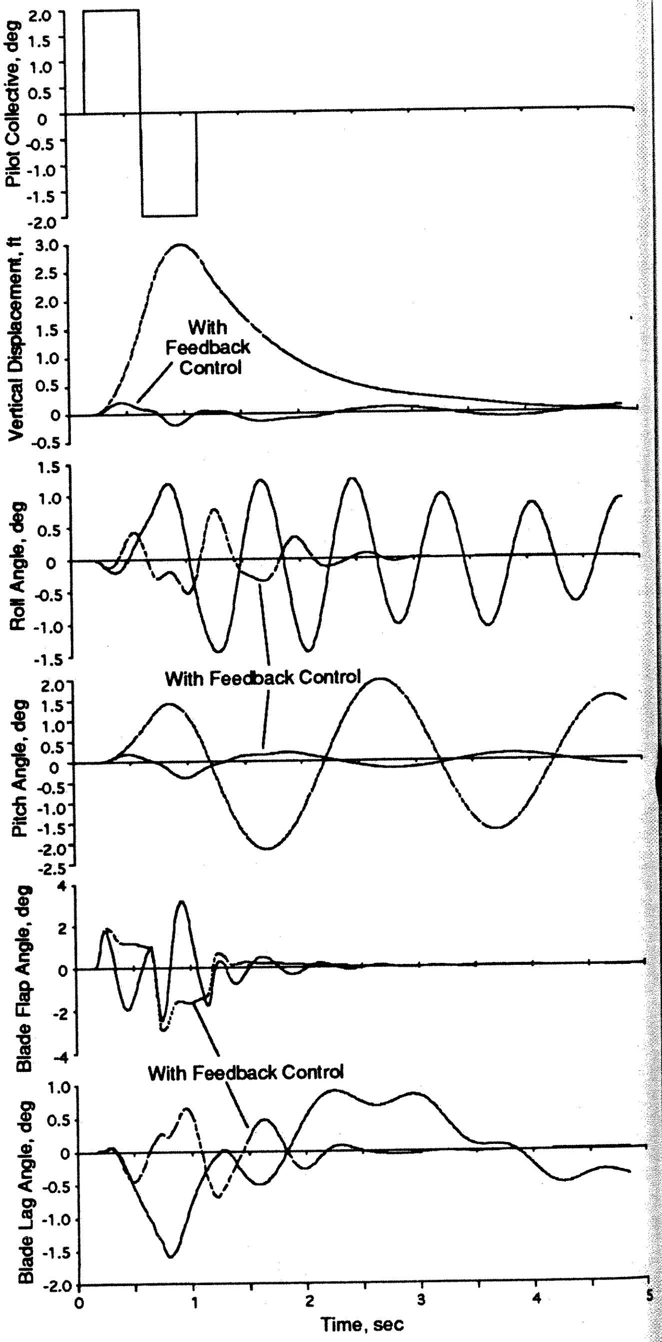

Fig. 18 Single rotor helicopter flight dynamic response with and without feedback control

Single Rotor Helicopter Engine/Drive Train Dynamics

Coupling between rotor, fuselage, engine/drive train dynamics, and engine or vehicle flight controls can lead to serious stability, loads, maneuverability, or handling quality problems in modern rotorcraft. 2GCHAS provides the capability to address these problems by combining the varied components of the rotorcraft in a single unified math model. The following results are intended to demonstrate some of these capabilities.

The effects of engine/drive train dynamics on the single rotor helicopter transient response, with and without engine feedback control, are shown in the next figures. The basic dynamics of the coupled vehicle and engine/drive train were presented in the fan plots of Fig. 7. The effects of engine feedback control are illustrated by the locus of roots plot presented in Fig. 19. The rotor blade collective lag/engine drive train mode is stabilized by the lower values of rotor speed-to-throttle feedback. Coupling between the engine/drive train destabilizes the fuselage roll mode at high gain. (The damping of both these modes is increased by a factor of 10 to make them more visible in the root locus plot.) The critically damped engine rigid body mode is stabilized with feedback.

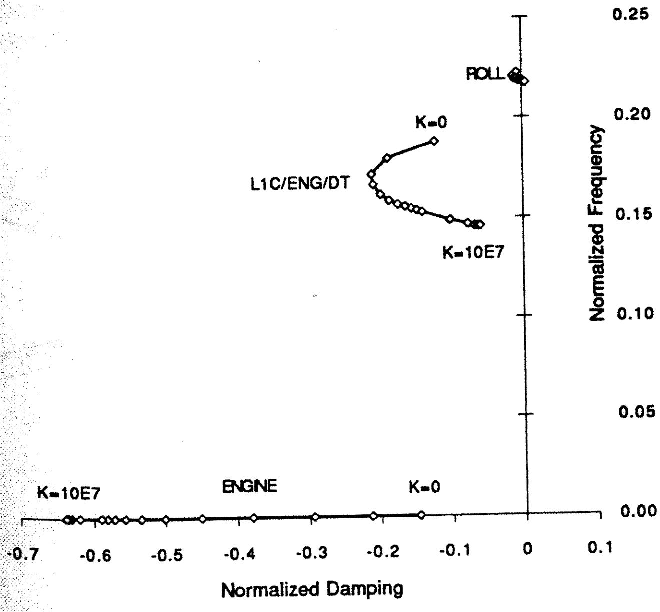

Fig. 19 Vehicle and engine/drive train system root locus with rotor speed feedback to engine throttle.

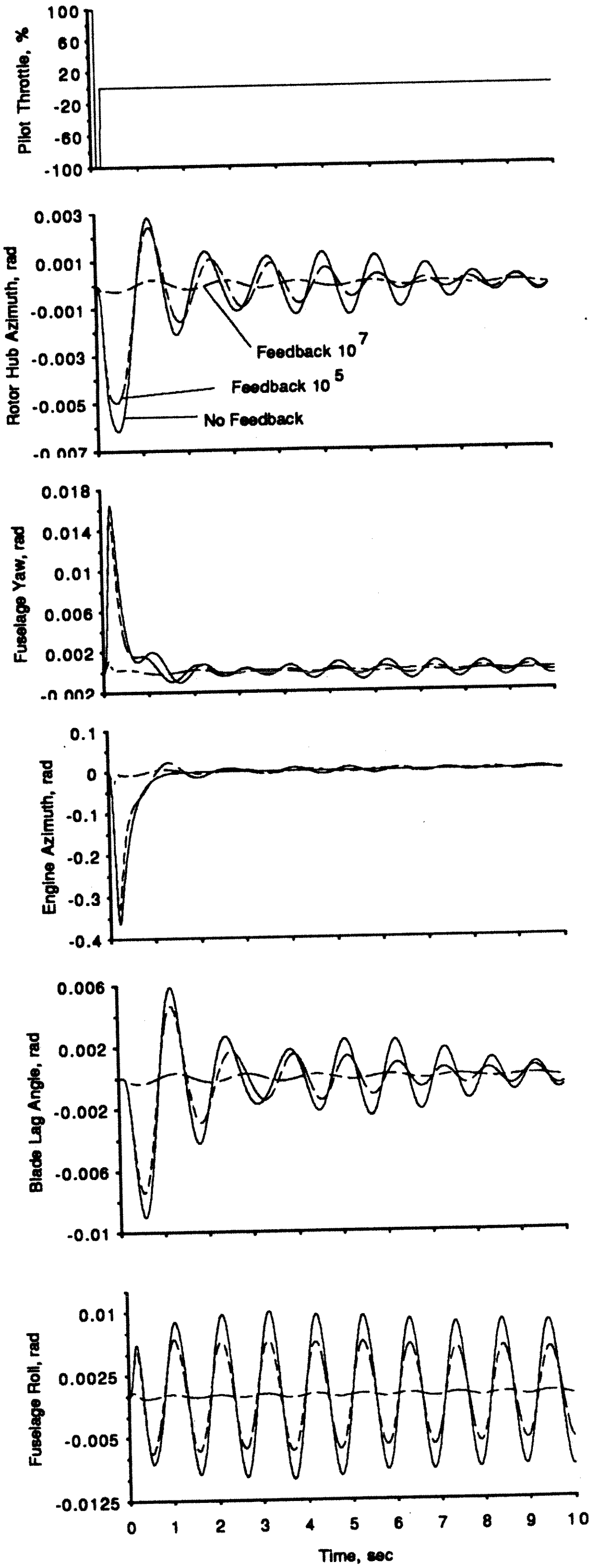

Fig. 20 Single rotor helicopter/engine/drive train dynamic response with and without feedback control.

The dynamic response of the system to a pilot throttle doublet in the hover flight (in vacuum) condition is shown in Fig. 19. Included are the rotor hub azimuth response, the engine speed response, the blade collective lead-lag angle response, and the fuselage yaw and roll responses. These results illustrate the complexity and highly coupled nature of the vehicle drive train dynamics. The effects of engine torque feedback control from rotor hub speed degree of freedom are shown to be stabilizing, although the transient responses and the locus of root results show that not all modes are stabilized by this feedback.

Tandem Rotor Helicopter Results

Dynamic and aerodynamic coupling in helicopter analysis is complex for single rotor configurations, but for multi-rotor configurations, these complexities multiply. Comprehensive analyses with general modeling capability must be able to treat a variety of arbitrary configurations. 2GCHAS has been applied for several different multi-rotor configurations, and to briefly illustrate some of these capabilities, results for a typical tandem helicopter configuration will be presented for cases involving rotor aerodynamics and blade airloads as influenced by rotor-to-rotor and fuselage interference effects, as well as a tandem rotor flight dynamic response including rotor and engine/drive train coupling.

Tandem Rotor Helicopter Model

The tandem rotor helicopter structural, engine/drive train, and aerodynamic models are shown in Figs. 21 and 22. The structural model consists of three subsystems, two rotor subsystems and the fuselage subsystem. The first rotor subsystem is for the counter-clockwise-rotating front rotor, and the second rotor subsystem is for the clockwise-rotating rear rotor. Both rotors have four articulated blades, identical to the single rotor helicopter configuration. The fuselage subsystem is composed of a single primitive structure representing both airframe and engine/drive train. The rotor and fuselage subsystems are joined by two rotating-nonrotating constraints at the hubs and drivetrain-rotor coupling constraints. The fuselage is composed of five elements: a rigid body and two horizontal linear beam elements representing the main fuselage, and two vertical linear beam elements representing rotor masts.

Similar to the single rotor model, the tandem engine/drive train (Fig. 22) is composed of a rigid body mass element representing engine inertia, located at the center of fuselage, and a spring element representing main drivetrain compliance, connected to the main shaft in a horizontal direction via a 50:1 reduction gear box. At the end of each spring element another spring element is connected vertically through a gear box and it reaches the rotor. Two rigid body mass elements

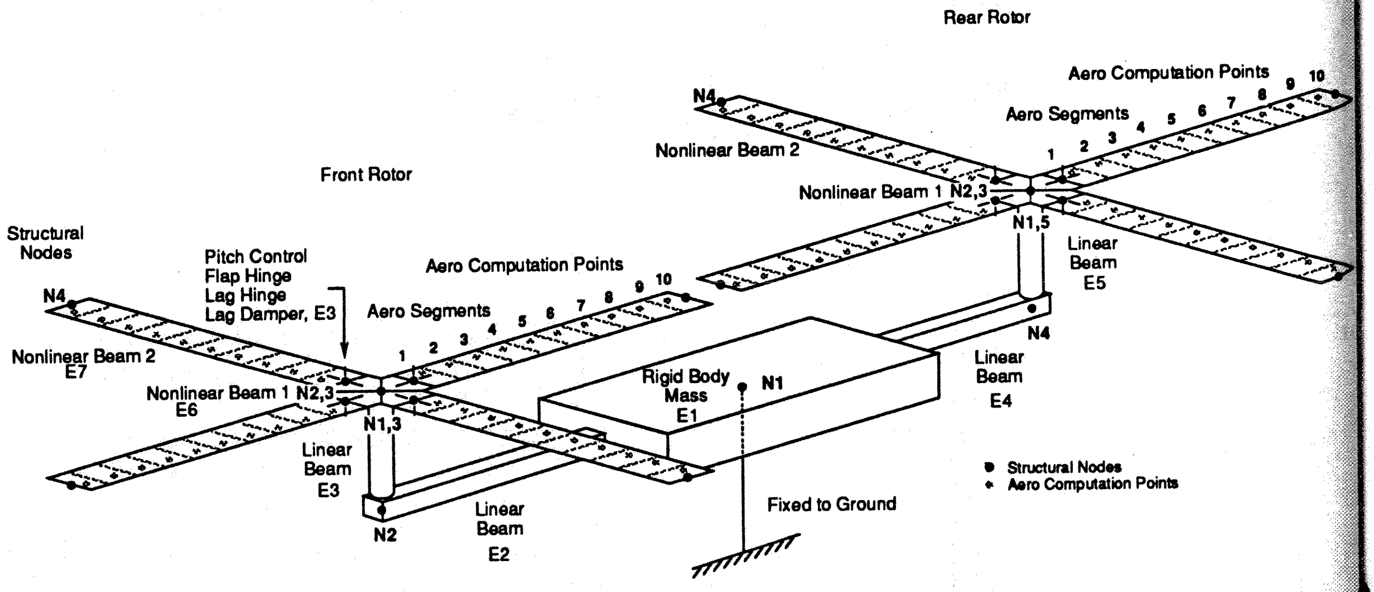

Fig. 21 Tandem rotor helicopter model.

are used to represent transmission rotational inertias. Multi-point constraints are used for gear boxes, which reduce engine speed and change the directions of rotation. A degree-of-freedom-type transfer function element is used to represent the engine torque generator dynamics, and two force-type transfer function elements are used to represent the output of engine torque generator to fuselage and engine inertia. A damper element represents internal friction from propulsion gases within the gas generator.

The aerodynamic modeling of the tandem rotor helicopter uses the simple airload option and uniform inflow for simplicity. To demonstrate aerodynamic interference effects, the interference flow field on each rotor from the other rotor is determined from the cylindrical vortex wake model. The interference from the fuselage flowfield is determined from the source-sink model.

Tandem Rotor Helicopter Rotor Forces and Blade Airloads

Figure 23 shows the rotor lift and drag forces (total aerodynamic forces acting on all blades) and blade lift versus azimuth for both the front and rear rotors at $r/R = 0.801$. The helicopter is operating untrimmed at 60 kts with specified rotor control inputs (collective, longitudinal, lateral of 7°, -2°, 0°, respectively), identical for each rotor. The effect of the fuselage and rear rotor upwash combine to increase the lift of the front rotor, while the lift of the rear rotor is reduced by the downwash from the front rotor and the rear fuselage. Furthermore, the vibratory content of both the lift and drag forces is higher for the rear rotor as a consequence of being in closer proximity to the front rotor wake than vice versa.

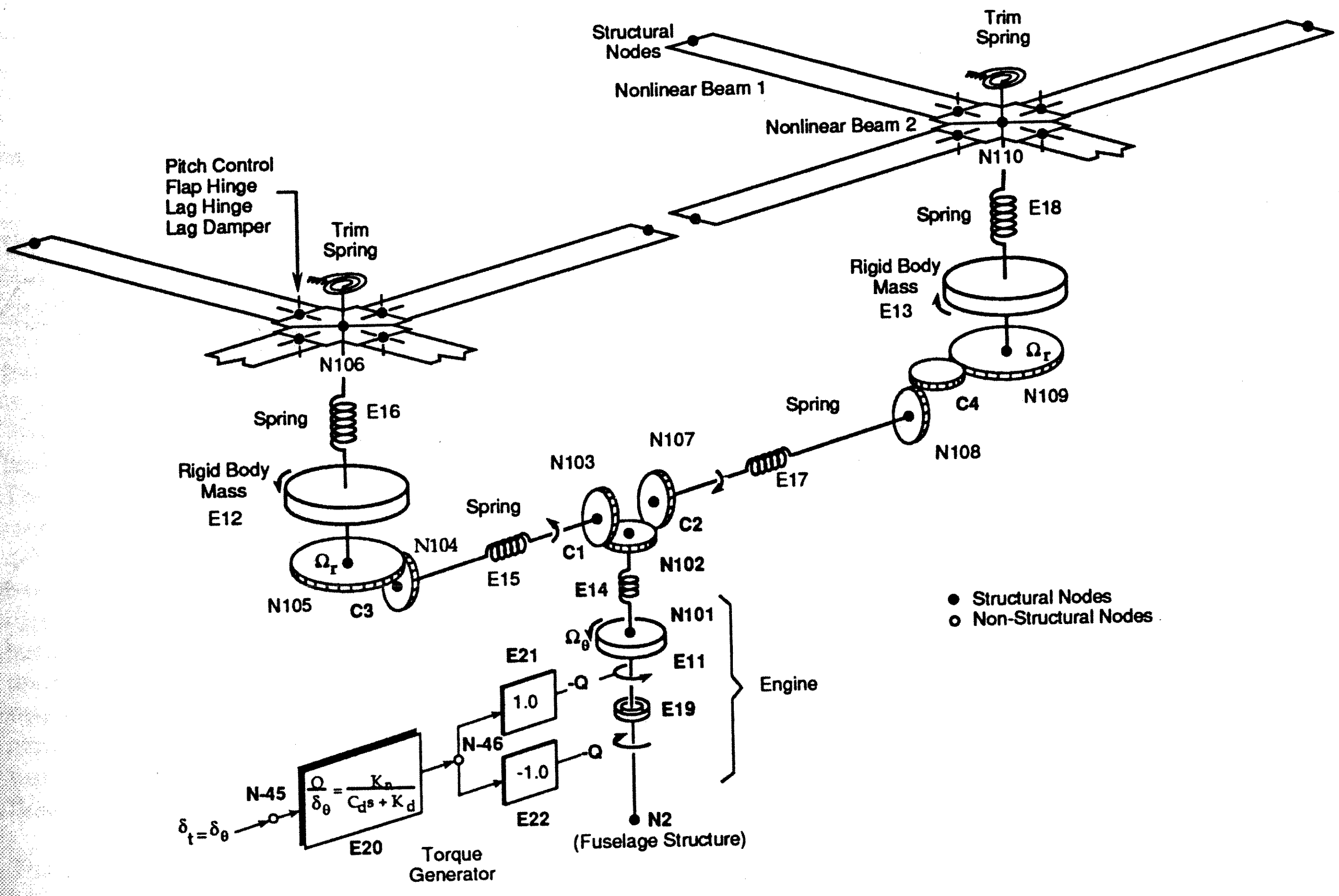

Fig. 22 Tandem rotor helicopter/drive train model.

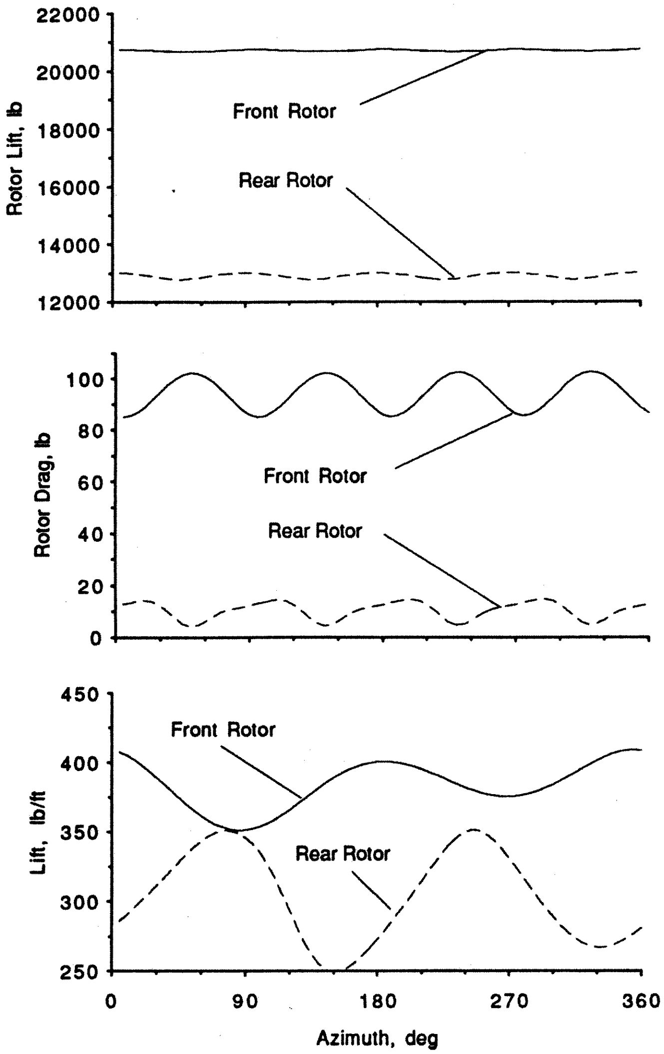

Fig. 23 **Tandem rotor helicopter airloads with fuselage and cylindrical vortex interference.**

Tandem Rotor Helicopter Flight Dynamic Response

A simple example will illustrate the effect of rotor blade, fuselage, and engine/drive train coupling on the flight dynamic response of the tandem rotor helicopter in a hover flight condition. The simple aerodynamic model will serve this purpose. A static equilibrium solution in hover at 7° collective pitch is obtained before initiating the linearized transient response analysis. A pilot collective control doublet is input and the fuselage, blade flap, blade lead lag, and the engine drive train responses are presented in Fig. 24. The results show expected responses including the higher frequency dynamics in the case where the engine/drive train model is included and rotor torque perturbations excite the engine/drive train degrees of freedom.

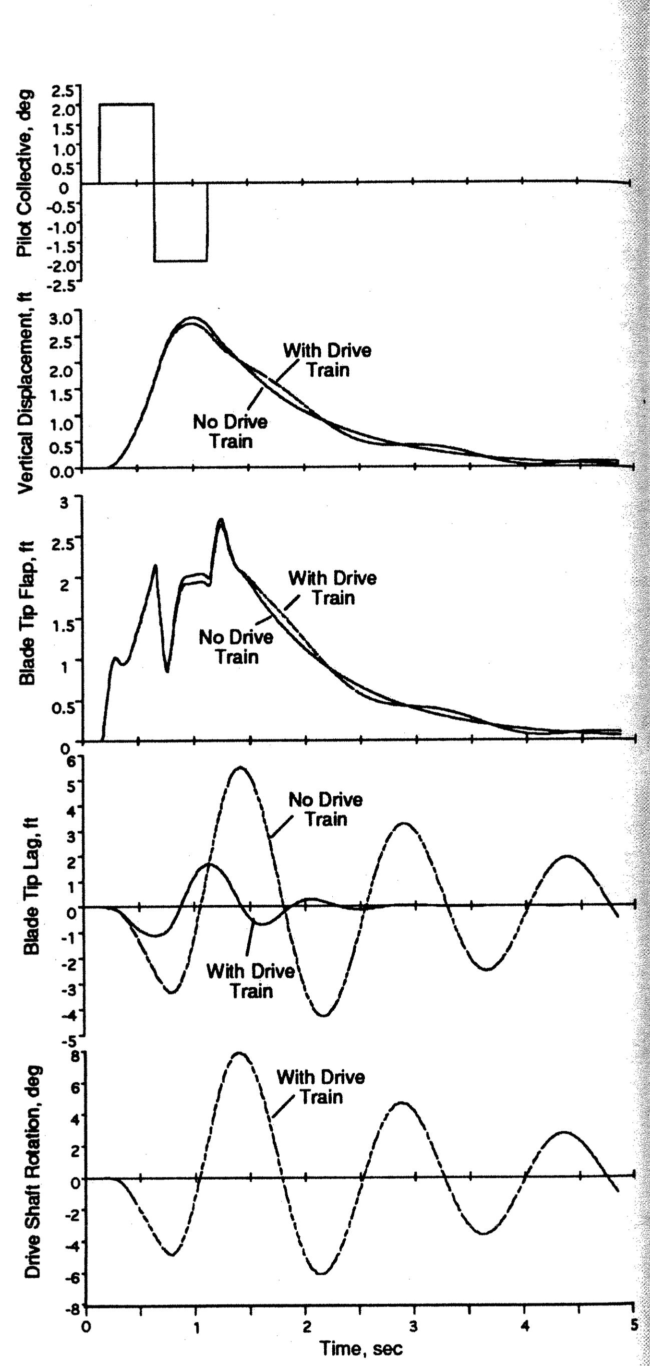

Fig. 24 **Tandem rotor helicopter flight dynamic response with and without engine/drive train.**

Bearingless Rotor Helicopter Aeromechanical Stability

Bearingless rotors, with cantilever blades, multiple load paths, with inherently nonlinear structural and aeroelastic behavior, represent a principal requirement for finite element analyses of rotorcraft aeromechanics. 2GCHAS, with its flexible modeling of arbitrarily complex rotorcraft, has been used to demonstrate this capability for a representative rotorcraft.

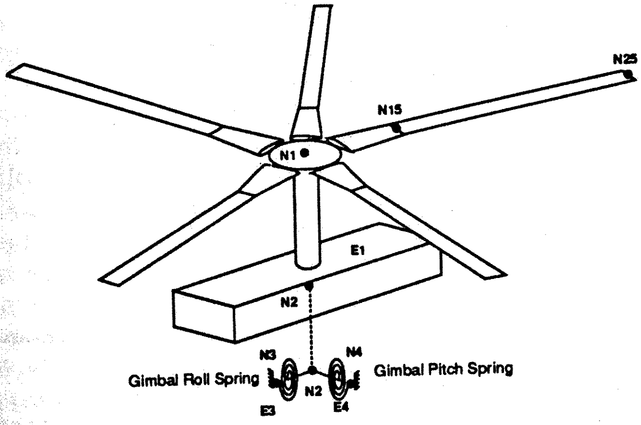

Fig. 25 Bearingless rotor helicopter model.

The bearingless rotor helicopter model has a five-bladed rotor with elastomeric dampers, with a gimbal-mounted fuselage restrained by low-stiffness pitch and roll springs to represent a model test of air resonance stability. The structural model is shown in Fig. 25. Each blade has eight elements. Two nonlinear beam elements define a flexible beam, one nonlinear beam defines the main blade. The torque tube is modeled by a nonlinear beam element. There are a translational spring and a damper between the inboard end of the torque tube and the hub (flexible beam) in the lead-lag direction. There is another translational spring between the hub and the torque tube in the vertical direction. A rotational spring represents the pitch control stiffness. The root end of each flexbeam is attached to the hub node. The outboard end of the torque tube is connected to the outboard end of the flexbeam.

The rotor is connected to the fuselage (represented by a rigid body mass element) through a mast modeled with a nonlinear beam element. The rigid body mass is constrained in the pitch degree of freedom by a torsional spring, one end of which is grounded. The rigid body mass is similarly constrained in its roll degree of freedom. The aerodynamic modeling for this problem uses the linear unsteady aerodynamic airloads with uniform inflow.

The *in vacuo* equilibrium solution is analyzed by 2GCHAS using the static analysis procedure. The equations are then linearized about the equilibrium state, and the multi-blade coordinate transformation is applied. The resulting equations have constant coefficients, and an eigenanalysis is performed on these equations.

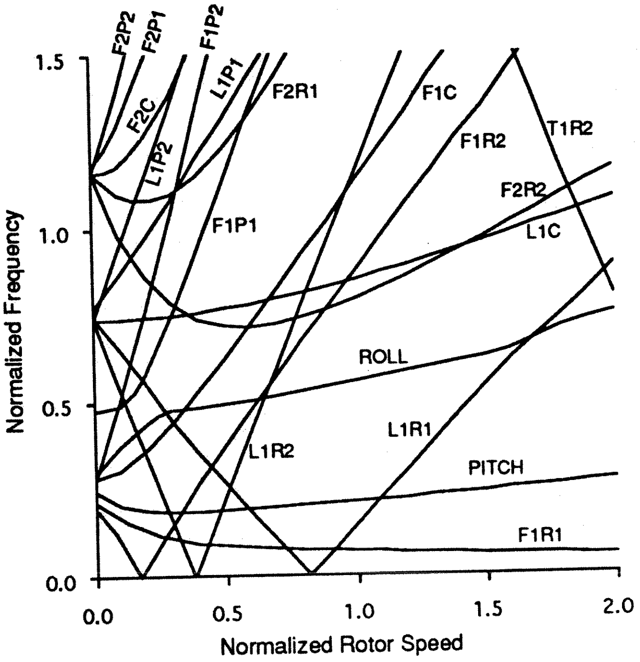

Fig. 26 Bearingless rotor helicopter frequency fan plot (*in vacuo*).

Results are shown for the modal frequencies *in vacuo* and damping versus rotor speed at 0° and 10° collective pitch in Figs. 26 and 27. Since the number of blades for a 2GCHAS analysis is arbitrary, the appropriate number of multiblade coordinate degrees of freedom is automatically presented. For a five-bladed rotor, each blade degree of freedom has a corresponding collective mode, a first and second progressing mode, and a first and second collective mode. For example, the first blade lead-lag bending modes are labeled in Fig. 26 as L1C, L1P1, L1P2, L1R1, and L1R2 respectively. The number of modes makes the frequency and damping plots more difficult to interpret, but the basic air/ground resonance characteristics are evident. The critical items of interest are coalescences of the first regressing first lag mode frequency and the fuselage pitch and roll modes. The damping results illustrate characteristic reductions in lead-lag mode damping at the frequency coalescences, increasing with collective pitch. The system is stable, however, due to the damping provided by the lead-lag damper.

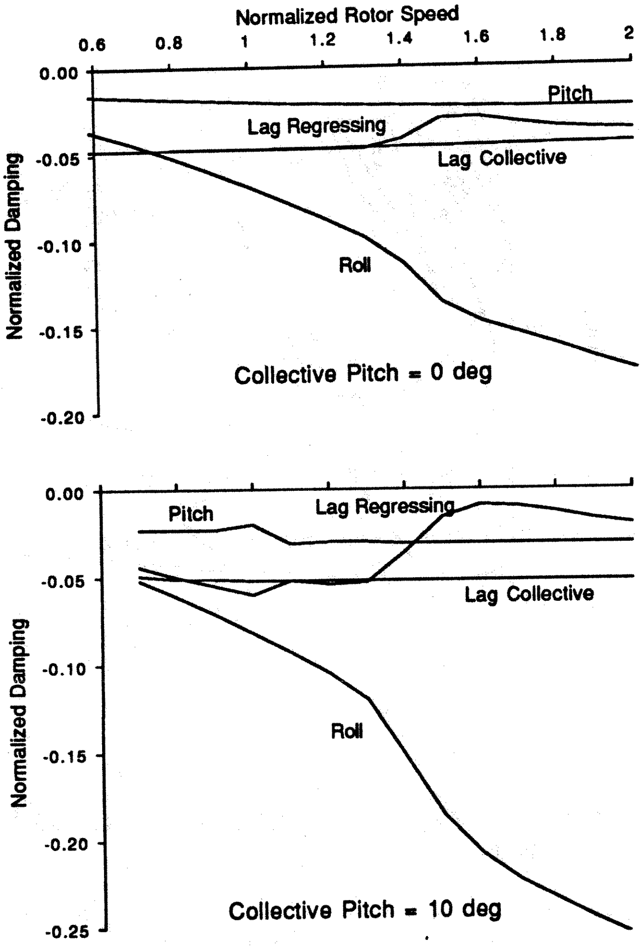

Fig. 27 Bearingless rotor helicopter damping plot.

Technical Issues

Development of a comprehensive rotorcraft analysis capability involves significant challenges for the researcher. These challenges arise from two sources: inadequate knowledge or prediction tools for specific aspects of the physics of rotary wing aircraft, and integrating narrow discipline math models into a practical comprehensive analysis tool for the entire vehicle. The following are a few examples of the technical issues confronting the researcher -- all of these require significant additional research before a system such as 2GCHAS can meet the full requirements expected by the technical user community.

Foremost among the technical issues is the development of stable, accurate, computationally efficient trim and transient solution algorithms for large, nonlinear, multidisciplinary problems that include aerodynamic, control, propulsion, structural components. Computers will increasingly employ parallel processing to improve execution time, and the solution algorithms must be adaptable to parallel computer architecture. *Optimization* is an issue that has not yet been addressed by 2GCHAS. Although several optimization packages are available that can be coupled with finite element codes, and it is probably possible to couple such a package to 2GCHAS, it remains to be seen if such packages are robust enough for the demands of a complex, multi-disciplinary task like comprehensive helicopter analysis.

Smart structures is a new technology with an enormous potential for improving rotorcraft design, but to exploit this technology effectively, comprehensive rotorcraft software must be able to analyze smart structural components, and integrate these components with the control system. Although the introduction of CFD analyses into comprehensive rotorcraft software will help resolve many aerodynamics questions, it appears that simpler aerodynamic models will be continue to be used in most analyses. Important aerodynamics issues include: the development of an accurate, nonlinear dynamic stall models for aeroelastic stability prediction; the development of an accurate blade-vortex interaction model for prediction of airloads and acoustic fields; and developing a model for describing the tip vortex structure, and the separation of the tip vortex from the blade.

The 2GCHAS user interface is a significant improvement over that used in virtually all other rotorcraft software packages, but further improvements can be obtained by the introduction of a graphical user interface (GUI). Since the 2GCHAS interface is menu driven, it already incorporates that aspect of GUI technology, but clearly, the interface will have to be considerably modified to make full use of a GUI's capabilities. Given the complexity of comprehensive rotorcraft analysis, additional research into user interface technology is appropriate, and apart from GUI techniques, one potential research issue is the application of artificial intelligence techniques to facilitate the modeling and analysis of complex systems.

Apart from these medium-term to long-term technical concerns, the Army will press ahead with enhancements in the short-term, which will improve the system to the greatest extent possible with existing technology. Projects that are already underway include: a preprocessor for generating beam element cross section properties for isotropic and anisotropic materials, including warping functions, and cross section constitutive constants; coupled CFD-rotorcraft dynamics; a graphical user interface (GUI); and an enhanced capability for modeling complex flight controls. Projects to begin shortly include: an alternative trim algorithm, employing either harmonic balance, or finite-elements-in-time; a panel method for predicting body interference; analysis of large motion flight dynamics; a "geometrically exact" blade element, which can accommodate arbitrarily large rotations and shear deformations; and a "joint library" to model the nonlinear kinematics of pitch links and articulated joints.

Concluding Remarks

2GCHAS has rotorcraft analysis capabilities that go beyond those available with previous systems, including a finite element basis that will accommodate virtually any rotorcraft configuration and hub design. In areas where technical features are not fully developed, the System has the capacity to accept more advanced analysis technology as it becomes available. Thus, one of the principal objectives of the 2GCHAS Project has been realized -- a strong basis for a broad-based comprehensive analysis has been established that should stimulate and encourage further development of rotorcraft analysis technology.

The results presented herein demonstrate that 2GCHAS has evolved to the point where extensive analysis capabilities for complex rotorcraft configurations have been achieved. Along with the companion paper addressing correlation and engineering validation with experimental data, 2GCHAS, is ready to be applied to rotorcraft engineering problems. Continued development of comprehensive analysis will be a central part of rotorcraft aeromechanics R & D, and it is now appropriate to focus on specific collaborations with researchers to integrate new technical capabilities within the framework of comprehensive analyses. Opportunities include such technologies as CFD and acoustic analyses.

2GCHAS has entered a key transition period. It has recently matured to the point of being a highly capable, flexible, rotorcraft aeromechanics analysis system. Like all large software systems it requires some degree of ongoing maintenance and support. More importantly, however, it will require a period of investment for the user to train with and begin to become familiar with its capabilities. Within the ATCOM RDEC, AFDD and the Directorate for Engineering are exploring ways to provide support to assist industry users with this problem.

Plans for engineering applications and user support include developing models for principal army aircraft to be used for feasibility studies of proposed system upgrades and for addressing fleet problems as they arise. Generally the model generation will be performed by the airframe manufacturer. The model will be validated by comparison with available data or other analytical models. ATCOM PMs currently identified for this type of support include: OH-58D Kiowa Warrior, AH-64 Apache/Longbow, CH-47 Chinook, and UH-60 Black Hawk. The Comanche is expected to be added at a future time. 2GCHAS will be a key tool to support new initiatives such as the National Rotorcraft Transporter (NRT), and provide support for upgrades and support of the Army aircraft fleet.

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