A REAL-TIME BLADE ELEMENT HELICOPTER SIMULATION FOR HANDLING QUALITIES ANALYSIS

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Abstract

Real-time helicopter simulations have traditionally neglected high frequency phenomena in order to achieve real time operation on affordable computers. Parallel processing technology can now provide real-time simulations with significantly improved modeling capability. This paper reports investigations being carried out by Advanced Rotorcraft Technology, Inc. (ART) on training and engineering analysis simulators to evaluate the effect of rotor model sophistication on simulated handling qualities. It also addresses the parallel implementation of rigid and elastic blade element simulations for real-time applications.

Introduction

Helicopter handling qualities analysts have always faced a major limitation. Piloted simulation is required but only the most costly supercomputers could process sophisticated rotor models in real-time. So while other disciplines utilize sophisticated rotor dynamics models in off-line analysis, handling qualities analysts have been forced to use low level approximations of rotor dynamics for real-time operations.

This paper describes Advanced Rotorcraft Technology, Inc. (ART) studies and developments contributing important cost reductions and sophistication enhancements to real-time simulation. The paper begins with an *Overview of the Elements of a Rotorcraft Simulation* and discusses levels of sophistication currently used by different simulations. The *Objectives and Approach* of each study is then given. This is followed by an overview of ART's *FLIGHTLAB System* and the use of *The FLIGHTLAB Executive and Simulation Library* in performing these studies. A review of *The Blade Element Model* and *The Rotor Map Model* is then given , followed by a description of the two comparitive investigations to be performed: a *Rotor Map versus Rigid Articulated Blade Element Model Comparison* for the UH-60 Blackhawk trainer at Fort Ord, California and an *Elastic versus Rigid Articulated Blade Element Model Comparison* at the Crew Station Research and Development Facility (CSRDF) at NASA's Ames Research Center. *Preliminary Results* of these investigations are then presented and the paper concludes with a discussion of *Future Comparisons* to be performed, a *Summary* of the major issues and *Concluding Remarks*.

Overview of the Elements of a Rotorcraft Simulation

Table I shows the major elements of a rotorcraft simulation. The level of sophistication currently in-use by some representative real-time and off-line simulations is also shown. Table I

characterizes the range of sophistication currently available in free flight simulations. More sophisticated implementations of these simulation elements may be available on static (wind tunnel) simulations, such as the use of Computational Fluid Dynamics in the Full Potential Rotor (FPR) simulation and the use of surface singularity panel methods for interactional aerodynamics in VSAERO.

For real-time simulations, the traditional approximation has been to reduce the complexity of the rotor simulation by restricting the frequency range of validity to the bandwidth of the pilot's response. This involved approximating the rotor as a disk and modeling the non-rotating frame dynamics of this disk only in the handling qualities frequency range. Examples of this approach are the Bailey model and the Rotor Map model shown in Table I. The Bailey model is an analytically derived closed form solution for the dynamics of the rotor disk and is used in the ARMCOP simulation [1]. The Rotor Map model [2] is obtained by tabulating the steady state loads and disk orientation as a function of flight condition from the more sophisticated Blade Element model. The dynamic response of the rotor disk is then generated by driving a low order filter with the quasistatic data to approximate transients in the handling qualities frequency range. While these rotor disk approaches make it possible to perform real-time simulation on affordable computers, it has always been recognized that their application must be limited to low speed flight with low gain control systems and moderate maneuverability, as they could not be experimentally validated beyond these applications. Within these constraints the model was typically tuned to match the flight vehicle at specific conditions using pilot comments and available flight test data. As a result, the traceability of these locally tuned models to sophisticated global models is often lacking.

The coming age of high speed rotorcraft with super augmented high-gain control systems will necessitate simulation models with improved bandwidth for handling qualities analysis. In addition, increasingly complex combat maneuvers will require training simulators with higher bandwidths and improved modeling of nonlinear phenomena. A blade element rotor model is necessary to satisfy these requirements. Blade Element models represent the dynamics of the individual rotor blades as opposed to approximating the dynamics of the blades with a rotor disk. This provides a higher bandwidth and significantly more nonlinear modeling potential than the rotor disk models. As shown in Table I, Blade element models can be further characterized as rigid blade and aeroelastic blade models. Some Blade Element models are already in use for real-time simulation. They are extremnely computationally intensive, however, so their use has been limited to facilities with costly computer systems. The rigid-articulated Blade Element GENHEL model [3] has been run in real time on a CDC 7600 computer at NASA Ames and on a four processor Gould SEL computer at Sikorsky Aircraft.

The two nonreal-time simulations listed in Table I represent the state of-the-art in free-flight rotorcraft simulation. REXHEL [4] is a combination of the GENHEL-based free-flight model and Lockheed's REXOR aeroelastic rotor simulation. It was implemented by ART to evaluate the interaction of Higher Harmonic control with the Stability Augmentation System for the RSRA X-wing aircraft. The Second Generation Comprehensive Helicopter Analysis System (2GCHAS) is currently under development by the U.S.Army Aviation Research and Technology Activity (ARTA) at NASA's Ames Research Center and is the most sophisticated rotorcraft simulation ever attempted [5]. It uses a finite element approach to modeling fuselage and rotor elasticity.

The available inflow models, as shown in Table I are also quite diverse. The Momentum and Glauert models [6] are the most commonly used in real-time simulation.and are usually limited to uniform and first harmonic components. A model recently developed by Peters [7] provides a high order harmonic representation coupled with radial mode shapes that appears to significantly extend the range of validity of these nonvortex models. Prescribed and free-wake vortex models

[8] are available in REXOR and 2GCHAS and represent the most sophisticated approach to inflow modeling currently used in free-flight simulations.

Interactional aerodynamics is probably the least understood and most poorly modeled phenomena in rotorcraft simulations. The most significant interactions are the effect of the fuselage on the inflow at the rotor, the effect of the rotor downwash at the tail and tail rotor, and the interaction between the tail rotor and the vertical stabilizer. These effects are usually modeled empirically and tuned to match experimental data or they are obtained from tables generated directly from experiments. The interaction between vortices and blades is also a significant effect but requires a vortex wake model to predict the position and intensity of the vortex. The interference of the ground plane with the rotor downwash is a predominant effect at low altitude and is usually modelled with empirical correction factors. If a vortex wake model is used, a mirror image of the wake can be used to simulate ground plane interference [9].

Solution methods contribute significantly to the accuracy of simulation models. Explicit (time-marching) solutions use data from the last cycle when current values are required but not available. This is a common approximation for real-time simulations. Implicit (simultaneous) solutions iteratively solve for the required current values before proceeding to the next time step. As shown in Table I, GENHEL uses an explicit solution method, solving for rotor loads as a function of fuselage accelerations on the previous cycle. REXHEL performs an implicit solution, iteratively solving for all accelerations at each time step. 2GCHAS will have the capability to invoke either solution method.

Objectives and Approach

This study has two primary objectives. The first is to demonstrate the capability to process sophisticated rotor models in a real-time piloted simulation using state-of-the-art parallel processing platforms. The second is to use these simulations to conduct a systematic comparison of the effects of model sophistication on simulation fidelity for handling qualities investigations.

Advanced Rotorcraft Technology has developed FLIGHTLAB, a generic parallel processing environment for flight simulation. The approach taken in this study will be to utilize FLIGHTLAB with a variety of parallel processing platforms to evaluate real-time simulations with varying levels of rotor model sophistication. A MicroVax based system with plug-in Motorola 88000 based auxiliary processor boards will be utilized to provide a real-time blade element simulation with rigid blades. A real-time blade element simulation with elastic blades will also be developed using the FLIGHTLAB system on an eight processor Silicon Graphics system and on an eight processor BB&N system.

The parallel processing systems running these sophisticated real-time rotor simulations will be interfaced to fully operational piloted simulation facilities in order to demonstrate the real-time input-output capability of the parallel platforms. A Direct Memory Access (DMA) interface will be used to provide a high-speed generic interface to an existing simulation host computer from the parallel processing system. This eliminates the need to rewire the cockpit interfaces and allows the existing host computer to be systematically off-loaded with some or all of the elements of the mathematical model.

Comparisons of rotor models with varying levels of sophistication will first be performed using off-line analysis to provide quantitative results. Piloted evaluations will then be performed to further assess the handling qualities fidelity. These piloted evaluations will be performed on two different facilities for two different levels of rotor model sophistication. A Rotor Map model and a Blade Element model with rigid blades will be compared using a UH-60 training simulator located at Fort Ord, California. A higher level of sophistication involves the use of elastic blade element models and this will be compared with a rigid Blade Element model using the Crew Station Research and Development Facility (CSRDF), a research simulator located at NASA's Ames Research Center.

A major impediment to such an investigation has been the difficulty of comparing different simulations. The large number of approximations required in even the most sophisticated of simulations make it unlikely that any two independently derived simulations are based on sufficient common ground to allow a direct comparison. A simulation environment that allows interchangeability of modular software for each element of the simulation can isolate the variability to a specific module and thereby facilitate the comparison. FLIGHTLAB's object oriented Simulation Library and data driven Executive provide the necessary environment to perform this comparison.

The FLIGHTLAB System

ART has applied parallel processing technology to achieve a real-time helicopter simulation with sophisticated mathematical models [10]. The software tools allow existing detailed simulations to be restructured for parallel processing. Low cost RISC technology processors may then be utilized to provide cost effective processing of real-time simulations using parallel architectures for expandability. The modular components of the FLIGHTLAB system, as shown in Figure 1, allow FLIGHTLAB to be configured for a variety of applications.

The heart of the system is the Computational Engine. It provides a low cost supercomputer using a parallel processing platform with ART's data driven parallel Executive. The Simulation Library provides object oriented simulation models to facilitate restructuring for parallel operation or reconfiguration for different vehicles and varying levels of modeling sophistication.

FLIGHTLAB Engineer's Workstation provides on-line monitoring and engineering analysis capability with real-time symbolic data access and a high-level vector/matrix oriented language for interactive data manipulation and display. The Programmer's Workstation allows existing FORTRAN programs to be decomposed into modules and reverse engineered into program structure charts and data flow diagrams to facilitate parallel restructuring of the software.

The Pilot's Workstation provides a high speed graphics capability for out-the-window scene generation and head-up displays. A three axis control stick and collective control lever provide the pilot's input and switches are used for control system configuration. A DMA inter-connect to the Computational Engine makes the pilot's Workstation an inexpensive pilot interface to the real-time simulation for preliminary evaluation and check-out.

In addition to being used as a "desktop real-time simulation facility", FLIGHTLAB can be interfaced to existing Piloted Simulation Laboratories using Direct Memory Access to exchange data with the simulation host computer. The host computer continues to drive the Crew Station

interfaces so no rewiring is required. The time and expense of recoding the mathematical model to run on the simulation host computer is also eliminated and the checkout time is reduced since much of the real-time checkout can be performed on the Pilot's Workstation prior to the interface to the Simulation Laboratory. FLIGHTLAB can be interfaced to an Avionics Laboratory in the same fashion, using the Pilot's Workstation to provide a low cost "Iron Bird" for hot bench testing of Avionics equipment.

The FLIGHTLAB Executive and Simulation Library

FLIGHTLAB's Simulation Library was designed to provide a generic environment for object oriented simulation development. This was an outgrowth of the development of a data-driven object oriented executive to facilitate the implementation of parallel software architectures on multiprocessor computer systems.

Figure 2 is a schematic representation of the input data used to configure a FLIGHTLAB simulation. Each node in this "data tree" represents a coordinate system in the vehicle. The data file describes the position and orientation of each coordinate system relative to its parent system and specifies the active degrees of freedom at each coordinate system. The Executive follows this road map, performing coordinate transformations as specified, until the motion at the reference point has been transformed to all coordinate frames. The location of the various helicopter subsystems (i.e. rotors, engine, stabilizers) are identified relative to these coordinate frames. Modules that simulate these subsystems are called from the library to generate the required aerodynamic and inertial forces based on the local motion.The resulting forces are then transformed back through the map of coordinate systems, and the net forces at each degree of freedom are identified and used to solve the equations of motion.

FLIGHTLAB's data driven approach allows simulations to be readily configured from a library of simulation modules. Modules with different levels of sophistication may be easily interchanged to isolate their effects. A variety of simulation modules developed by different organizations for different vehicles can be "genericized" and added to the Simulation Library for use in building simulations or performing comparative studies. The simulation can also be distributed over multiple processors by running the Executive on each processor with a different data file describing the simulation modules assigned to that processor and their interconnection.

The Blade Element Model

The most sophisticated rotor model currently utilized is the blade element model. The blade element approach models the dynamics and loads of each blade individually. It accomplishes this by dividing each blade into segments and computing angle of attack, Mach Number, and dynamic pressure at each of these segments as a function of the local motion and inflow. The blades may be modeled as rigid or flexible blades. Rigid blade motion includes both the hub motion and the effects of articulation, such as flapping and lead-lag hinges. Flexible blade motion also includes the local elastic deformation and rate of deformation. Airfoil tables are used to compute the aerodynamic loads at each segment as a function of the angle of attack, Mach Number and dynamic pressure at the segment. The air loads for each segment are then summed to provide forcing functions about the blade degrees of freedom and a net reaction at the hub. For rigid blades the rigid degrees of freedom are driven by loads about the hinges. Rigid blade models require a minimum of five segments with ten degree azimuth updates. A computer with fifteen times the computational power of the VAX (fifteen Vax Units of Performance, or VUPS) is required to

accomplish a real-time simulation of the UH-60 with four blades and a lead-lag and flapping hinge on each blade.

For elastic blades, the elastic degrees of freedom are driven by generalized forces [4]. These are computed as vector dot products of the segment air loads and mode shapes. Such a model generally requires at least seven segments with five degree azimuth updates. The computational power required for real-time operation of the UH-60 simulation with the lead-lag and flapping degrees of freedom and three elastic blade modes on each of the four blades is ninety-five VAX units of performance (VUPS).

The advantages of a blade element model are that it is a physically based model that provides high bandwidth response fidelity and includes the effect of interharmonic coupling on the low frequency response characteristics. Because the model is described in terms of physical parameters of the rotor system, the global fidelity may be improved by tuning these parameters. This provides a physically significant mechanism for tuning the simulation across the flight envelope with a minimum number of parameters. The disadvantage is that the computational intensity makes real-time operation difficult to achieve on all but the most costly single processor computer systems.

The Rotor Map Model

A rotor map model is generated from a blade element model by applying harmonic analysis to generate a table of steady-state rotor aerodynamic coefficients as a function of flight condition [2]. The independent variables for this table are advance ratio, collective pitch, and total inflow while the dependent variables are the coefficient of thrust C_T, the rotor drag coefficient C_H, the Y force coefficient C_Y, and the rotor torque coefficient C_Q. Collective and first harmonic flapping and lead-lag coefficients are also included in the table as a function of these flight conditions. The rotor map outputs are passed through filters with linear rotor dynamic response characteristics in order to approximate the rotor transient response in the handling qualities frequency range.

The advantage of the rotor map model is the low computational requirement resulting from the low bandwidth of the linear rotor dynamic model and the simplicity of the table look-up approach to generating rotor aerodynamic loads. The rotor map model could be processed as slow as twenty Hertz. Another advantage is that it is easily tunable to achieve local fidelity since the coefficients for each flight condition may be varied without affecting other flight conditions. This tuning practice however, eliminates traceability to the blade element model from which it was derived.

The disadvantages of the rotor map model are severe. The map is a function of the temperature and pressure at which the blade element response was generated so these variables must also be included as independent variables if these conditions change significantly. This adds to the complexity of the map. Also, the steady and first harmonic coefficient approximations to the rotor variables that are used in the rotor map can be very inaccurate when the stall region is significant, such as at high speed flight and during high G maneuvers. Another disadvantage is that the linear rotor dynamics used in the model is inaccurate for large maneuvers.

Rotor Map Compared to Blade Element Model of a Rigid Articulated Blade

This evaluation is sponsored by the U.S. Army Aviation Systems Command (AVSCOM) Aviation Research and Technology Activity (ARTA) at Moffett Field, California with the cooperation of the Project Manager for Training Devices (PMTRADE). The objective is to perform a systematic comparison of rotor map and blade element models on a real-time motion base simulator with a visual display in order to evaluate the effect of these models on handling qualities fidelity for a training simulator.

The approach is to use the UH-60 Training Simulator at Ford Ord, California. This trainer was developed for the Army by CAE Link and uses a Rotor Map model. The FLIGHTLAB Computational Engine will be interfaced to the existing Perkin Elmer 3250 simulation host computer through a DMA interface. A MicroVAX II with a Motorola 88000 based processor board will be used for the Computational Engine in the FLIGHTLAB System. The Blade Element rotor simulation to be used in the FLIGHTLAB Simulation Library for execution on this Computational Engine was developed initially by NASA Ames personnel [3] from math models supplied by Sikorsky Aircraft. The FLIGHTLAB Blade Element model will replace the existing CAE Link Rotor Map model by exchanging data with the rest of the simulation through the DMA interface. The performance of the simulation will be monitored and analyzed using the FLIGHTLAB Engineer's Workstation.

The CAE Link math model has been implemented on the MicoVAX at ART's facility in order to perform an off-line checkout of the Blade Element Rotor interface. Analytical comparisons of the Rotor Map and Blade Element model on the MicroVAX computer are in progress. The interface hardware and required software drivers for the MicroVax and the Perkin Elmer interface have been purchased and checked-out. The installation of the FLIGHTLAB System at Fort Ord will begin on September 18th with piloted evaluations to follow starting October 2nd.

Elastic versus Rigid Articulated Blade Element Model Comparison

This investigation is jointly sponsored by the U.S. Army Aviations Systems Command Aviation Research and Technology Activity and the NASA Ames Military Technology Office. The first objective is to demonstrate the capability to drive a comprehensive manned flight simulation facility in real-time with an elastic blade element model. The second objective is to conduct pilot comparisons of the elastic and rigid blade element models on a major simulation facility in order to evaluate their effect on handling qualities fidelity for analysis applications.

The approach is to use the Crew Station Research and Development Facility (CSRDF) at NASA's Ames Research Center. The first step in this project was to develop generic rotorcraft simulation modules to support an elastic blade element rotor model. Off-line comparisons of rigid and elastic blade element models were then performed to evaluate their impact on handling qualities. The potential for real-time operation with an elastic blade element model was evaluated by first using the FLIGHTLAB Programmer's Workstation to design a parallel architecture for an eight processor system. A number of candidates platforms were benchmarked to determine the potential for real-time operation on these platforms using eight processor configurations. The eight processor parallel architecture is now being implemented on the platforms that have been determined capable of supporting real-time operation. These platforms will be interfaced to FLIGHTLAB's Pilot's Workstation in order to interactively demonstrate the real-time operation of

an elastic blade element rotorcraft simulation. Following this demonstration the parallel platforms will be interfaced to the CSRDF to demonstrate real-time operation with full input-output capability. The last step will be to conduct pilot evaluations of the elastic versus rigid blade element models using the CSRDF.

The generic elastic blade element modules have now been developed and integrated into FLIGHTLAB's Simulation Library. A parallel architecture has been designed and benchmarks for candidate eight processor systems have been completed. The two platforms selected to date are the BB&N TC2000 eight processor system and the Silicon Graphics IRIS 4D/280GTX. Implementation of parallel software architectures is in progress on both systems. Demonstration of real-time operation with the FLIGHTLAB Pilot's Workstation will be performed by mid-October and the CSRDF installation should be completed in January with piloted evaluations to follow.

Preliminary Analytical Results

FLIGHTLAB'S Simulation Library (SIMLIB) has been used to perform off-line comparisons of rigid and elastic Blade Element models for a UH-60 simulation. SIMLIB's modular architecture allowed the elastic degrees of freedom to be added directly to a rigid articulated blade element model, thereby insuring that all other elements of the simulations were identical. The rigid degrees of freedom, present in both versions, included the 6 degree of freedom fuselage motion and flapping and lead-lag hinges on each blade for a total of 14 degrees of freedom. The Elastic version added 3 coupled flap-lag modes to each blade to produce a 26 degree of freedom simulation. Five blade segments were found to be sufficient for the rigid blade model but eleven segments were required for the elastic blade model due to the complexity of the mode shapes.

The rigid/elastic comparison was performed to determine the significance of elastic degrees of freedom to handling qualities analysis. The elastic model used has not yet been validated and is therefore not necessarily more representative of the real flight vehicle than the rigid blade model.The impact of elastic degrees of freedom on helicopter handling qualities, however, may be assesed independently of the accuracy of the simulations by performing a controlled comparison where the only difference is the blade elasticity. The elastic blade model validation is currently being carried out by ART in connection with the Black Hawk (UH-60) Rotor Airloads Flight Research Program at NASA's Ames Research Center [11]. Under this program, flight test data from a highly instrumented rotor blade will be obtained and used in connection with Maximum Likelihood parameter identification to estimate values of the simulation parameters that produce the best match between simulation and flight test results.

Figure 3 shows a comparison of the trim conditions for the elastic and rigid blade models. With the exception of the collective and pedal controls , the hover trims are close. The increased collective is probably required because elasticity reduces the effective coning angle. The higher collective setting produces more drag and consequently requires more pedal for anti-torque control. As the airspeed increases, the rigid and elastic blade trim conditions become more different. This is due in part to the increase in interharmonic coupling with advance ratio, causing more of the high frequency elastic response to multiplex into the low frequency and affect the trim. Note the pronounced effect of elasticity on the collective and lateral cyclic controls.

Figure 4 is a comparison of longitudinal static margins for the rigid and elastic models as a function of velocity. This is an important handling qualities parameter and is seen to be significantly different for the two cases. Again, at hover the effects of elasticity are small, but as velocity increases the static stability of the elastic blade model increases. Figure 5 shows a

comparison of the dynamic response of the rigid and elastic blade models to a 3211 input profile. As can be seen from the pitch angle and rate response, the elastic model appears to have a higher level of stability and reduced responsiveness to the control input. Note the high level of vibratory pitch acceleration in Fig. 5.c. The lack of a Bifilar model in the simulation probably makes the vibratory levels excessively high. A Bifilar model is being developed for use in the Black Hawk Rotor Airloads Research Program.

Figure 6 shows the longitudinal frequency response of the elastic and rigid blade element models in hover. The control effectiveness of the longitudinal cyclic stick is seen to be reduced by the blade elasticity. At the 60 knot forward flight condition shown in Figure 7 the control responsiveness of the elastic blade model is still reduced and now the phase of the response is also quite different. The blade elasticity has affected the dynamic response characteristics in the handling qualities bandwith.

Figures 8 and 9 compare the lateral frequency response of the two models at hover and 60 knots. A significant reduction in lateral stick sensitivity is seen at 60 knots which is consistent with the high level of lateral control required to trim at 60 knots, as shown in Figure 3.c. The phase response characteristics of the two models are also quite different at 60 knots.

Future Comparison

The modular architecture of the object-oriented FLIGHTLAB Simulation Library facilitates systematic comparisons of varying levels of model sophistication. Elastic and rigid blade element models have been compared off-line and a Rotor Map model is being compared with the rigid Blade Element model in preparation for piloted evaluations of the two models at Fort Ord. Additional comparisons to be performed at the Fort Ord facility include a comparison of an enhanced control system simulation that was developed at NASA Ames with the current control model used in the CAE Link software and a comparison of an enhanced engine model developed jointly by NASA Ames and NASA Lewis [12] with the CAE Link engine model. Fuselage flexibility at both the pylon and the tail may also significantly affect low frequency characteristics and should be investigated. One of the most interesting aspects of rotorcraft models is the inflow model. This has traditionally been limited to momentum theory models in order to achieve real-time operation. However, the limitations of these models is well known. A prescribed-wake model may be implemented in real-time by using additional processors to expand the power of the Computational Engine. Off-line evaluations of the enhanced validity in the handling qualities frequency range should first be performed.

Summary

The FLIGHTLAB System has provided a generic and systematic approach to achieving real-time operation of sophisticated simulation models on state-of-the-art parallel processing platforms. The object oriented Simulation Library and data driven Executive facilitate restructuring for parallel processing and systematic comparison of varying levels of model sophistication. The interactive Engineer's Workstation supports on-line monitoring and analysis with real-time symbolic data access. The Pilot's Workstation provides a low cost pilot interface to the real-time simulation for preliminary analysis and checkout. The Programmer's Workstation facilitates incorporating existing software into the Simulation Library and supports interactive optimization of parallel architectures.

The rotor map versus rigid Blade Element rotor model comparison will be conducted using the CAE Link UH-60 Trainer at Fort Ord. The capability to process a rigid Blade Element model in real-time has been demonstrated using a single Motorola 88000 Processor Board on a MicroVAX system. An off-line analytical comparison is in progress using the MicroVAX implementation of the CAE Link math model.

The rigid versus elastic Blade Element rotor model comparison will be conducted using the CSRDF Facility at NASA Ames. The capability for real-time processing for the elastic Blade Element rotor model has been analytically predicted for both the eight processor Silicon Graphics and BB&N computer systems and will be demonstrated shortly on both systems. Preliminary analytical results for the elastic versus rigid Blade Element models show a significant change in trim, static margin, ands frequency response in the handling qualities bandwidth for the two models.

Concluding Remarks

A comprehensive study of the effects of the varying levels of sophistication of each element of a rotorcraft simulation on the fidelity of the simulation in different bandwidths has yet to be performed. Such a study would be an invaluable aid to establishing systematic requirements for simulation mathematical models as a function of their specific missions. In addition, the relative cost of implementing the different levels of sophistication in real-time should be determined to assess the most cost effective approach to supporting real-time simulations with specified bandwidths of fidelity in the required flight envelope. Modern computer technology can provide cost effective real-time simulation with models considerably more sophisticated then those currently in use for handling qualities analysis.

FLIGHTLAB allows state-of-the art computer hardware to be utilized with sophisticated simulation models for real-time operation. This provides a common basis for both off-line and piloted evaluation allowing handling qualities analysts to utilize the same level of sophistication in their simulations that is used in other areas of helicopter engineering. Systematic comparison of the effects of rotor model sophistication on handling qualities fidelity for both training and research applications is underway. The preliminary results indicate that high frequency response characteristics can significantly affect helicopter handling characteristics and should be included in real-time simulations. Parallel processing technology provides the key to achieving this capability with affordable systems.

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Table 1 Capabilities of Current Helicopter Sumulatons

	Real Time			Non Real Time	
	ARMCOP	FLYRT	GENHEL	REXHEL	2GCHAS
Rotor Models					
Bailey Model	X				
Rotor Map		X			
Blede Element					
Dynamic response					
Rigid articulated			X		
Aeroelastic load model				X	
Aeroelestic finite element					X
Aerodynamic load models					
Lifting line theory					
with 3D corrections			X	X	X
with dynamic stall				X	X
Lifting surface theory					
Fuslarge Models					
Rigid	X				
Aeroelastic modal				X	
Aeroelastic finite element					X
Inflow Models					
Non-potential Models					
Uniform Momentum					
Quasistatic					
Dynamic	X	X	X		
First Harmonic Momentum					
Dynamic .		X			
Glauert	X	X	X		
Potential Models					
Prescribed wake					X
Free wake				X	
Interference Models					
Empirical models		X			
Experimentally generated table			X	X	X
Sureface singularity panel method					
Drive Train Model		X	X	X	X
Engine Model		X	X	X	

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Figure 1: FLIGHTLAB

THE INTEGRATED FLIGHT LABORATORY

HIGH-SPEED EXTERNAL I/O
PROVIDES PLUG-IN COMPATIBILITY
WITH USER'S PILOTED SIMULATION
AND AVIONICS TEST FACILITIES

HIGH-SPEED GRAPHICS
WORKSTATION PROVIDES
REAL-TIME VISUAL DISPLAY
FOR INSTANT PILOT-IN-THE-
LOOP EVALUATION

USER'S
PILOTED
SIMULATION
FACILITY

USER'S
AVIONICS
LABORATORY

PILOT'S
WORKSTATION

COMPUTATIONAL
ENGINE

PARALLEL PROCESSING SYSTEM
WITH RISC TECHNOLOGY PROCESSORS
PROVIDES COST EFFECTIV E
SUPERCOMPUTER, EXPANDABLE
TO MATCH THE APPLICATION

ENGINEER'S
WORKSTATION

SIMULATION
LIBRARY

PROGRAMMER'S
WORKSTATION

COMPUTER AIDED ENGINEERING
AND INTERACTIVE USER
INTERFACE PROVIDES FINGERTIP
DATA ACCESS, DISPLAY AND
ANALYSIS

OBJECT-ORIENTED SIMULATION
LIBRARY PROVIDES BUILDING
BLOCKS FOR DATA-DRIVEN
CONFIGURATION OF DYNAMIC
SYSTEM SIMULATIONS

CASE TOOL ALLOWS USER'S
SOFTWARE TO BE INCLUDED
IN SIMULATION LIBRARY AND
FACILITATES DEVELOPMENT
OF PARALLEL ARCHITECTURES

59-013

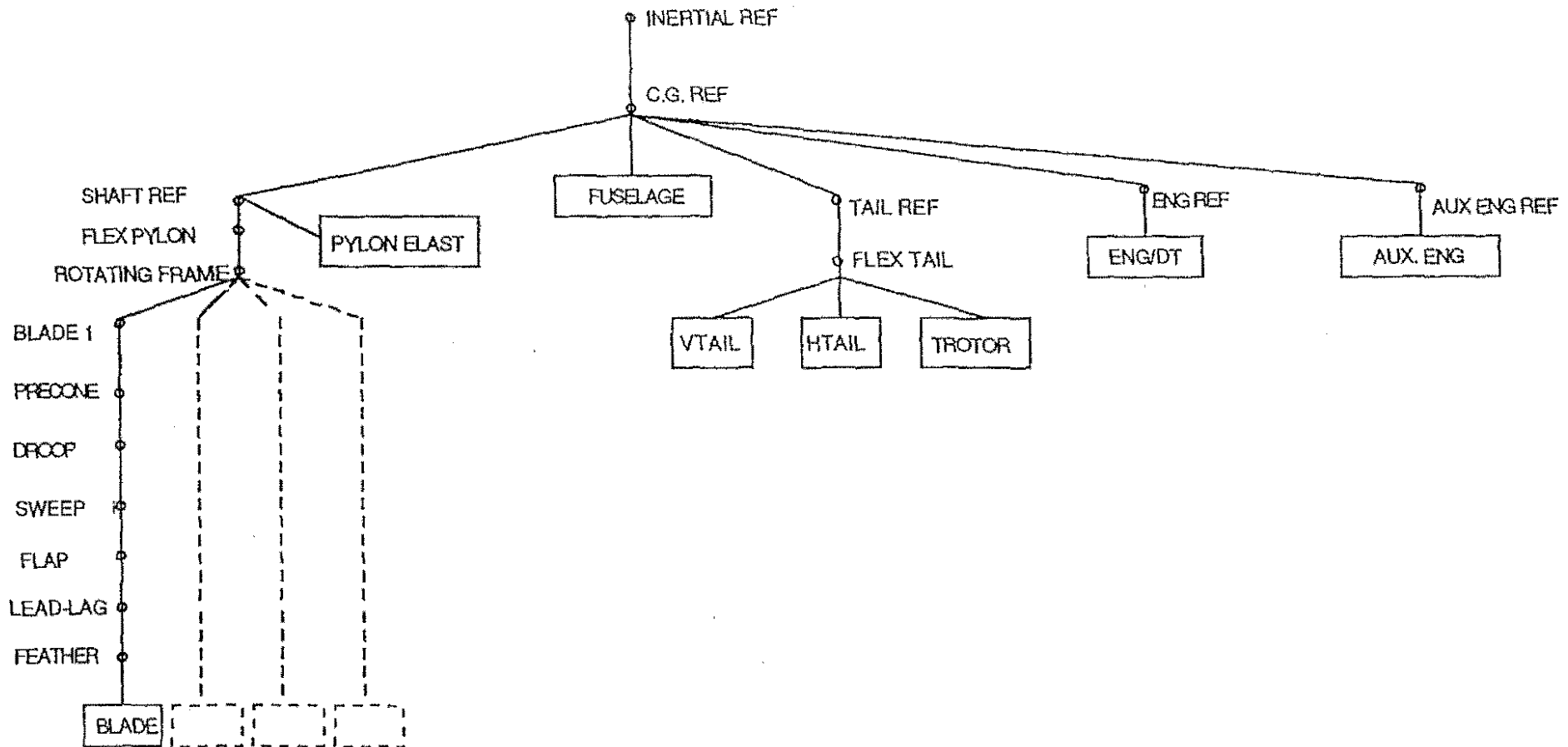**Figure 2:** Schematic Representation of Input Data for FLIGHTLAB Simulation

59-014

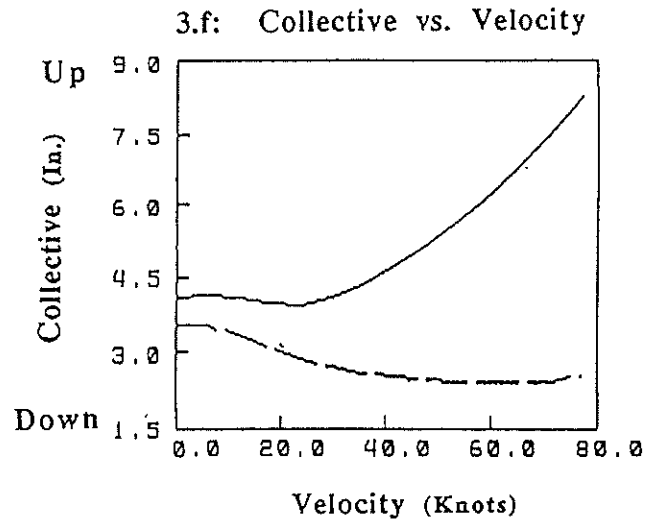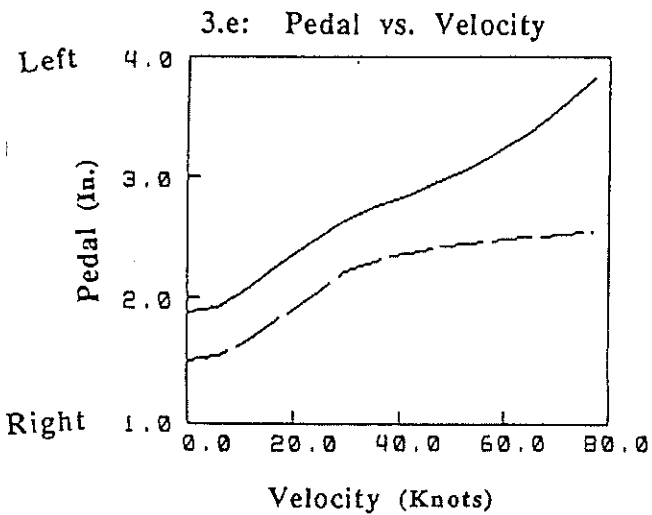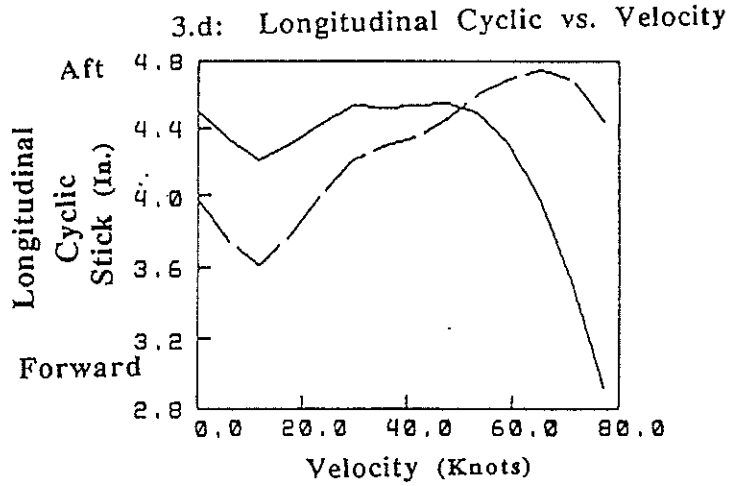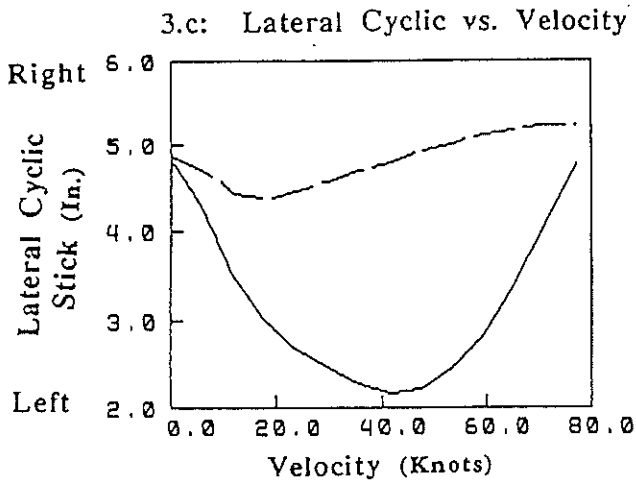# Figure 3: Trim Comparisons

—— Elastic Blade   --- Rigid Blade

3.a: Roll Angle vs. Velocity

Right / Left — Roll Angle (Deg.) vs. Velocity (Knots)

3.b: Pitch Angle vs. Velocity

Up / Down — Pitch Angle (Deg.) vs. Velocity (Knots)

3.c: Lateral Cyclic vs. Velocity

Right / Left — Lateral Cyclic Stick (In.) vs. Velocity (Knots)

3.d: Longitudinal Cyclic vs. Velocity

Aft / Forward — Longitudinal Cyclic Stick (In.) vs. Velocity (Knots)

3.e: Pedal vs. Velocity

Left / Right — Pedal (In.) vs. Velocity (Knots)

3.f: Collective vs. Velocity

Up / Down — Collective (In.) vs. Velocity (Knots)
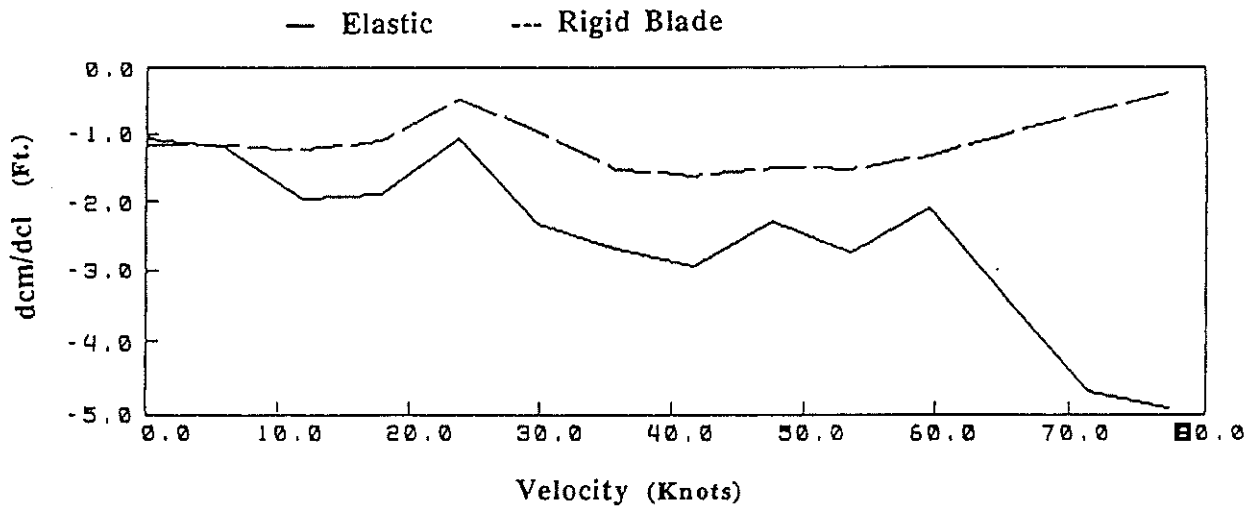
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Figure 4: Longitudinal Static Margin Comparisons

— Elastic --- Rigid Blade

dcm/dcl (Ft.) vs **Velocity (Knots)**

Figure 5: Dynamic Response Comparisons at 60 Knots

— Elastic --- Rigid Blade

5.a: Pitch Angle Response

5.b: Pitch Rate Response

5.c: Pitch Accel. Response

5.d: Long Stick Input
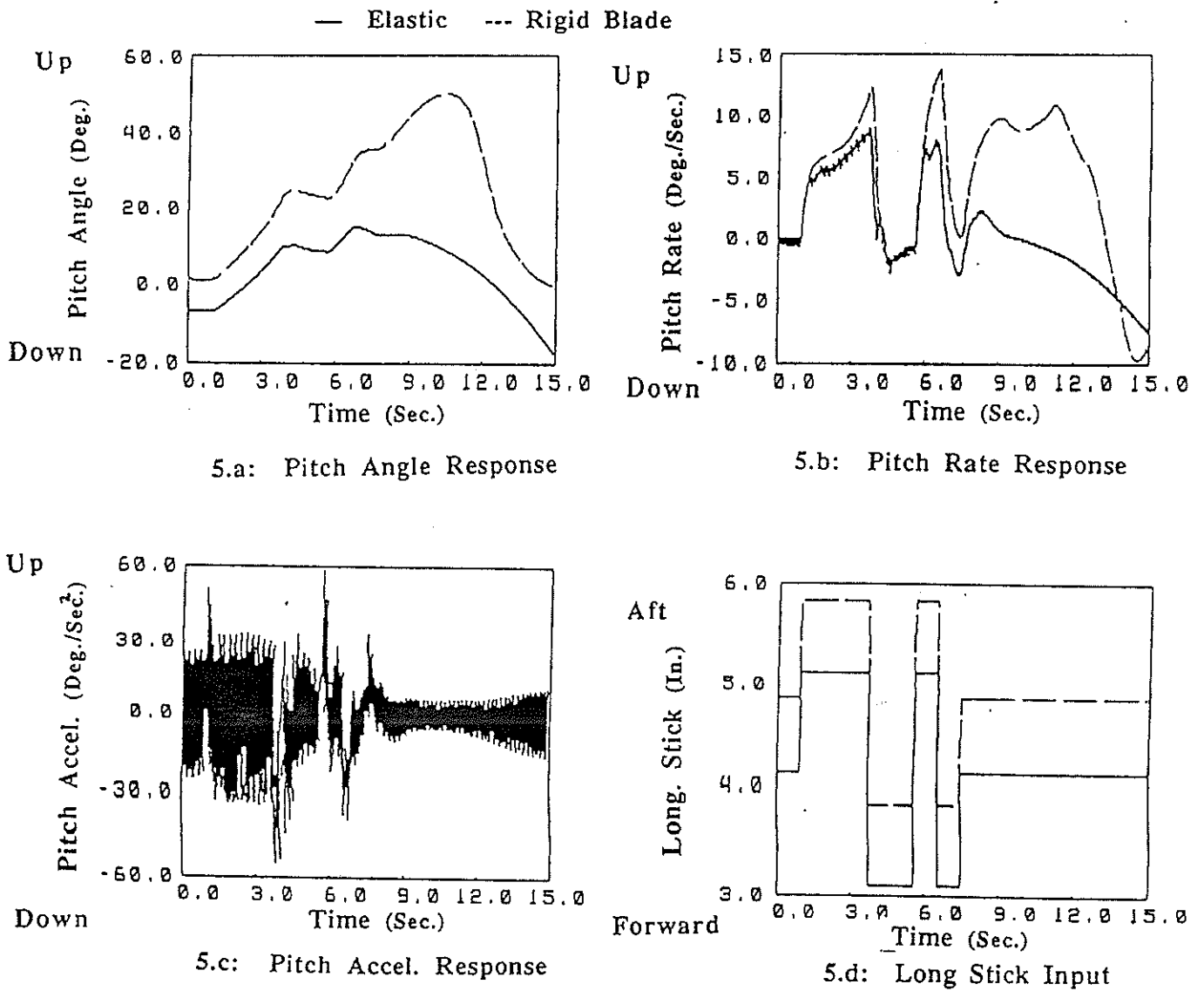
Figure 6: Longitudinal Frequency Response Comparison at Hover

— Elastic Blade   ---Rigid Blade

Log Mag. [q(w)/xB(w)]

Phase [q/(w)/xB(w)]

Frequency (Rad./Sec.)
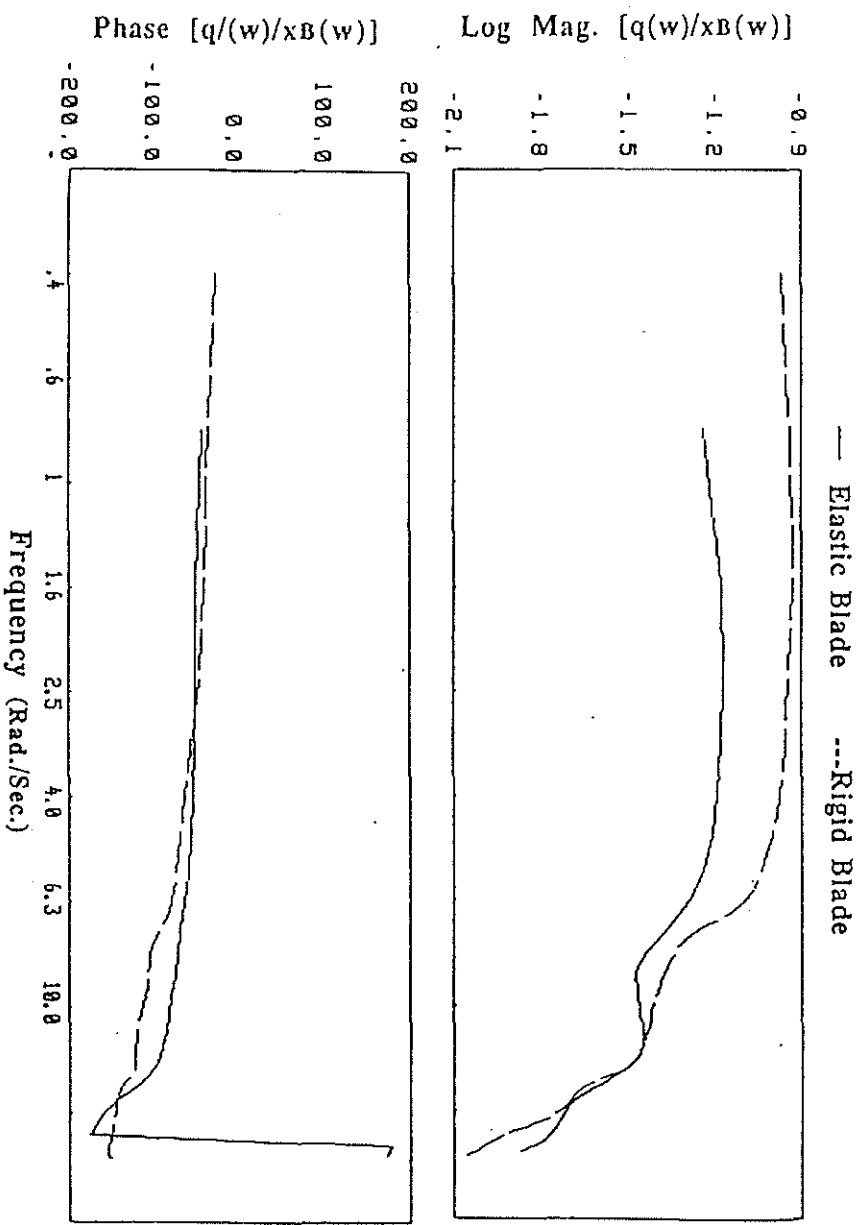
Figure 7: Longitudinal Frequency Response Comparison at 60 Knots

— Elastic   --- Rigid Blade

Log. Mag. [q(w)/xB/(w)]

Phase [q(w)/xB/(w)]

Frequency (Rad./Sec.)

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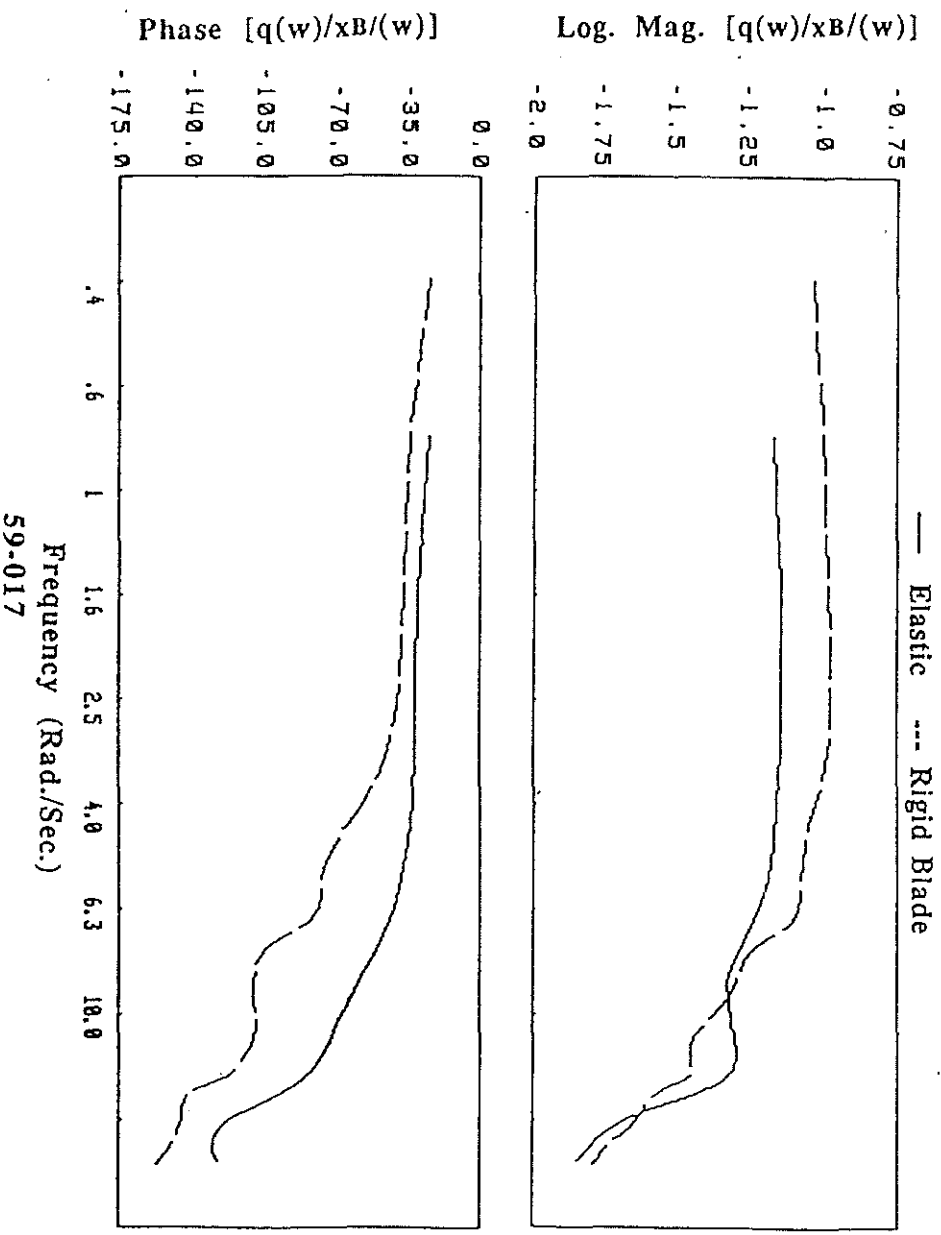
Figure 8: Lateral Frequency Response Comparison at Hover
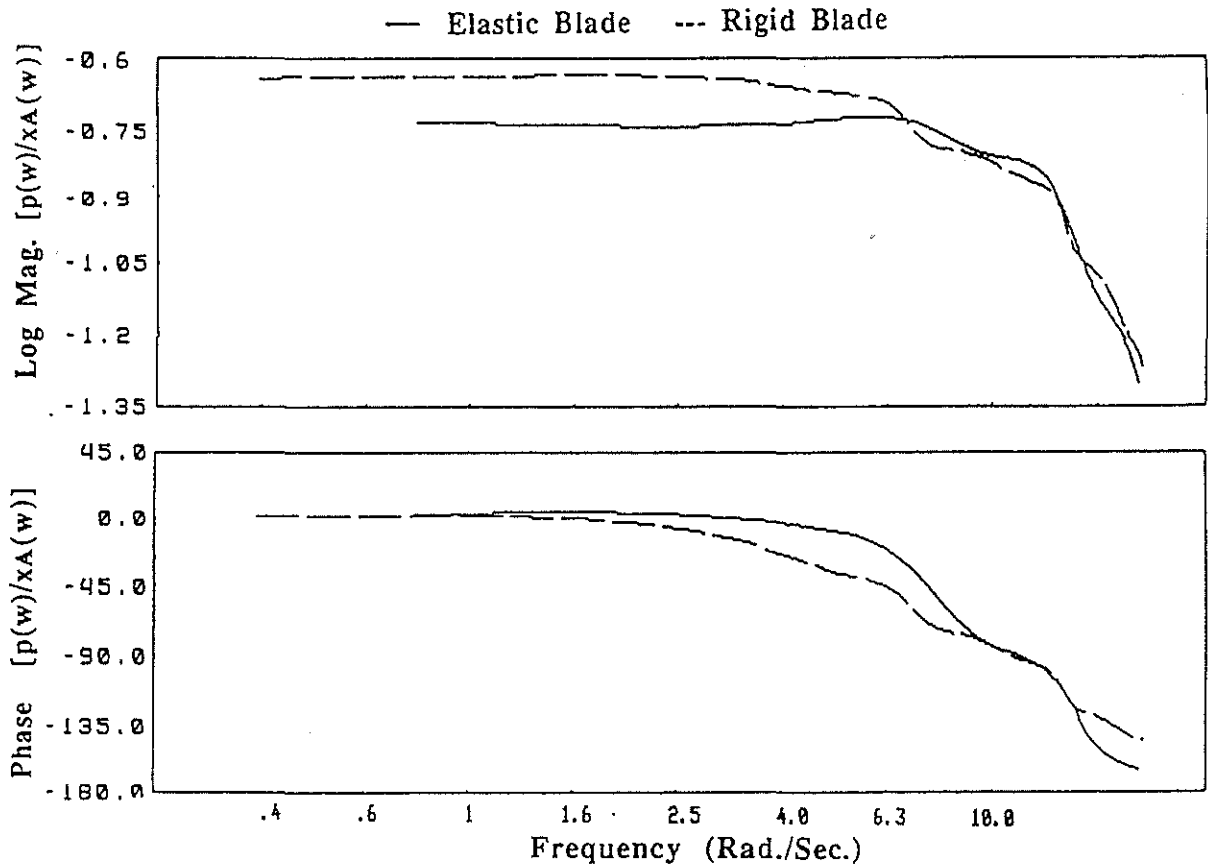
— Elastic Blade --- Rigid Blade

Frequency (Rad./Sec.)

Figure 9: Lateral Frequency Response Comparison at 60 Knots

— Elastic Blade --- Rigid Blade

Frequency (Rad./Sec.)