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Comparisons of Elastic and Rigid Blade-Element Rotor Models Using Parallel Processing Technology for Piloted Simulations

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Comparisons of Elastic and Rigid Blade-Element Rotor Models Using Parallel Processing Technology for Piloted Simulations

GARY HILL, RONALD W. DU VAL,* JOHN A. GREEN,* and LOC C. HUYNH*

Ames Research Center

Summary

A piloted comparison of rigid and aeroelastic blade-element rotor models was conducted on the Crew Station Research and Development Facility (CSRDF) at Ames Research Center. FLIGHTLAB, a new simulation development and analysis tool, was used to implement these models in real time using parallel processing technology. Pilot comments and quantitative analysis performed both on-line and off-line confirmed that elastic degrees of freedom significantly affect perceived handling qualities. Trim comparisons show improved correlation with flight test data when elastic modes are modeled. The results demonstrate the efficiency with which the mathematical modeling sophistication of existing simulation facilities can be upgraded using parallel processing, and the importance of these upgrades to simulation fidelity.

Introduction

Developing the next generation of advanced rotorcraft—capable of higher speeds and greater maneuverability, with precise, superaugmented control systems and hingeless rotors—will require expanded-bandwidth, real-time simulations that include aeroelastics and structural dynamics. These disciplines can no longer be left uncoupled, and more engineers on the design staffs will need access to these higher-fidelity simulations. Advanced Rotorcraft Technology (ART), Inc., the U.S. Army Aeroflightdynamics Directorate, and NASA Ames's Military Technology Office have pursued parallel processing as a cost-effective means of meeting this need. In a series of research activities, rotorcraft models of increasing complexity have been parallelized for real-time operation. Under a Small Business Innovative Research Program (SBIR), a piloted workstation was developed, which was driven by a MicroVAX II computer converted to a parallel processor by adding four processor boards to the MicroVAX's backplane. On that parallel processor, the Rotor Systems Research Aircraft/X-Wing (RSRA/X-Wing), with possibly the most complex aerodynamic interactions ever modeled, was flown through conversions between rotary and fixed wing (ref. 1). Later, the same modified MicroVAX II replaced the aerodynamic rotor map with a blade-element representation on the UH-60 Black Hawk training simulator at Fort Ord, California, and piloted comparisons were performed (ref. 2). This paper reports on an extension of this technology to a blade-element rotor model that adds aeroelastics and structural dynamics. Again with the UH-60 as the subject, this "global" simulation model with blade flexibility was demonstrated in real time on two commercial parallel processor computers, and interfaced with the Army's Crew Station Research and Development Facility (CSRDF) at the NASA Ames Research Center.

The authors would like to thank the Army Aeroflightdynamics Directorate at Ames Research Center and, in particular, the Crew Station Research and Development Branch for providing both access to the CSRDF and the necessary support personnel to carry out this investigation. They would also like to thank Alex Gallico and Guy Beauchesne of CAE Electronics for their help and support.

Objectives

As a follow-on to the effort at Fort Ord (ref. 2), this study had four objectives. The first was to develop a free-flight rotorcraft simulation model with aeroelastic and structural dynamics modeling; the second was to design a parallel processing architecture for this global model to permit real-time operation; the third was to run the real-time simulation interactively with a full-simulation facility; and the fourth was to perform piloted simulations comparing the model with conventional rigid body modeling.

Methods

In this study, the global simulation was developed and adapted for parallel processing using ART, Inc.'s FLIGHTLAB system, a tool for developing optimal parallel software architectures for real-time operation from a modular library of elements. FLIGHTLAB includes

1. A library of simulation elements to synthesize a desired vehicle configuration, a dynamic assembler to

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set up data structures, and a solver routine for integrating solutions.

2. An interactive programmer's workstation for developing and optimizing parallel architectures by decomposing existing codes into modules, mapping data dependencies of these modules, and profiling their execution times.

3. An engineer's workstation for on-line, real-time data access and engineering analysis. This workstation is also interactive, with symbolic data access, high-level engineering analysis, and graphical display capabilities.

4. A pilot's workstation with a three-axis side arm controller and an out-the-window visual scene with a head-up display (HUD).

Blade-element aerodynamic rotor models divide each rotor blade into segments and use airfoil tables to compute each segment's aerodynamic load from the angle of attack, Mach number, and dynamic pressure produced by local motion and flow. Airloads from the segments are summed to derive forces about the blade degrees of freedom and to calculate reactions at the hub. Both the rigid and the elastic blade modeling include hub/fuselage motion, flapping and lead-lag hinge articulation, and blade feathering.

This global model is a free-flight, blade-element, real-time simulation that includes component elasticity. Aeroelastics and structural dynamics are modeled by mode shapes derived from finite-element analysis. When the modal representation was added to the rigid blade-element model, the number of blade elements had to be doubled from five segments per blade to ten in order to obtain proper high-frequency-dynamics fidelity. The global model also contains hinge articulations in addition to coupled elastic degrees of freedom.

FLIGHTLAB's free-flight rigid blade-element model was validated to match the UH-60 blade-element model of the NASA version of Sikorsky Aircraft's Master General Helicopter Program (GENHEL) (ref. 3). This simulation model of the UH-60 helicopter, obtained from Sikorsky, has been updated at NASA Ames and validated against flight test data (ref. 4). The FLIGHTLAB aeroelastic rotor model was validated against Lockheed's REXOR aeroelastic rotor model (ref. 5), and the global (free-flight aeroelastic) model was validated against available flight test data (ref. 6). FLIGHTLAB's data-driven configuring capability facilitated the comparative analysis and validation. Modifications such as the interchange of elastic and rigid modules and altering the hinge sequence in the modeling would require extensive recoding in most simulation models.

After creating and validating the global model, parallel architectures were designed to provide a real-time capability. FLIGHTLAB's parallelizing features determined that an eight-node (each node is an individual CPU) parallel computer, each node having a CPU speed approximately 17 times faster than the MicroVAX II, would suffice. The global model was then benchmarked in serial mode on commercial parallel processors of the RISC class. Speeds of up to 21 times that of the MicroVAX II were obtained; thus it appeared that real time was feasible.

The next step, that of actually running the massive global model in real time, was facilitated by the cooperation of the computer manufacturers, who generously provided technical assistance and free access to their computers. The two parallel-processing computer systems used were a Silicon Graphics IRIS (SGI) 4D/280 GTX with eight processors, and a BBN TC2000 with sixteen processors. Identical parallel architectures were installed on both, and real time was confirmed by timing checks and simulated flight from the pilot workstation. Interface to the CSRDF's VAX 8650 host computer was through Ethernet. Existing visual and cockpit protocols remained intact while the vehicle's simulation math model, on the host computer, was replaced by the math model running under FLIGHTLAB on the parallel platforms.

The complete Black Hawk simulation model was updated every 10° of rotor azimuth travel, which resulted in a 6-msec integration cycle. Only the first two blade flapping and inplane bending modes were used in this experiment. The parallel processing architecture as implemented on the eight-processor SGI computer and eight of the sixteen BBN computer processors is shown in figure 1. It used five processors for the math model: four processors dedicated to the rotor (one per blade), and one processor for the fuselage, tail, control system, and engine model. A sixth processor drove an engineer's workstation, and a seventh served the Ethernet interface to the CSRDF host VAX 8650 at 60 Hz. Integration of the parallel processor with the CSRDF is shown schematically in figure 2.

Pilot tasks were chosen to assess the effects of aeroelastic degrees of freedom on perceived fidelity. Hover maneuvers included bob up/bob down and lateral dash/quick stops. High-speed flight maneuvers included slalom maneuvers that require rapid bank reversals to control lateral position, and dolphin maneuvers with rapid collective changes to control vertical position. The pilots performed frequency sweeps to collect engineering data.

Results and Discussion

The following analysis compares trim, stability, and dynamic responses of the rigid and aeroelastic

blade-element models. There are differences between the two simulation models in all three areas, especially at high speed.

Longitudinal trim of the rigid and elastic models are compared with flight test data (ref. 6) in figure 3. Pitch attitude, longitudinal cyclic position, and collective position are plotted for flight speeds from –50 to 160 knots. At low speeds, the rigid and elastic models show little difference in their trim characteristics. At hover, pitch attitude and longitudinal cyclic position agree well, but results for both rigid and elastic models deviate from flight test results at transition speeds. One explanation could be the extreme sensitivity of trim to horizontal stabilator incidence setting, which varies with airspeed in the transition range. The flight test report gave no indication whether the stabilator position had been calibrated or not. Trim comparisons for lateral/directional axes are not included, as differences were inconclusive or less significant.

The rigid model variations from flight test results increase with higher airspeeds. This airspeed-dependent effect is relieved in the elastic model by the added high-frequency content. The widest differences occur at 160 knots, and are seen in pitch attitude (4°) and collective position (2 in.), on the right side of figure 3. Significantly more collective control is required to produce the same thrust, because not all of the force from flexed blades is generated in the direction of rotor thrust. This increased in-plane component due to blade flexure, and the additional airfoil drag from higher collective pitch combine to significantly increase the effective rotor drag, requiring more pitch-down attitude to balance drag with thrust.

The accuracy of both the NASA Ames and Sikorsky Aircraft UH-60 GENHEL simulation models has been improved by the use of a quasi-static approximation to blade flexibility derived from flight test data. In figure 4, this "dynamic twist" approximation is added to the FLIGHTLAB rigid blade model and significantly improves the fit at high speed. The aeroelastic model, however, still provides a closer fit to the flight test data, and does not require tuning since its improved fit results from higher fidelity physical modeling. We shall see that the global model also represents transient elastic effects.

To compare stability characteristics of the rigid and elastic models, a six-degree-of-freedom linear model with eight state variables was constructed by making perturbations about the trim points. Roots of the linearized models were collected a sufficient time after the perturbations to allow higher-frequency modes to reach steady state, assuring an accurate quasi-static approximation for these modes.

Damping ratio and natural frequency of the roll/pitch, short period, and dutch roll modes are plotted against airspeed for the rigid and elastic models in figure 5. High-frequency elastic modes would not be expected to affect the six-degree-of-freedom response, but these results show that elasticity has an impact on the stability characteristics. The greatest differences occur at higher airspeed, as is the case with trim. These linearized models represent the open-loop dynamics, so the effects are not related to control-system coupling. Airspeed dependence suggests that a periodic coefficient effect could be responsible for the coupling of elastic effects into the handling-qualities range.

The roll and pitch gyroscopic modes are aperiodic at airspeeds below 100 knots, but at higher speeds coalesce into a coupled roll/pitch mode. The damping and natural frequency of this second order pair are plotted in figure 5(a). At low speed the overdamped system has a pair of real roots. Their real axis locations are plotted as natural frequency. The pitch roots of the rigid and elastic versions are indistinguishable, but differences in the roll root as a result of elasticity are noticeable. When the system is underdamped the natural frequency of the resulting complex root pair is plotted instead of the real axis locations, and rigid and elastic each become a single line. The short-period mode (fig. 5(b)) is unstable for most of the speed range for both models, although the elastic model has more stability than the rigid model does at high speed. The dutch-roll mode (fig. 5(c)) is stable for most of the speed range in both models although a significant reduction in damping for the elastic model is seen at speeds greater than 100 knots, resulting in instability at 140 knots, whereas the rigid model remains reasonably stable. The heave mode and the spiral mode do not exhibit much difference between rigid and elastic models, and are not shown.

Next we compare dynamic responses of the rigid and elastic models. Figures 6 and 7 show the pitch rate response to a 3-2-1-1 longitudinal cyclic input for both open loop control and with the stability augmentation system (SAS) on. Figure 6 shows data for the models at hover, where a small, static trim difference exists at time zero. Response differences increase with time in the open loop system because of the unstable short period pitch mode identified in figure 5. But when the SAS provides low-gain feedback, no difference between elastic and rigid models is observed. The SAS stabilizes the models without coupling the elastic response into the handling-qualities range.

Open-loop and SAS-on responses at 150 knots forward speed are similarly compared in figure 7. The rigid model exhibits significantly different open-loop time response than the elastic model, confirming the stability analysis in figure 5. Rigid-model pitch response is divergent, as

predicted by linear analysis of the short-period pitch mode. Response to the 3- and 2-sec steps by the elastic model indicates less stick sensitivity for low-frequency inputs. Response of the elastic model to the higher-frequency 1-sec doublets in the 3-2-1-1 input shows significant elastic excitation and coupling with the airframe degrees of freedom. With the SAS on, the elastic model's pitch rate drops to almost nothing at the end of the first pulse. Response to high-frequency inputs is almost identical for both models. The SAS suppresses open-loop excitations by higher-frequency inputs, but low-frequency differences, such as trim, are still significant. It is obvious that the higher-order dynamics do affect handling qualities, and need to be considered in the formulation of flight control laws for higher speeds. This assessment was later confirmed during the piloted simulations.

More evidence of elasticity's impact on closed-loop control is provided by the SAS-on frequency responses at hover and 150 knots. Figure 8 shows the pitch-rate response to longitudinal cyclic control for the rigid and elastic models. The magnitude of the transfer function is presented in the upper plots and the phase is given in the lower plots, both as functions of the frequency of the input. This comparison again shows virtually no difference at hover. At 150 knots the two models differ significantly at low frequency, but they exhibit no differences at high frequency. This is consistent with the time-domain results of figure 7 and further indicates that the SAS suppresses the rotor modeling differences in the higher-frequency range.

From the analytic phase, the study proceeded to the piloted simulation. Installation and interface of the parallel processing computers at the CSRDF was accomplished in only three weeks and was followed by two weeks of piloted evaluation. Several NASA and Army test pilots participated in the evaluation, some of whom were involved in the rotor-map versus blade-element comparison at Fort Ord (ref. 2). Data was collected on-line using the engineer's workstation and was correlated with pilot comments, off-line comparisons, and flight tests.

The CSRDF simulator cockpit is equipped with dual, four-axis side-stick controllers in lieu of conventional cyclic and collective. The UH-60 SAS and the flight-path stabilization (FPS) control system were modified to use the CSRDF side arm controllers in place of the center stick and collective lever. The opportunity was taken to also integrate the advanced control system known as ADOCS (Advanced Digital Optical Control System) from the facility (ref. 7). Since the UH-60 control laws were not designed for a side stick inceptor, is it not surprising that the ADOCS control system was preferred by the research pilots. However, one must remember that the objective was to compare rigid and elastic simulations and to discern their effect on handling qualities and flight control design, and not just to calibrate another Black Hawk simulation model.

The research pilots performed bob up/bob down and lateral dash/quick stops at hover, and slalom and dolphin maneuvers in high-speed flight. The aeroelastic degrees of freedom were turned on and off, both in-the-blind and on request, to assess fidelity perception. Every pilot was able to detect the differences indicated by mathematical analysis. Those differences were more noticeable at higher speeds, and during performance of exacting, high-gain control tasks. The dominant effect was increased damping, which is the logical consequence of adding structural flexibility to a physical representation.

A more surprising result was obtained from frequency sweeps performed by the pilots to compare elastic and rigid modeling with the low-gain SAS and advanced high-gain ADOCS. Figure 9 shows pitch-rate amplitude and phase response to longitudinal cyclic control, at hover. The left side of figure 9 (SAS on) duplicates the left side of figure 8 except for scale. No differences between rigid and elastic models are noted. With the ADOCS controller (right side of figure 9), the static gain is five times greater than with the SAS, and a significant difference is exhibited between the rigid and elastic models, particularly in the higher-frequency range. The elastic model is less sensitive to pilot inputs than the rigid model is, an effect consistently confirmed by the pilots. Since there are no periodic coefficient effects at hover, these differences are most likely a result of coupling between elastic and rigid body modes induced by the high-gain ADOCS controller. For future applications employing high-gain controllers, the need for elastic modeling, even at hover, is demonstrated.

More analytic comparisons between rigid and elastic models with the ADOCS configuration are shown in figures 10 through 12. The formats are taken from the recently issued ADS-33C handling qualities specification (ref. 8). The equivalent time delay versus bandwidth for the elastic and rigid models is plotted in figure 10. The frequency response data for the pitch attitude response to longitudinal cyclic control at 80 knots is shown at the bottom of the figure. The bandwidth and equivalent time delay shown in the top graph were taken from these plots. Elastic and rigid models are both to the right of the level-1/level-2 border, but inclusion of blade elastics reduced the margin by one-half.

Figure 11 shows the vertical response to collective input with the ADOCS controller, at hover. Time response of the rigid and elastic models to a collective step is shown

at the bottom of the figure with the curve fit of the low-order equivalent altitude response model overlaid. The curve fit is good in both cases. The identified time constant and time delay parameters of the low-order equivalent response models are shown in the tables at the top of the figure for the rigid and elastic models and compared with the ADS-33C specification for level-1 and level-2 response. Responses were similar for both elastic and rigid models, and are well within the level-1 category for both cases.

Figure 12 shows an "attitude quickness" comparison of rigid and elastic models at 80 knots using the ADOCS. The time response plots at the bottom of the figure show the longitudinal cyclic input and the resulting pitch-rate and pitch-attitude responses for specific elastic and rigid trials. The increased level of control input required to achieve the same pitch response with the elastic model is a result of the reduced sensitivity of the elastic model. This effect was previously noted, in the time-response plots of figure 7 and the frequency-response plots of figures 8 and 9. This characteristic was repeatedly confirmed by the pilots, and they felt that the elastic model response was more realistic. The top plot, of the peak pitch rate to peak attitude change ratio versus peak attitude change, is representative of maneuverability or quickness; it shows a significant difference between rigid and elastic models for the 80-knot flight condition, although both models are well above the level-1 boundary.

Conclusions

The following conclusions were drawn from this investigation.

1. The ability to process the aeroelastic model in real time on both the SGI and BBN parallel-processing systems was successfully demonstrated.

2. The ability of parallel processors to support a real-time interface with a full-simulation facility while maintaining real-time operation was demonstrated.

3. The aeroelastic free-flight model compared well with flight test data in off-line comparisons, and exhibited improvements both statically and dynamically over the rigid blade model.

4. Pilots perceived the effect of the aeroelastic degrees of freedom on the handling qualities and rated this effect as an enhancement of simulation fidelity.

The comparisons between the rigid and aeroelastic models demonstrated two mechanisms for coupling between the high-frequency elastic modes and the low-frequency airframe response. A speed-dependent effect, probably due to interharmonic coupling produced by the periodic-coefficient rotor model, resulted in significant differences between rigid and elastic trim conditions at high speed; comparison with flight test data confirmed the elastic model to be more accurate. A gain-dependent effect was demonstrated by comparison of SAS and ADOCS responses at hover. The high-gain ADOCS was seen to produce significant coupling of the elastic degrees of freedom with the airframe response, whereas the low-gain SAS suppressed dynamic differences in the rotor models without producing additional coupling. A comparison of open-loop stability characteristics versus airspeed showed a speed-dependent difference that tended to stabilize the short-period mode and destabilize the dutch-roll mode. Comparison of rigid and elastic models using the ADS-33C handling qualities criteria further demonstrated significant differences between the two models and quantitatively supported the pilot's qualitative assessment that the elastic model was significantly less sensitive to control inputs than the rigid model was.

The major impact of parallel-processing technology on rotorcraft simulation is expected to be greater productivity. The most immediate impact will be elimination of the recoding and verification usually required when the simulation model is transferred to a large simulation facility. The fact that smaller, less expensive computers are able to drive larger facilities like CSRDF means there can be more backup computers for continuous operation of the expensive visual and motion bases, and additional machines for preparing the next entry, at no additional cost. The common on-line engineering-and-analysis tool will also realize substantial productivity advantages.

A second advantage is that combining aeroelastics and structural dynamics in the simulation model increases the fidelity of rotorcraft real-time simulations. Inclusion of these disciplines is a necessity for the development of high-speed and high-agility rotorcraft. Hingeless rotors, high-gain flight control systems, higher harmonic control (active vibration suppression), all require concurrent engineering.

A third advantage is achieved by lowering the cost of computers capable of running blade-element models. These more physical representations add fidelity to training simulators, tie the trainer simulation model to the engineering simulation model, reduce expensive tuning, and provide greater flexibility to modify the model for aerodynamic changes.

The FLIGHTLAB system provides a unified tool for the development, parallelization, analysis, and real-time operation of flight simulations. Its use in this application expedited the cost-effective utilization of the CSRDF facility.

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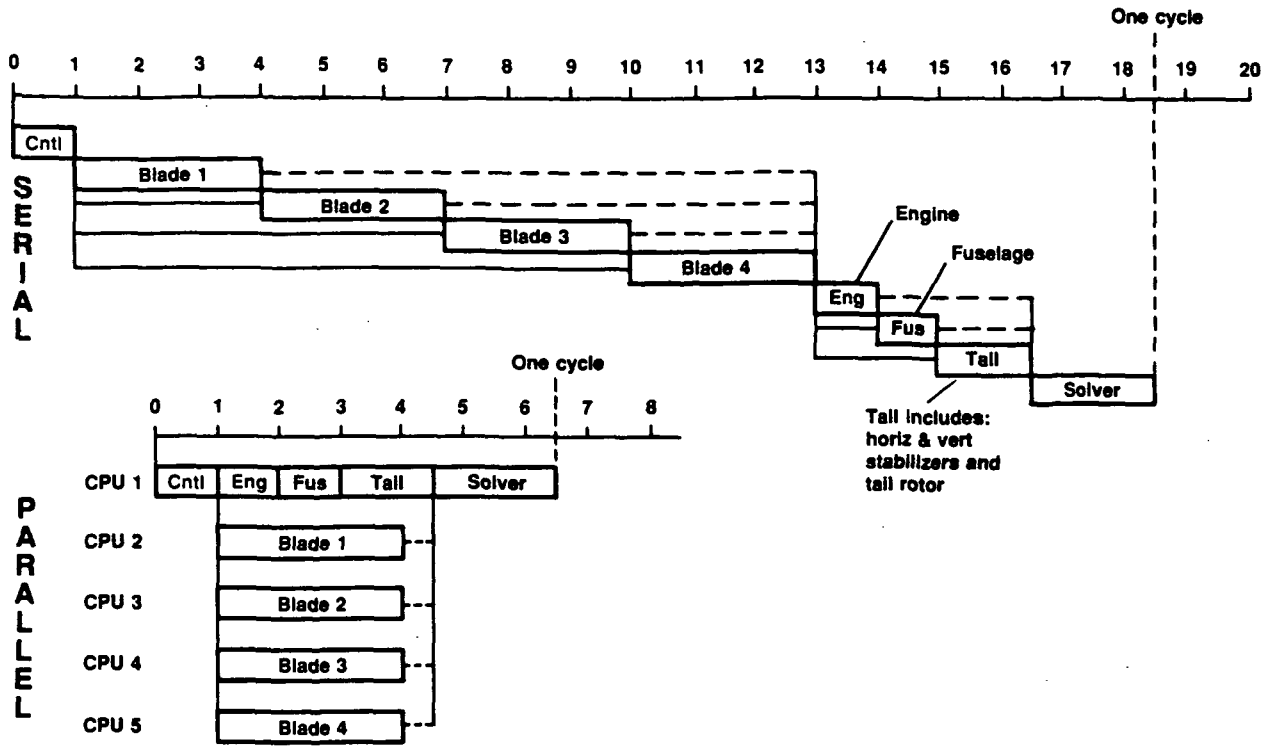

Figure 1. The parallelization process.

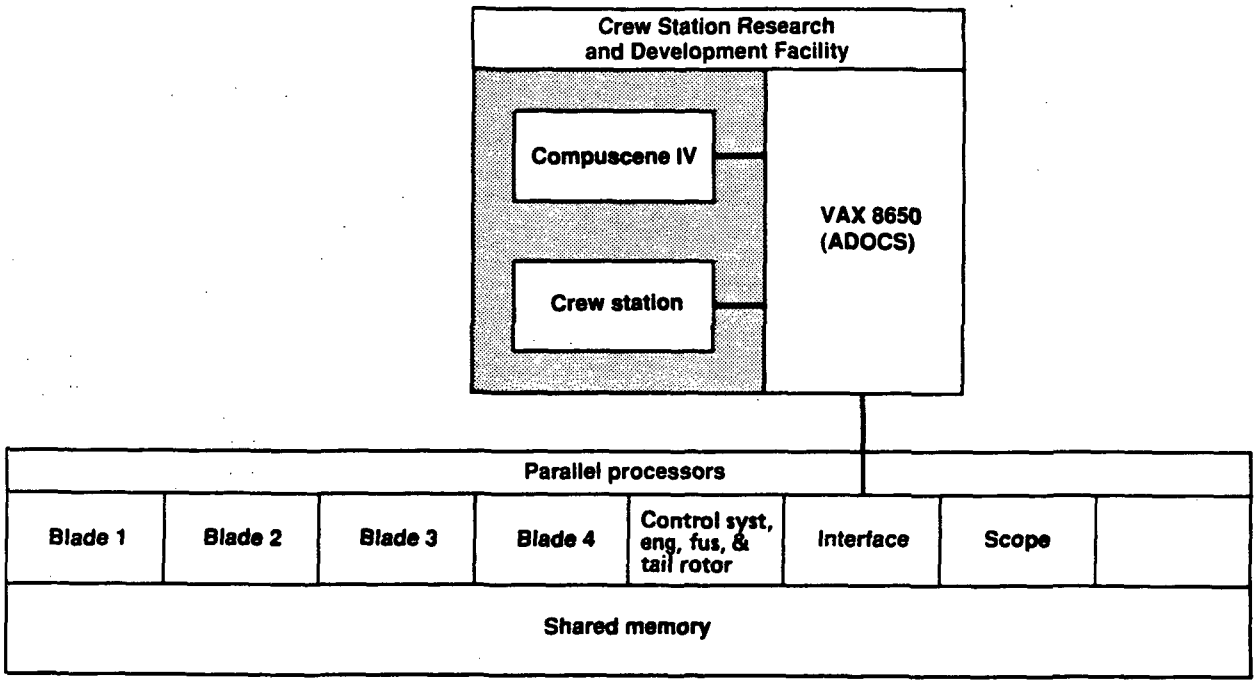

Figure 2. CSRDF/parallel processor architecture.

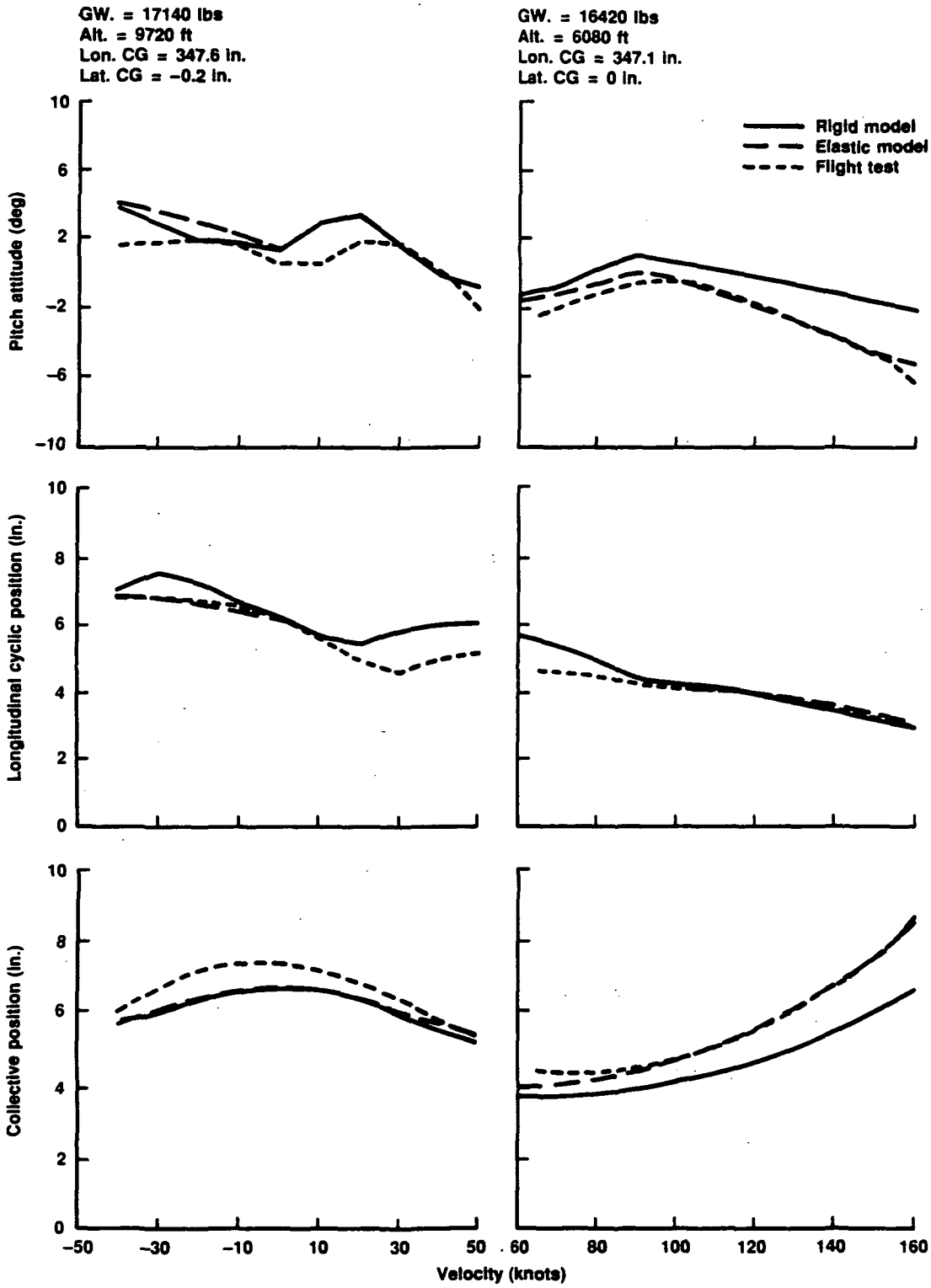

Figure 3. Trim comparison of rigid and elastic models with flight test data.

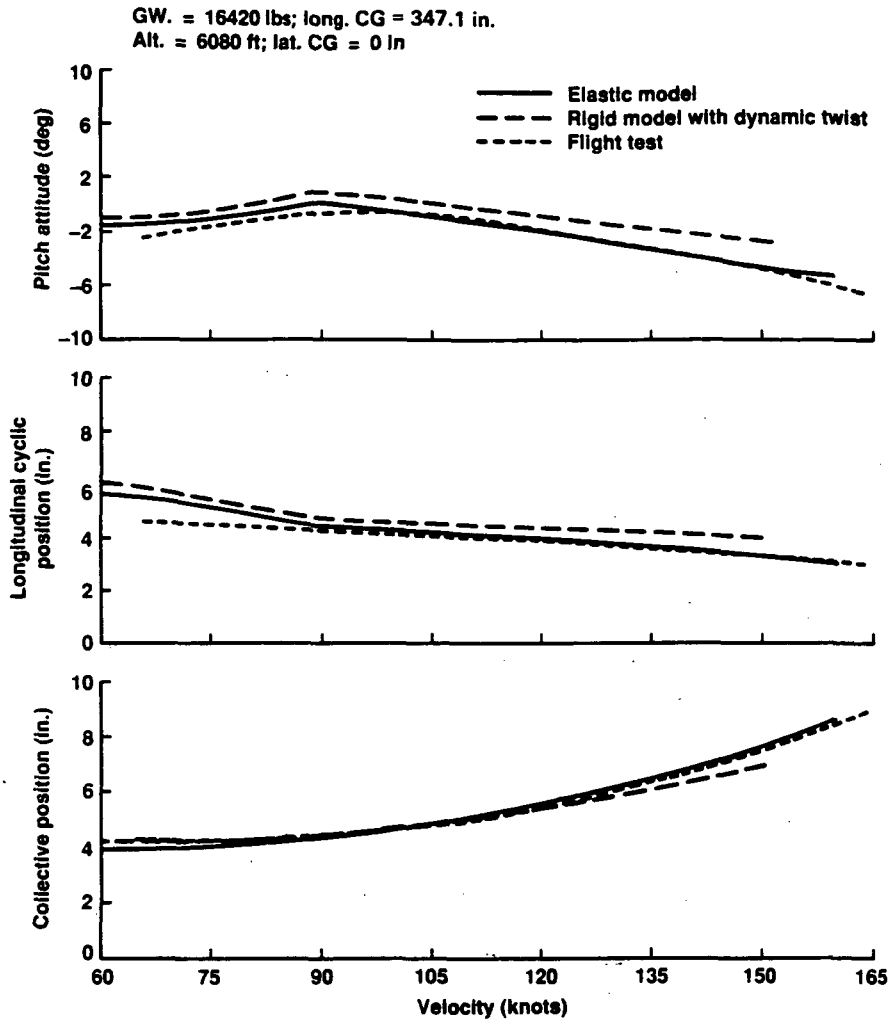

Figure 4. Trim comparison using dynamic twist.

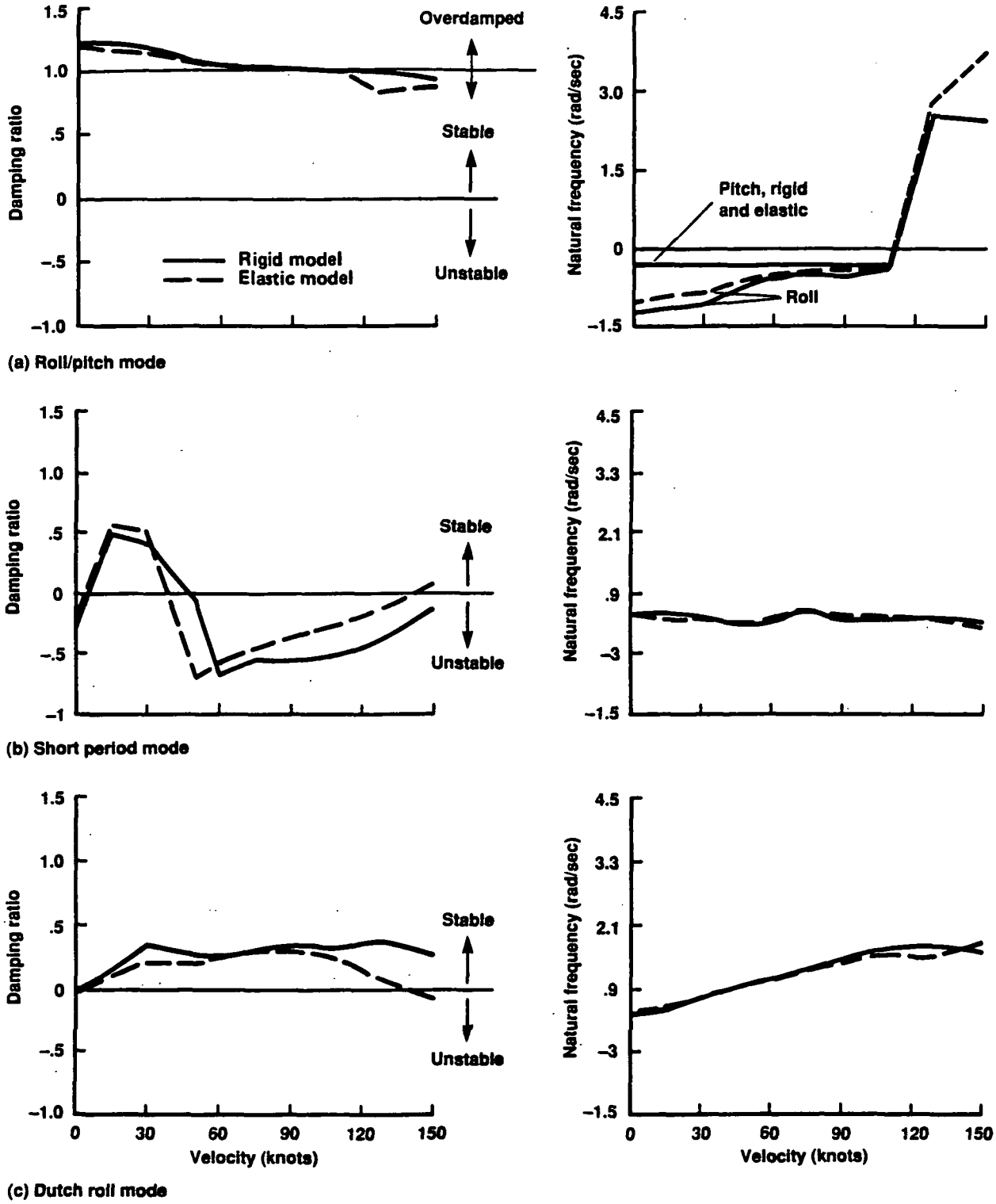

Figure 5. Damping and natural frequency for the open-loop roll/pitch, short period, and dutch roll modes.

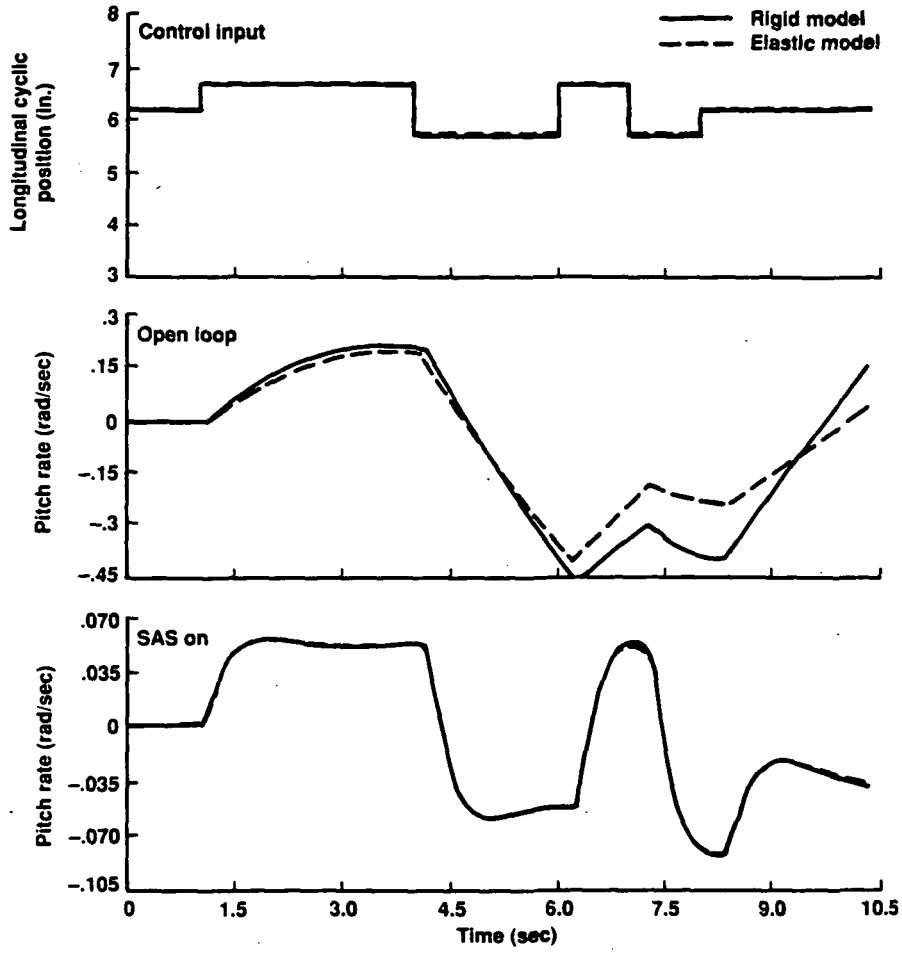

Figure 6. Dynamic comparison of rigid and elastic models at hover.

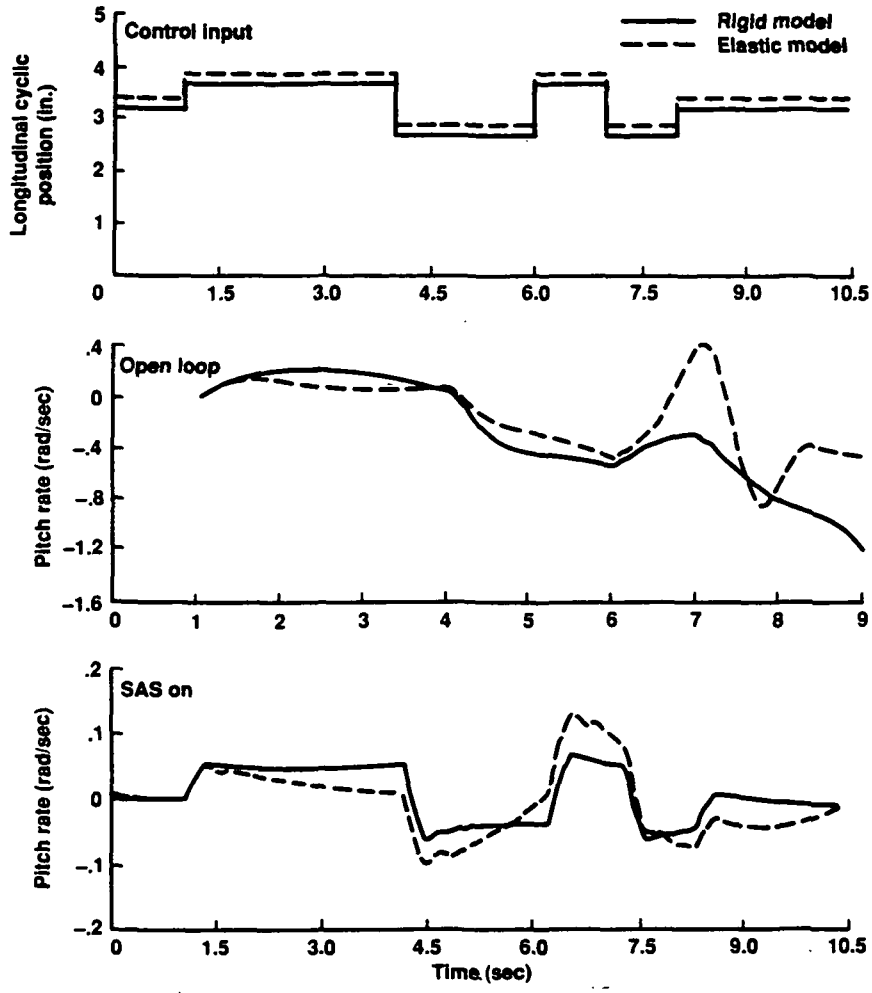

Figure 7. Dynamic comparison of rigid and elastic models at 150 knots.

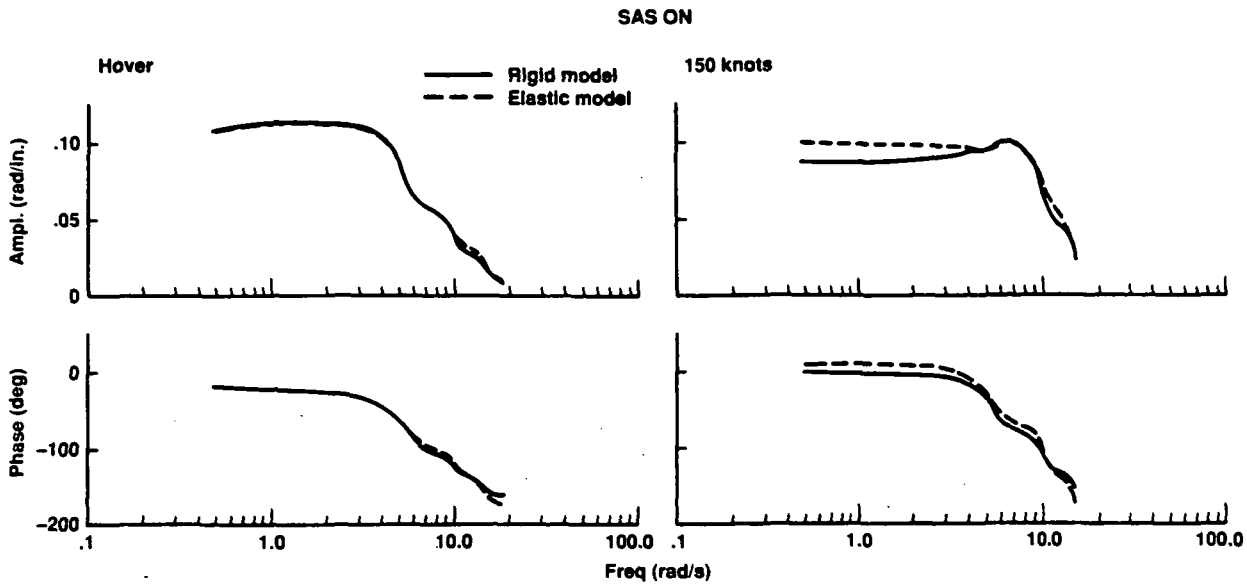

Figure 8. Comparison of rigid and elastic pitch-rate transfer function at hover and at 150 knots.

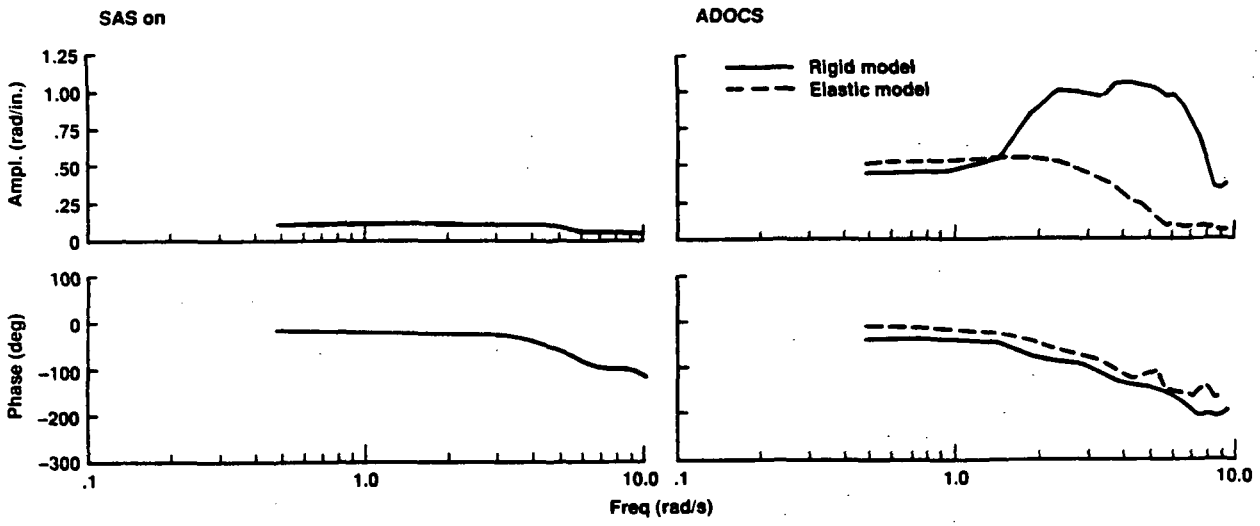

Figure 9. Comparison of rigid and elastic pitch-rate transfer function at hover for SAS and ADOCS controllers.

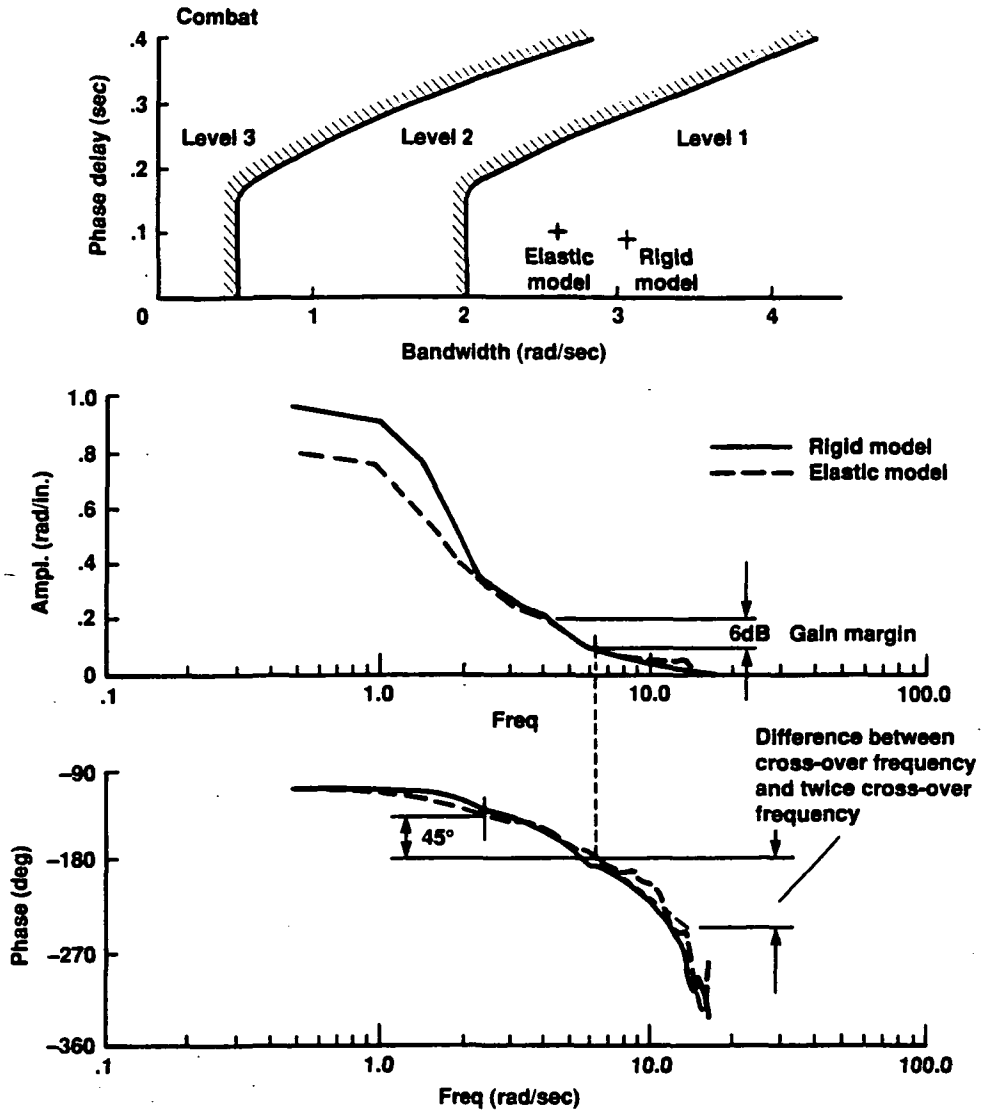

Figure 10. Short-term pitch response to control inputs using the ADOCS controller (80 knots) (air combat limits).

Maximum values for height response to collective controller

Level	$T_{\dot{h}_{eq}}$ (sec)	$\tau_{\dot{h}_{eq}}$ (sec)
1	5.0	0.20
2	∞	0.30

Actual values for height response to collective controller

Level	$T_{\dot{h}_{eq}}$ (sec)	$\tau_{\dot{h}_{eq}}$ (sec)
Rigid	1.7	0.17
Elastic	1.9	0.16

$T_{\dot{h}_{eq}}$ – Time to equalize climb rate

$\tau_{\dot{h}_{eq}}$ – Phase delay to equalize climb rate

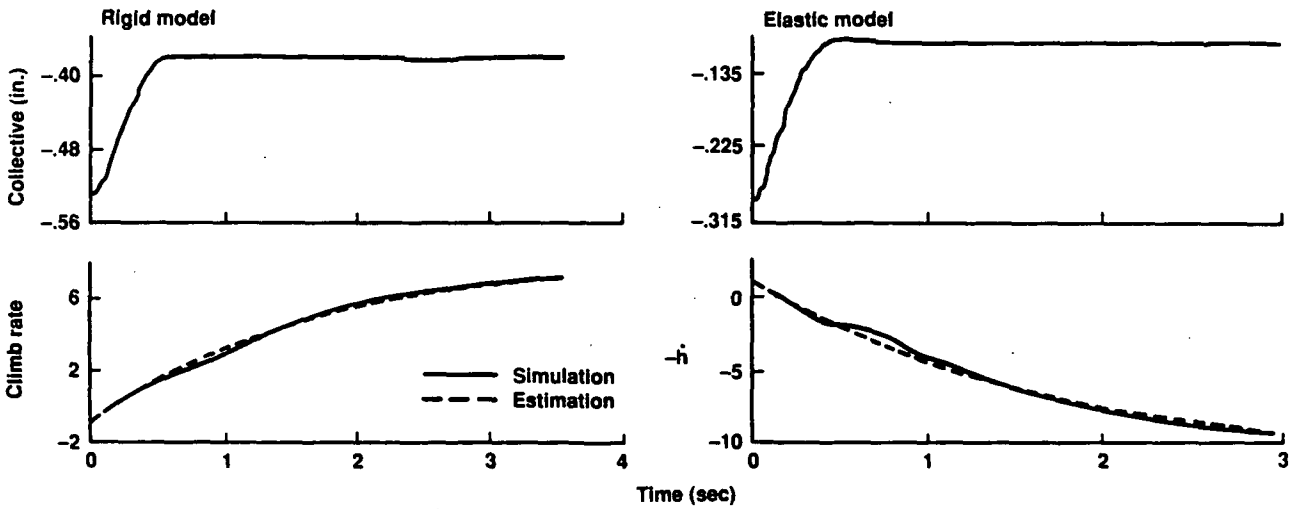

Figure 11. Height response to collective inputs using the ADOCS controller (hover).

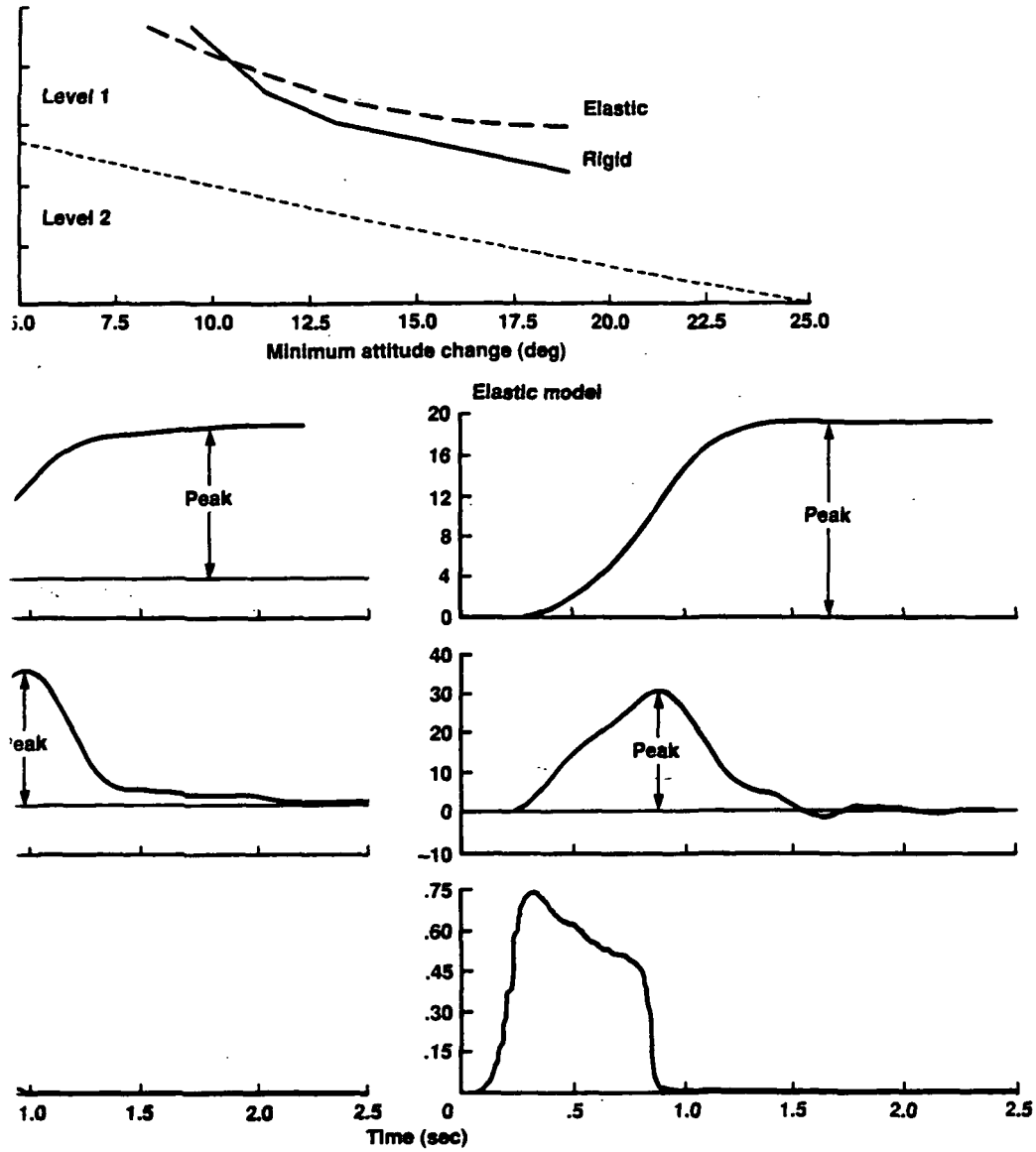

Figure 12. "Attitude quickness" comparisons for rigid and elastic models using the ADOCS controller (80 knots).

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16. Abstract

A piloted comparison of rigid and aeroelastic blade-element rotor models was conducted at the Crew Station Research and Development Facility (CSRDF) at Ames Research Center. FLIGHTLAB, a new simulation development and analysis tool, was used to implement these models in real time using parallel processing technology. Pilot comments and quantitative analysis performed both on-line and off-line confirmed that elastic degrees of freedom significantly affect perceived handling qualities. Trim comparisons show improved correlation with flight test data when elastic modes are modeled. The results demonstrate the efficiency with which the mathematical modeling sophistication of existing simulation facilities can be upgraded using parallel processing, and the importance of these upgrades to simulation fidelity.

17. Key Words (Suggested by Author(s))

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