N88-16643

ROTORCRAFT FLIGHT-PROPULSION CONTROL INTEGRATION

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SUMMARY

The NASA Ames and Lewis Research Centers, in conjunction with the Army Research and Technology Laboratories have initiated and completed, in part, a joint research program focused on improving the performance, maneuverability and operating characteristics of rotorcraft by integrating the flight and propulsion controls. The background of the program, its supporting programs, its goals and objectives, and an approach to accomplish them are discussed in this paper. Results of the modern control governor design of the T700 and the Rotorcraft Integrated Flight-Propulsion Control Study, which were key elements of the program, are also presented.

BACKGROUND

Dynamics interface problems involving the engine/fuel control and the helicopter rotor/airframe have been around for a long time. They include engine torque and fuel control system oscillations, multi-engine load-sharing, undesirable rotor speed variations during maneuvers, and excessive helicopter vibration. The helicopter rotor and drive train system have lightly damped torsional dynamic modes which are within the bandwidth of the engine fuel control system as shown in figure 1. This figure is a bar chart of frequencies at which various dynamic modes commonly occur in rotorcraft. It also shows the frequency ranges involved in rotorcraft design and analysis tasks and that the majority of these tasks require models that are accurate in a frequency range up to 10 hertz. In addition, the trend towards using lower inertia rotor systems in modern helicopters reduces the level of kinetic energy stored in the system and makes the rotor even more susceptible to large variations in its rotational speed during rapid maneuvers. These rotor and speed transients can increase pilot workload and can eventually lead to under-utilization of the aircraft's maneuvering capability because of pilot apprehension.

Toward the end of the 1970's the U.S. Army Applied Technology Laboratory instituted a contractural program designed to provide a complete report of past and present engine/airframe/drive-train dynamic interface problems. The result of this effort was a series of reports from several helicopter airframe manufacturers who documented their specific problems with vehicles developed over the last several years (refs. 1 to 5). The ultimate benefit was to be the accumulation of data that would eventually lead to a solution of these generic dynamic interaction-type problems. Although much of the documentation dwelt upon vibration and oscillatory loading problems related to rotor harmonics excitations, stability and response problems associated with the combining of two or more components or systems were universally stated. Dynamic interface problems of this type are among the last to be seen in the design of a subsystem such as an engine since they involve the presence of another subsystem such as a drive train and rotor.

The dynamic interface problems that are not anticipated in the design stage can surface later in the ground or flight test phases of a helicopter development program, requiring costly add-on modifications to "fix" the problems. The prediction of, and solution of, these problems require complementary interaction between manufacturers and the several technical disciplines. In future years, the satisfactory design of fully integrated systems will require more coordination among the airframe, engine, and control manufacturers.

PROGRAM GOALS AND OBJECTIVES

To examine potential benefits that might accrue from integrating the flight and propulsion controls, NASA Lewis and NASA Ames initiated a joint program to investigate advanced concepts in digital active flight-propulsion controls aimed at (1) improving precision flight path control, (2) expanding the operational flight envelope, and (3) reducing pilot workload. These goals are accomplished by applying a systems approach to the design of an integrated flight-propulsion control system to improve performance and handling qualities of the helicopter and evaluating the system through piloted simulation and actual flight.

APPROACH

The program orginally conceived consisted of three phases as shown on figure 2. Phase I included modeling and analysis and Phase II concerned itself with piloted ground-based simulation with integrated flight-propulsion controls. Phase III was a proposed flight hardware and software development program leading to a flight evaluation which has since been canceled. Phases I and II were part of an on-going NASA research and technology base program, and Phase III was a planned future activity. In executing this program, a coordinated effort was made which, in addition to NASA Ames and Lewis Research Centers, involved the participation of university, industry, and elements of the Army Aeromechanics and Propulsion Laboratories.

In Phase I, effort focused on the development and use of a comprehensive mathematical model for the combined helicopter/engine system for nonreal-time simulation of flight dynamics and parametric studies. A specific helicopter/

engine system, namely an Army/Sikorsky Black Hawk UH-60A with its GE T700-701 engines is used as the baseline. NASA Lewis Research Center developed the baseline T700 engine/fuel control system model for integration into the Black Hawk mathematical model. This engine model was correlated and validated by T700 ground tests conducted at NASA Lewis. NASA Ames correlated and validated the total system model with Black Hawk flight test data. The primary research emphasis of this phase of the program was to determine and quantify the key parameters that significantly influence the engine/helicopter rotor/airframe coupling and overall systems performance. Piloted simulations using both the vehicle and propulsion models developed by the respective flight and propulsion centers were conducted on the Vertical Motion Simulator (VMS) as depicted in figure 3 to assess the influences of those key system parameters on the handling qualities for important missions such as NOE flight, helicopter air combat, and search and rescue operations.

Coordinated contract effort and in-house research was pursued in Phase II of the program to develop integrated flight-propulsion control concepts. The contract effort involved a team of engine fuel control specialists and engine and airframe manufacturers. Promising concepts were evaluated on the nonlinear helicopter-engine model over a wide range of flight conditions and then further assessed using ground-based simulations and engine test. The merits were evaluated with respect to handling qualities, pilot workload, maneuver performance, engine performance, and mission capability using representative military and civil mission tasks.

SUPPORTING PROGRAMS

A number of supporting programs sponsored or conducted by NASA and the Army over the last several years are summarized here to provide background on previous work that led to and related to the current program.

Engine Governor Response Study

At NASA Ames, under a collaborative program with the Army Aeromechanics Laboratory, a sequence of piloted simulation experiments were conducted on the VMS to investigate, in a generic sense, the effects of engine response, rotor inertia, rotor speed control, excess power, and vertical sensitivity and damping on helicopter handling qualities in hover and representative low-speed NOE operations (refs. 6 to 8). It was found that variations in the engine governor response time can have significant effect on helicopter handling qualities as shown in figure 4. Satisfactory (Cooper-Harper pilot rating) handling qualities and rotor speed control were acheived only with a highly responsive governor. An effective engine governor time constant of no more than 0.25 seconds was required to achieve a satisfactory level of handling qualities over a wide range of aircraft vertical damping. Increases in the effective engine governor time constant resulted in poor rotor overspeed and underspeed control.

In addition to requiring rapid engine response time, an appropriate level of excess power, or thrust-to-weight ratio, is required to achieve satisfactory handling qualities for many maneuvers. The excess power requirements for the NOE tasks were investigated with various levels of vehicle vertical damping. In addition to the required engine response time mentioned earlier, an appropriate level of excess power as shown in figure 5 was found to be required to achieve satisfactory handling qualities for the bob-up task evaluated. Results indicated that the required level of excess power is a strong function of the vertical damping and is minimized at a vertical damping of around -0.8 radians per second.

The thrust response of a helicopter is influenced not only by engine governor dynamics and vertical damping, but also by the energy stored in the rotor which is a function of its inertia. The experimental results indicated, however, that increase in rotor inertia had only a minor but desirable effect on handling qualities. The effect of handling qualities on requirements for pilot monitoring and control of rotor speed was found to be significant. Thus, techniques to relieve the pilot of the task of monitoring and control of rotor speed warrant serious consideration.

Small Turbojet Engine Program

NASA Lewis and the Army RTL Propulsion Laboratory have participated in a cooperative program to conduct digital controls research for small turboshaft engines (ref. 9). The emphasis of the program is on engine test evaluation of advanced modern control logic using a flexible microprocessor-based digital control system. The digital control system used is designed specifically for research on advanced control logic. Control software is stored in programable memory. New control algorithms may be stored in a floppy disk and loaded into memory to facilitate comparative evaluation of different advanced control modes. Software checkout is accomplished prior to engine test by connecting the digital control to a real-time hybrid simulation of the engine.

The engine used in the facility was a General Electric YT700. The hydromechanical control was modified to allow electrohydraulic fuel metering and variable guide vane actuation by the research digital control. The research objective was to demonstrate improved power turbine speed governing using modern control theory as compared to the baseline governor control.

Modern Control Governor Design Study

Under the program described above, General Electric recently completed a study under contract to NASA Lewis for the design of a turboshaft speed governor using modern control techniques (ref. 10). Among the objectives of this research program was a requirement to design a high performance power turbine speed governor using modern control methods. A power turbine governor was designed using the linear quadratic regulator (LQR) method of full state feedback control. A Kalman filter observer was used to estimate helicopter main rotor blade velocity. Simulation results, as shown in figure 6, show that the modern control provides better rotor speed governing than the baseline control. Shown is the power turbine speed response to an acceleration caused by a 40 to 70 percent collective pitch increase in 0.1 second. The transients were made with the Black Hawk rotor using the nonlinear DISCUS model, the manufacturer's reference performance standard transient model model of the T700 engine, without load demand spindle compensation. Overall, compared to the baseline T700 power turbine speed governor, the LQR governor in this study reduced droop up to 25 percent for a 490 shaft horsepower transient in 0.1 second simulating a wind gust, and up to 85 percent for a 700 shaft horsepower transient in 0.5 second simulating a large collective pitch angle transient. Unfortunately, the control design was never evaluated experimentally since the program was terminated at NASA Lewis. More detail on the modern control technique used in this study follow later in this paper.

Adaptive Fuel Control Program

The Adaptive Fuel Control program, sponsored by the Army ATL Research and Technology Laboratories, is an outgrowth of the full authority digital electronic control used on the ATDE (refs. 11 to 13). The objective of Phase I, the feasibility investigation, was to determine the feasibility of designing an electronic control with the capability of adapting its control characteristics while in operation to optimize engine performance. The first step was to identify the prospective adaptive concepts to be investigated and then analyze them using a flight dynamics simulation. The concepts which proved feasible were incorporated into a preliminary design. Phase II of the program was to use the results of Phase I to fabricate an electronic control and conduct bench and engine tests. Phase III is a current activity of the program which brings the adaptive controller into a flight test program. The objective here is to verify the performance of the adaptive control during flight for expected improvements in maneuverability, engine control, torsional stability and pilot workload. In addition, the modern control concept discussed in the previous section will also be flight evaluated.

The Adaptive Fuel Control program has identified significant benefits in agility and reduced pilot workload through the use of several digital fuel control elements for improved rotor speed governing. References 11 to 13 present the results of the program to date. Using combined aircraft and propulsion control simulations, improvements in handling qualities and vehicle performance were noted. For example, significantly reduced rotor speed droop following power recovery from autorotation was shown. Conventional fuel controls in rotorcraft have particular trouble with flight profiles that generate high g fields. A typical example of such a maneuver is the quick-turn evasive maneuver. Figure 7 illustrates the performance of the adaptive control in comparison to the conventional baseline control for such a maneuver. The maneuver was performed from level flight at 120 knots. A bank angle of 60° and 2.5 g's were achieved. The critical issue here is the engine torque recovery when the pilot rolls out of the turn at the 6 second mark. Since collective pitch is not being modulated and the rotor is decoupled from the power turbine, the baseline control has no information with which to arrest the decay rate of the rotor. A subsequent rotor speed droop occurs to the detriment of aircraft flying qualities. The adaptive control, however, sensing rotor speed decay, invokes its rotor decay anticipation feature to spool up the engine and provide for a smooth engine torque recovery. Power recovery time delays are eliminated, rotor speed droop and subsequent overspeed are minimized, and engine torque applications are smooth. When compared to the baseline case, a significant improvement in flying quality has been achieved with the adaptive control.

The Adaptive Fuel Control study also identified a significant benefit from variable rotor speed during cruise. Rotor speed optimization was found to reduce fuel consumption by 5 to 10 percent for some cruise conditions. Although the focus of the program is on improved propulsion controls, it provides a strong basis further work on integrated flight-propulsion controls.

ROTORCRAFT INTEGRATED FLIGHT-PROPULSION CONTROL STUDY

On the basis of the program described above, the next logical step in the progression of the programs described above was to consider vehicles which will have both digital flight and propulsion controls and to identify the benefits in mission performance for a fully integrated digital flight-propulsion control system. As a part of satisfying that need, NASA Lewis contracted with Sikorsky Aircraft Division of United Technologies Corporation to investigate the benefits of integrating the flight and propulsion control systems in helicopters. The Sikorsky UH-60A Black Hawk helicopter with General Electric T700 engines was used as a typical modern rotorcraft for this effort because state-of-the-art vehicle and propulsion simulations were available for domestic dissemination.

Sikorsky Aircraft conducted a study whose primary objective was the identification of the benefits associated with an integrated flight-propulsion control system for rotorcraft. This was accomplished by designing such a system, following appropriate concept screening, then incorporating and evaluating the integrated control in a NASA supplied Black Hawk/T700 simulation and further recommending experiments to be conducted by NASA using the VMS at NASA Ames with their modified Black Hawk simulation. The work was performed at Sikorsky Aircraft and was supported by General Electric and the Chandler Evans Division of Colt Industries. A detailed report will be available in the near future (ref. 14).

Study Summary

An eclectic approach, taking the best features of past flight and propulsion control concepts, as opposed to a global approach, an approach which considers the system without prior control system knowledge, was taken in a study of the integration of digital flight and propulsion controls for helicopters. The basis of the evaluation was a current simulation of the UH-60A Black Hawk helicopter with a model of the GE T700-GE-701 engine developed by NASA.

A list of segments of flight maneuvers to be used to evaluate the effectiveness of the resulting integrated control system was composed based on past experience and an extensive survey of the recently acquired U.S. Army Air-to-Air Combat Test (AACT) data.

A number of possible features of an integrated system were examined. Those chosen were combined into a design that replaced the T700 fuel control and part of the Black Hawk control system. This design consisted of portions of an existing pragmative adaptive fuel control design by Chandler Evans and an LQR-based power turbine speed governor design by General Electric. These design features were integrated with changes in the baseline Sikorsky flight control system.

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A cursory assessment of the design is presented here with a summary provided for each of the major elements of the study.

Aircraft Modeling

Aircraft simulation model. - The mathematical model of the Black Hawk is a generalized and modularized analytical representation of a total helicopter system developed under Sikorsky's Master Generic Helicopter (MGH) system (ref. 15). It normally operates in the time domain and allows the simulation of any steady or maneuvering condition which can be experienced by a pilot.

The basic model is a total force, nonlinear, large angle representation in six rigid degrees of freedom. In addition, rotor rigid blade flapping, lagging and hub rotational degrees of freedom are represented. The latter degree of freedom is coupled to the engine and fuel control. Motion in the blade lag degree of freedom is resisted by a nonlinear lag damper model.

The total rotor forces and moments are developed from a combination of the aerodynamic, mass and inertia loads acting on each simulated blade. The rotor aerodynamics are developed using a blade element approach. The fuselage is defined by six component aerodynamic characteristics which are obtained from wind tunnel data which have been extended analytically to large angles.

The baseline flight control system for the Black Hawk presented in this model covers the primary mechanical flight control system and the Automatic Flight Control System (AFCS). The latter incorporates the Stability Augmentation System (SAS), the Pitch Bias Actuator (PBA), the Flight Path Stabilization (FPS) and the stabilator mechanization. The analytical definition of the control system incorporates the sensors, shaping networks, logic switching, authority limits and actuators.

Model correlation. - The present MGH representation of the Black Hawk has been correlated with flight test data (ref. 16). In trim, the small number of rotor blade segments and lack of detailed corrections prevent its use for predicting aircraft performance to within performance guarantee levels. However, trim attitudes and control positions are adequately forecast. Dynamically, MGH shows good correlation with aircraft motion taken from flight test data. The simulation system is routinely used for the successful prediction of design values for primary control systems, SAS, first torsional engine/rotor oscillations and aircraft coupled and uncoupled motions.

Propulsion System Modeling

High-fidelity propulsion system modeling is necessary in the investigation of integrated flight and propulsion controls for rotorcraft. Because advanced propulsion control strategies may involve monitoring or estimation of internal engine states, an accurate internal representation of the engine is required. The present generation of real-time blade-element rotor helicopter simulations such as GEN HEL, a derivative of MGH models, are able to accurately model individual blade dynamics at such a bandwidth necessary for propulsion system modeling. Because rotorcraft propulsion system load demand typically varies from zero power to full power, the model must be valid over the full power range of the actual engine. It must also be valid over a complete range of ambient operating conditions. Engine param- eters of primary importance to real-time handling qualities investigations include output torque and dynamics of the gas turbines which are necessary for pilot sound cueing as well as for modeling of power output. Also important are parameters used by the fuel control system, such as compressor discharge static pressure and internal engine temperatures. Of somewhat less importance are the internal mass flows, which may be used to determine proximity to limits such as compressor stall.

Available real-time models are based on simple power versus fuel flow relationships. In more sophisticated models, engine dynamics are based on experimentally determined partial derivatives of changes of output torque to changes in turbine speed and fuel flow. Such models are unsatisfactory because needed internal engine states may not be modeled. In addition, dynamic characteristics of existing models have shown poor results in validation with experimental data (ref. 16). Partial derivative models tend to be valid only for a limited range of operating conditions. Because they are not based on the physical phenomena which they represent, their validity is always in question when used under conditions at which they are not optimized.

A relatively high level of fidelity is achievable by using an engine model made up of individual engine components, each of which is modeled based on physical laws relating the dynamics of mass flow and transfer of energy. Such component-type simulations are used by engine manufacturers to study the transient behavior of engines, but they are usually far too complex for use in real-time digital simulation. A component engine model which is simplified for real-time use is the most promising alternative to partial derivative engine representations. It was therefore chosen in this study to be appropriate for the study of flight and propulsion controls integration.

In addition to a sophisticated engine model, accurate physical models of the fuel control system, mechanical actuators and linkages, and the engine sensors are necessary for a correct representation of closed-loop propulsion system dynamics, engine protection control, and the effects of modification of the propulsion system control. Similarly, the vehicle drive train and accessory loads must be modeled so that an acceptable representation of the power requirements of the vehicle is obtained.

Engine description. - The engine modeled, shown in figure 8, is a General Electric T700-GE-701, a small turboshaft engine of the 1500 horsepower class which is used in the UH-60A Black Hawk and the AH-64 Apache helicopters. It consists of a five stage axial and a single stage centrifugal flow compressor, a low-fuel-pressure through-flow annular combustion chamber, a two stage axial gas generator turbine, and a two-stage independent power turbine (ref. 17). The first two stages of the compressor use variable geometry inlet guide vanes and stator vanes, and air is bled from the compressor exit to cool the gas generator turbine. The power turbine has a coaxial driveshaft which extends forward through the front of the engine where it is connected to the output shaft assembly.

The T700 baseline, or bill-of-material, fuel control system provides power modulation for speed control, overtemperature protection, and load sharing between engines for multiple-engine installations. It consists of a hydromechanical control unit (HMU) for fuel metering as a function of schedules of gas generator speed and power demand, and an electrical control unit (ECU) which performs power turbine speed governing and overtemperature protection (ref. 18). A feed-forward compensation of load demand is achieved by adjusting the set point as a function of collective control. The compressor variable geometry is also controlled as a function of inlet temperature and gas generator speed. The ECU provides output shaft speed control by driving a torque motor in the HMU based on a power turbine speed error signal. The torque motor, which is controlled by the ECU, adjusts the HMU fuel demand downward so that an electrical system failure results in a higher power. Power turbine inlet temperature is also monitored and fuel flow is reduced when it exceeds limits. Power may also be increased if torque is determined to be lower than that of another engine operating in parallel.

Engine model. - As a part of ongoing research in turboshaft engine technology, a component-type mathematical model was developed by NASA Lewis for real-time hybrid computer simulation (ref. 19). It is a greatly simplified version of the component version of the component-type analysis program developed by the manufacturer and, although it is inappropriate for engine development purposes, it is at a level of sophistication necessary to model the operating condition of the engine as well as engine transient behavior. It was chosen to serve as the basis for development of a digital simulation which is adequate for use with real-time blade-element rotorcraft simulations.

A diagram of the major components separated by mixing volumes is shown in figure 9. The four major components are separated by fluid mixing volumes. Each of the fluid mixing volumes is associated with flow passages within the engine where thermodynamic states are quantifiable. States of the gas in each control volume are expressed in terms of pressure, temperature and mass flow. They are determined as functions of energy transfer across each component. Equations describe each component in terms of the component state, thermodynamic states upstream and downstream of the component, energy applied to or from the component, and efficiencies of energy transfer. Dynamics of the rotating components are modeled by relating changes of angular rotation of a given component to its moment of inertia and the applied torque. A load from an external source is required to determine power turbine and output shaft speed. Losses associated with fluid dynamic or mechanical processes are represented by single or multivariable functions based on previously derived or empirical data. Inputs to the simulation consist of ambient temperature and pressure at the inlet, pressure at the exhaust, and fuel flow.

Modeling simplifications made in the development of the NASA Lewis hybrid simulation model were based on a general simulation technique developed at NASA Lewis (ref. 20) as well as experience with small turboshaft engines. Power turbine efficiency as a function of its speed was neglected because, for the designed use of the model, the power turbine deviates only a few percent from its design speed. No modeling of compressor surge, heat soak losses or exhaust pressure losses was attempted. Linear relationships were used to describe secondary effects such as bleed flows. Dynamics of the variable geometry guide vanes were assumed to be instantaneous. A digital program was then produced using the Continuous System Modeling Program (CSMP) which accurately reproduced steady-state operation of an experimental test article operated at NASA Lewis.

In the development of a real-time model, the CSMP model was used as a basis to develop a program in FORTRAN using real-time digital programming methods. During the validation, it was discovered that the original model contained too much simplification to correctly model engine dynamics. Consultation with the engine manufacturer resulted in the addition of models for losses caused by heat dissipation within the gas generator and exhaust flow downstream of the power turbine. A model of power turbine efficiency as a function of its speed was also found to be necessary to model the low power closed-loop dynamic response properly. The HMU required the addition of metering valve and collective anticipation lags, fuel transport delay and combustor lag, and models of sensor hysteresis. The ECU also required a more sophisticated model of torque motor dynamics.

Real-time implementation of engine model. - Each of the control volumes within the engine is associated with a temperature, pressure and change of mass of the air and fuel. During steady-state operation of the engine, a state of equilibrium exists between the control volumes for each of these parameters. A change in the state of any control volume creates pressure and mass flow changes in the other control volumes until a new equilibrium is achieved. The dynamics associated with this change are very rapid and therefore have a negligible effect on the lower frequency engine and vehicle dynamics. Discrete modeling of such high frequency dynamics necessitates stepping forward in time with extremely small increments resulting in a high computation overhead which is unacceptable for real-time simulation. A quasi-static approximation of the volume dynamics of the engine was therefore made. High-speed dynamics were eliminated by approximating pressures and mass flows within the mixing volumes to be in equilibrium at all times.

Several existing real-time and nonreal-time computer models of turbojet engines use the quasi-static volume dynamics approximation (refs. 21 to 23). Methods differ in the application of a numerical scheme which allows an iterative convergence to equilibrium with a minimum use of computation time. An opened iteration scheme is normally used, sometimes in conjunction with a set of predetermined partial derivatives of engine states. However, an opened iteration does not allow control of convergence or of the amount of error produced. A fixed-point iteration method was found to meet the requirements of computational efficiency and small error. A successive overrelaxation technique was used to control the speed of convergence.

Engine model validation. - Steady-state engine performance was verified to be within normal limits of operation by comparison with the experimental engine operated by NASA Lewis and with DISCUS. Loading conditions were duplicated by using a model of the NASA Lewis test engine dynamometer described in reference 9. The load is variable based on a simulated collective pitch control input. This input is used to trim the engine at the design shaft speed for a specified fuel flow. Excellent agreement was obtained with the manufacturer's model. Gas generator speed was found to have a maximum error of 1 percent while output torque error is less than 4 percent. Hot section temperatures also correlated well with a maximum error in gas generator turbine inlet temperature of less than 1 percent with a corresponding error in power turbine inlet temperature of slightly over 1 percent. Comparison of the real-time model with NASA experimental engine test resulted in fair agreement. The experimental engine is a prototype model which does not reproduce specification performance. Real-time model turbine speeds were within 3 percent of the test engine speeds. However, temperatures at the power turbine inlet were 6 to 7 percent lower than those of the test engine.

Transient operation was validated by comparison to DISCUS-generated time histories. The control system was disconnected so that transients resulting from direct fuel flow inputs could be compared. Under these conditions, large changes of fuel flow result in large changes of power turbine speed. Power turbine efficiency is modeled as a function of its speed in the real-time model only for small speed excursions about the design point. Transient data were therefore received from executions of the manufacturer's program with the power turbine dynamics suppressed, allowing power turbine speed to be constant. Output torque was then used as a measure of engine power. Fuel inputs were applied as instantaneous steps.

Results are illustrated in figures 10 and 11. As shown in figure 10, the two simulations are in close agreement for a step increase from mid-power to high power. Gas generator speed is overestimated by approximately 2 percent, due mainly to performance map approximations, whereas the output torque responses correlate well. Power turbine inlet temperature is underestimated by the real-time program. This discrepancy is a characteristic of the model which was experienced under all validation conditions. Because the error is small and dynamic characteristics are retained, the modeling of power turbine temperature is considered adequate. Low power engine performance is shown in figure 11, which represents a step decrease in fuel flow to below idle power. The real-time model torque again shows close agreement with DISCUS. Gas generator dynamics are also accurately modeled.

An example of the closed-loop engine performance with the blade-element helicopter simulation is shown in figure 12. Flight test data obtained from reference 16 were used as inputs to the real-time program and test results are included for comparison. Turbine speeds and torque output are reproduced correctly. Discrepancies seen in fuel flow are attributed to the location of the sensor used on the test vehicle. This sensor was mounted upstream of the HMU's sensor and therefore did not correctly reproduce the fuel flow transients.

Integrated Flight-Propulsion Control Design

The following sections highlight each element of the integrated control design concept and explain its purpose and the techniques used to integrate the feature into the overall system. Because the design is presently a computer simulation, no attempt was made to determine which part of the control software belongs on which processor or the optimal routing of signals between sensors, actuators, and processors that might be applied to a practical flight vehicle implementation. Memory requirements and execution speeds were not considered.

The core of the controller is a modern control power turbine speed governor whose reference speed may be modulated by various combinations of variables representing present or anticipated airframe-engine states. The power turbine governor itself consists of a linear quadratic regulator state feedback algorithm in which rotor tip speed is estimated by a Kalman filter. Additional adaptive logic is used to anticipate rotor decay and help recovery from the declutched state. The traditional collective pitch-to-load demand spindle input to the fuel control is retained but in digital form. The equally traditional collective pitch-to-tail rotor collective link is replaced by a measured engine torque-to-tail rotor collective link. An indication of power available to hover is provided for the pilot. A cue for inhibiting the application of collective input while the fuel control is on its acceleration schedule is provided by a logic signal. A variety of collective movements following engine failure, depending on height and velocity, are available. A switchable fuel consumption minimizer operating in conjunction with added loops in the AFCS is also available.

Linear quadratic regulator power turbine speed governor. - The purpose of a power turbine governor for helicopter applications is to maintain constant power turbine governor speed in the presence of torque load changes in the helicopter rotor system. Such governors in the past have used feedback of the speed error from some reference value to regulate fuel flow to the engines with an integrator added to the error loop so that the steady-state error could be removed. This results in a governor that maintains speed at the reference value (isochronous) under all steady loads, transients loads not withstanding.

A limitation on this form of governor is caused by the existence of two torsional resonances in the drive train system. The resonances are caused physically by the engine and drive-train rotational freedom working against the blade lag freedom. The torsional resonances of the UH-60A articulated rotor blade/drive system occurs at a frequency of the order of 2.7 hertz with the torsional resonance of the tail rotor/drive-train at about 7 hertz.

The advent of all-digital controls has made the proportional-plus-integral governor easier to implement and has opened the door to more sophisticated mathematical techniques for overcoming the torsional mode problem. Use of higher order notch filters to attenuate response at the first torsional frequency have been implemented successfully (ref. 24). General Electric's approach in the integrated control study presented here is to employ a linear quadratic regulator (LQR) design which allows the bandwidth to be increased and thus improve the response time of the system.

The LQR technique was used to design the power turbine speed governor and a Kalman filter was included in the control system to estimate the helicopter main rotor blade velocity as one of the states in the design (ref. 10). The effect of the LQR governor in the frequency domain is to attenuate the resonant first torsional mode peak.

The LQR governor was analyzed in the frequency domain using standard Bode plot techniques to determine the system stability margins, speed of response, and disturbance rejection characteristics. The frequency response of the closed-loop LQR and T700 baseline systems was calculated for a main rotor torque disturbance and a tail rotor torque disturbance to analyze the effects on power turbine speed and helicopter main rotor speed. The simulated disturbance was a sine-wave frequency sweep. Each disturbance was input separately. The response of power turbine speed to a main rotor disturbance is shown for the LQR governor and for the T700 baseline governor in figure 13. The figure shows that disturbances are rejected better by the LQR power turbine speed governor than by the T700 baseline governor. The LQR governor provides adequate phase and gain margin for good stability and robustness. The resonant peak attenuation combined with large phase margin allows the system gain to be higher and results in the increased bandwidth.

The higher bandwidth also translates directly into better performance in the time domain. Shown in figure 14 is a load disturbance in the rotor system caused by a simulated wind gust of 40 feet per second over a distance of 200 feet. The LQR power turbine speed governor reduced the speed droop from 3.25 percent to 1.3 percent. The baseline control has several small oscillations before the system stabilizes. The LQR governor virtually eliminates these oscillations demonstrating its better phase margin.

<u>Pragmatic adaptive control elements</u>. - The adaptive fuel control as designed and currently under development by Chandler Evans is fully described in references 11 and 25.

Figure 15 shows a block diagram of the integrated control system which includes the LQR power turbine speed governor, the gas generator acceleration governor (NDOT) and the adaptive elements. The fuel flow features of the control, other than the LQR governor, derive from the pragmatic adaptive system.

The adaptive features which affect the power turbine set speed in the integrated control system are applied to the LQR power turbine speed setpoint. These features include rotor decay anticipation, rotor droop recovery, load factor enhancement, torque sharing, and minimum fuel optimization. Collective rate anticipation was not included since the LQR governor had its own collective pitch maps.

For the autorotational rotor decay anticipation, the adaptive control provides a flag which signals when the system goes into autorotation. This flag is used by the LQR governor to temporarily convert it into a proportional-plus-integral controller with a low gain since the LQR feedback paths add no information to the LQR control during autorotation. The autorotational rotor decay anticipator, acting upon the autorotation flag, generates an incremental power turbine speed reference to the LQR controller to keep the power turbine at a higher acceleration potential so that engagement of the engine and rotor will occur at a higher engine speed and thereby reduce droop. The effect of this control element was discussed earlier in the Adaptive Fuel Control Program section.

The logic of the droop compensator subsystem is to detect that a droop has occurred and to inhibit the likely torque and subsequent speed overshoot that will follow. This is accomplished by deliberately delaying the governor demanded fuel flow. As the droop starts to diminish, a signal is generated that reduces the power turbine speed reference, thus, reducing torque load and speed overshoot.

Three further subsystems can influence the fuel flow by changing the power turbine speed reference signal in the LQR power turbine speed governor. The first is a dual installation torque sharing device which is the digital equivalent of the baseline T700 controller. This controller indirectly speeds up the gas generator of the low torque engine to match the output of the nondegraded engine by applying an incremental power turbine speed reference signal proportional to the torque error to the lower engine.

The second subsystem is the minimum fuel consumption optimizer. This is an extremely simple algorithm which, when switched on in cruise, samples the fuel flow at intervals and perturbs the power turbine speed reference signal to change the rotor speed. Figure 16 shows the results achieved by the simulated MGH Black Hawk system.

The third subsystem is the load factor enhancement feature. In general, it is possible to increase the aerodynamic load factor capability of a helicopter by increasing the rotor speed. Figure 17 shows the order of magnitude of the effect as predicted by the MGH simulation. The form of this subsystem involved ramping an increment in rotor speed reference proportional to pitch rate and keeping it on for a set time after the load factor is removed. This tends to keep the engine spooled up for a longer time and thus able to better deal with large torque increases should the rotor pop in and out of an autorotative state.

The integrated control nominally operates on the LQR power turbine governor. In extreme maneuvers, it will be limited on the top end by the NDOT governor and on the low end by the bottom governor and NDOT deceleration limiter. On each cycle of the control computer these limits determine the upper and lower extremes of the allowable fuel flow.

The acceleration schedule is the usual control which seeks to inhibit compressor surge by allowing the gas generator to accelerate in a preprogrammed fashion with maximum acceleration as a function of gas generator speed. Chandler Evans has also incorporated their adaptive surge margin compensation feature which also uses a lagged compressor discharge pressure to further stabilize surge recovery.

The gas generator topping speed action simulates the action of the power available spindle in acting as an upper limit throttle on gas generator speed and thus maximum engine power output. The intent of this limiter on the baseline T700 fuel control is to give the pilot some control if the electronic function should fail. Its retention in the integrated control gives similar control action.

The temperature limiting section is a straight-forward digital implementation of a power turbine inlet temperature limiter. A logic switch, which is triggered by the engine-failed status flag of the other engine in a twin engine installation, can boost the allowable temperature for emergency power situations.

The lowest output of the above three governor sections is passed to the gas generator acceleration governor (NDOT) section which produces an error signal from the difference between its integrated value and the sampled gas generator speed value and then calculates a weighted proportional-plus-integral type gain which it multiplies by lagged compressor discharge pressure. The resulting fuel flow is the gas generator fuel flow which is compared with the LQR power turbine speed governor flow on a lowest-wins basis. The three components of the gas generator speed governor thus serve as alternate top limits to the fuel flow.

A prescribed deceleration schedule is provided to ensure sufficient margin from flame-out. This path has an integrator in it which is controlled by back-calculation in an exactly similar way to the NDOT governor while it is not actually governing the fuel flow. A bottoming governor, which prevents the gas generator speed from falling below a prescribed self-sustaining lower limit, is also supplied.

The last two flow limits are compared on a highest-wins basis with the LQR power turbine speed governor demand. The resulting fuel flow is the demanded fuel flow value that is passed to the stepper motor which regulates very precisely the pumping of fuel into the engine. A power turbine speed actuated overspeed switch cut-off value is present on the engine side of the stepper motor to deal with runaways such as shaft failures.

Other pragmatic adaptive features. - The flame-out detector relies on the accuracy and constancy of the relationships between a gas generator deceleration and the gas generator speed at which flame-out occurs and the range of gas generator decelerations at given gas generator speeds which are part of normal operations. Figure 18 shows the relationships of the normal decelerations at various gas generator speeds. The detection boundary is the line that appears to give adequate clearance to avoid false signals at legitimate gas generator decels while giving as much warning as possible.

The power available to hover computation uses nominal maps of corrected engine torque and power turbine inlet temperature to calculate the maximum torque available from the engine. These maps are continually updated to include any engine degradation. The torque required to hover is calculated from a map of the ratio of hover-torque-required to current cruise torque versus airspeed as shown graphically in figure 19. While cruising at constant airspeed, the current cruise torque is used to determine the torque required to hover for the current conditions. Maximum torque available is then compared against torque required to hover. A positive difference indicates a surfeit of torque and a hover is therefore feasible.

Airframe originated features. - The collective pitch-to-tail rotor collective link has been removed in the integrated control in favor of a sum of engine output torques-to-tail rotor collective link. The ideal link would be one which produces a yawing moment proportional to the main shaft torque load. The shaft torque is very difficult to measure and the production of yawing moment via manipulation of a tail rotor collective pitch mechanism is not truly linear. The integrated control solution is to use the sum of the engine output torques as an approximation to the main rotor shaft torque and live with the nonlinearities inherent in the tail rotor collective yaw controls. Another alternate approach, which was outside the scope of this study, is to consider model-following type control laws wherein rotor torque is modeled in a nonlinear mode and included in the control system in closed-loop fashion.

Another feature programmed into the control is the use of the fuel control status flag, which indicates that the engine is on its acceleration schedule, to inhibit the pilot from applying increasing torque loads via the collective pitch input faster than the engine can absorb these loads without allowing droop to occur. In the mechanization proposed here, the status flag signals an electric clutch mechanism on the collective lever which adds retardant stick force when the lever is moved in the upward or torque increasing direction. In use, a pilot would pull collective until he felt the force increase and then maintain a steady pressure which would allow the stick to step upward in very small increments as the controller switched rapidly on and off the acceleration schedule. The collective pitch control thus increases at an optimal rate constrained by constant rotor shaft speed. Figure 20 shows the response obtained in an autorotative recovery by simulating the pilot's collective lever pull limiter with a simple integrator switched on and off by the status flag as it indicates being on the acceleration schedule. The response to the same input without the inhibitor control is also shown.

The last feature to be considered in airframe originated integrated control items is that of automatic control action required under single or dual engine failures. Figure 21 illustrates the response from flight test of a modern helicopter to a dual engine failure at high speed simulated by a dual throttle chop. The Black Hawk does not respond anywhere nearly similar since the relatively heavy rotor tends to keep the shaft speed higher and the large fin area, coupled with the more effective speed of the tail rotor, make the directional stability much greater. Hence, sideslip never develops and the roll response due to the dihedral effect is very mild. Since no problem existed on the Black Hawk and a change in rotor mass to provoke the effect would have a large impact throughout the integrated control design, no further studies were conducted. It seems quite possible, if needed, the engine flameout warning flag could be used at higher airspeeds to impress a tail rotor pitch input early enough to prevent the yaw and consequent roll response.

At low speeds, a large part of the prohibited area is created by the requirement to allow the pilot time to recognize the engine failure and react to it. The automatic control envisioned would recognize the height-velocity area in which failures occurred and take appropriate action immediately on perceiving the failure flag. The application of cyclic and collective would depend on the area of the altitude-velocity diagram where failure occurred. It would be preprogrammed or possibly use the power-to-hover and performance mapping information of the pragmatic fuel controller to make logical decisions. The stick would be moved by clutch mechanisms which could be overriden by a pilot using stick force alone. The movement-causing forces would be faded out after several seconds.

Control System Evaluation

The evaluation of the integrated flight-propulsion control was conducted in two phases. The first evaluation, presented here, was accomplished using the MGH simulation facilities at Sikorsky. The second part was to be a pilot-in-the-loop study on the NASA Ames VMS. At this writing, the VMS evaluation has not yet been accomplished.

Generic mission tasks. - A selection was made of simple segments of maneuvers that could be reasonably and simply simulated on Sikorsky's MGH simulation of the T700 powered UH-60A Black Hawk, and that would highlight the advantages of an integrated flight-propulsion control system. The first maneuver segments were the results of gathering comments from pilots and designers at Sikorsky on the type of maneuvering mentioned above.

The search of the AACT data for the integrated control study concentrated on maneuvers that exhibited a rotor speed excursion of more than 5 percent on any aircraft which implies a 10 percent change in stick sensitivity with consequent difficulties in pilot control. In this manner, the search and classification reaffirmed the significance of the first selections and added the side acceleration maneuver and the roll reversal maneuver. The final selections included classic autorotative recovery, bob-up and remask, quick-stop, quick-turn deceleration, engine failures, side accelerations, and roll reversals. Most of the results were taken from the AACT data and all of the data were on aircraft other than the Black Hawk. Details of these maneuvers are given in reference 14.

Evaluation using MGH Black Hawk simulation. - The evaluation was performed by flying the simulation through the series of maneuvers listed above. In general, the Black Hawk simulation was flown with the SAS on and FPS off. Both sub-systems could be expected to be incorporated in a total integrated control design. With the SAS active, this is a way of acknowledging that incorporation. The FPS functions of the Black Hawk were largely inappropriate for this study. The coordinated turn feature was provided by the input maneuver controller. Leaving the FPS feature on caused interference with the controller so it was turned off for all flights. The attitude hold feature was the opposite of what was required for the fuel minimization scheme.

Reference 14 contains the time history comparisons of the maneuver segments simulated, using the base control and the integrated control.

Table I is a summary of the autorotational recoveries in terms of rotor droop and overshoot speed peaks during the maneuvers.

In summary, the integrated control is superior only during large split autorotational recoveries when moderate to slow collective pulls are used in the maneuver. Small split recoveries from fast to slow pulls do not show any significant advantage for either control version. However, rotor speed overshoot is controlled in a vastly superior manner by the integrated control. This is due primarily to the LQR power turbine speed governor. Details of the results of the other maneuver flights are also given in reference 14.

CONCLUDING REMARKS

The emergence of digital engine controls in such programs as the Army ATDE and the parallel development of digital flight controls in the Army ADOCS program, makes possible the future application of a fully integrated digital flight-propulsion control system. Although the microelectronics technology required for integrated control is now available, additional research is needed to understand the full implications of the technology. The NASA/Army research program described in this paper is a comprehensive attempt to develop an approach. The payoff will be a generation of rotorcraft with the maneuverability and agility required for military missions and the superior handling qualities and low pilot workload needed for all-weather civil missions.

The real-time component-type digital simulation of a turboshaft engine fills a need in the pilot-in-the-loop investigations involving non-constant rotor speeds and widely varying rotor loads especially in integrated flight-propulsion control applications. Performance-related questions can also be addressed in real-time. The model reproduces dynamics associated with gas generator spool-up or spool-down caused by large changes of power. Engine degradation is also easily modeled by modifying compressor or turbine flow and energy functions. The engine control system is separate and may be modified or replaced depending on user requirements. This capability allows effective pilot evaluations of new control implementations or of special modes of fuel control system operation.

The integrated flight-propulsion control scheme evaluated in this study was found to be superior to the basic control in most areas. This was in spite of the fact that the baseline control is already a harmonious match of engine and airframe which exhibits few of the problems of other aircraft or, at worst, on a diminished scale as seen in the AACT data.

While fixed-base simulation is a useful tool for the preliminary investigations of control studies such as this, the essence of the evaluation has to be a motion simulation because the critical factor is the extent to which rotor speed droop affects control power and how a pilot copes with the subsequent control problem. To this end, a simulation experiment on a motion simulator in real-time is necessary.

The eclectic approach of selecting versions of elements already existing results in many design compromises that should not have to be made. It is strongly recommended that airframe, engine and controls teams establish a small integrated design team at the start of a program to deal with all aspects of the required integration concepts using modern integrated control design methodologies that have emerged in recent times. Variable rotor speed control, which will require integrated control to be implemented effectively, should also be the object of further study.

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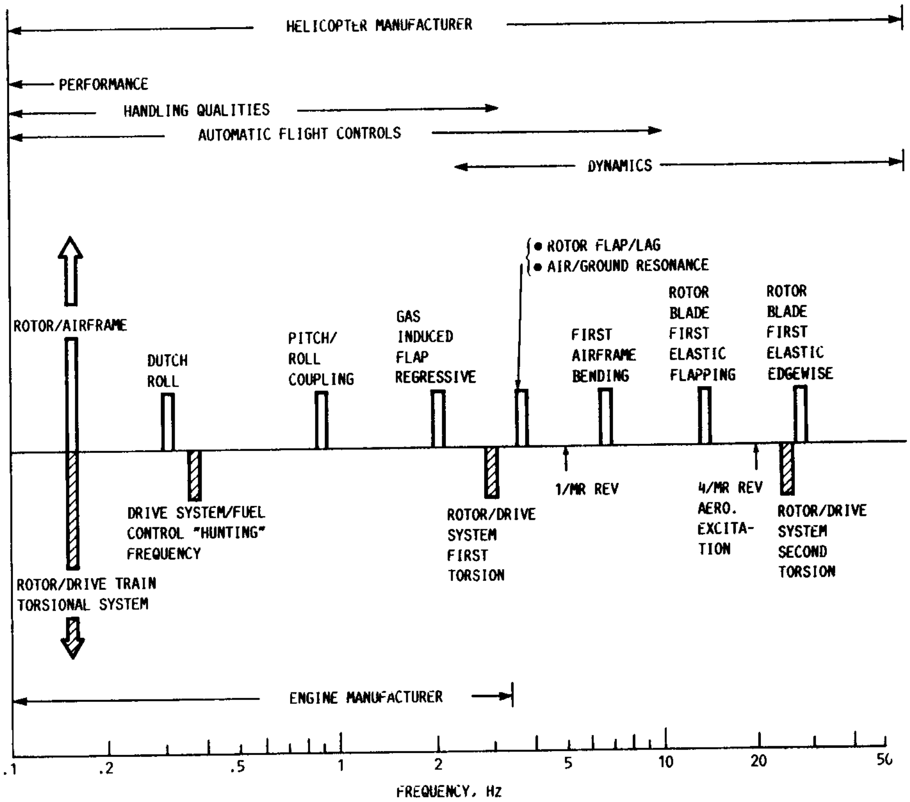

FIGURE 1. - MODAL FREQUENCIES OF INTEREST IN ENGINE-FUEL CONTROL DESIGN AND MODELING.

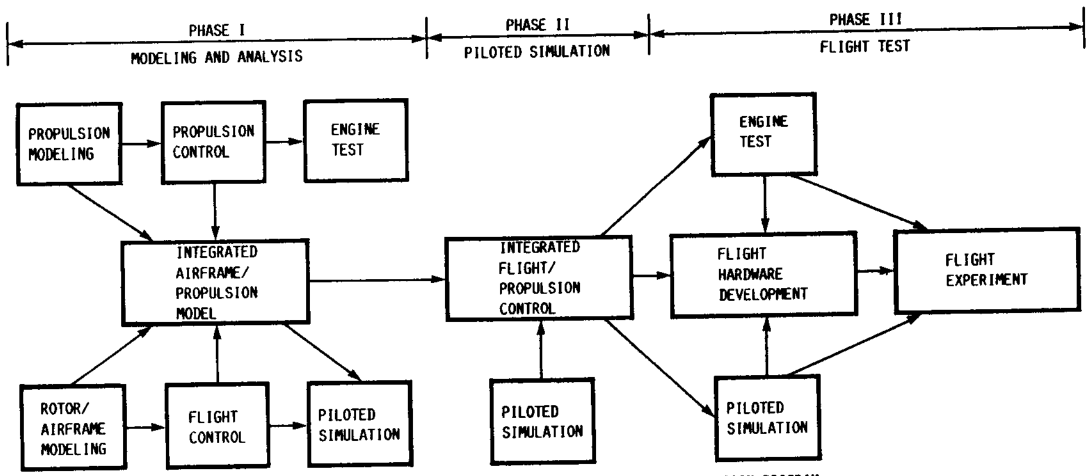

FIGURE 2. - ROTORCRAFT FLIGHT-PROPULION CONTROL INTEGRATION PROGRAM.

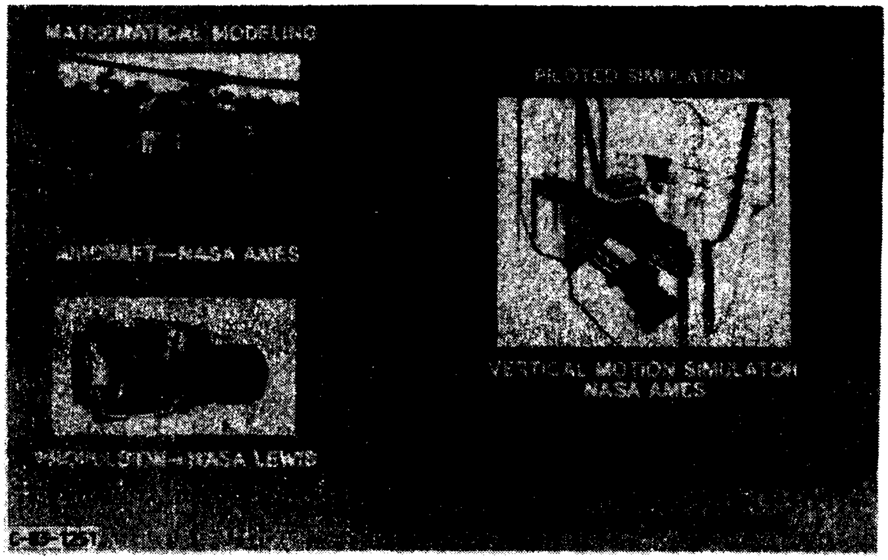

FIGURE 3. - ROTORCRAFT FLIGHT/PROPULSION CONTROLS RESEARCH AMES RESEARCH CENTER/LEWIS RESEARCH CENTER.

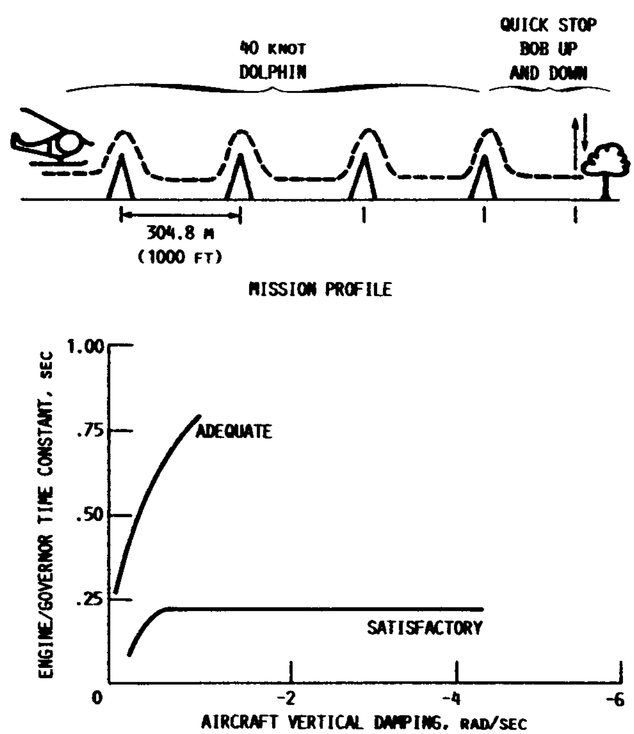

FIGURE 4. - EFFECT OF ENGINE RESPONSE ON HANDLING QUALITIES.

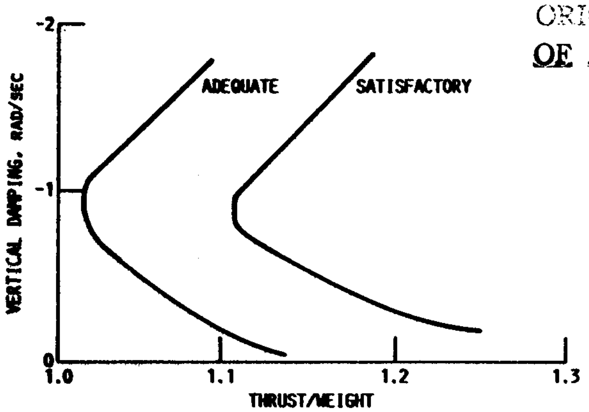

FIGURE 5. - EFFECT OF EXCESS THRUST AND VERTICAL DAMPING ON HANDLING QUALITIES.

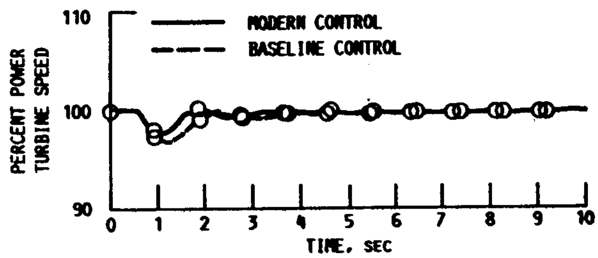

FIGURE 6. - UNCOMPENSATED ENGINE ACCELERATION TRANSIENT CAUSED BY A 40 TO 70 PERCENT COLLECTIVE PITCH BURST.

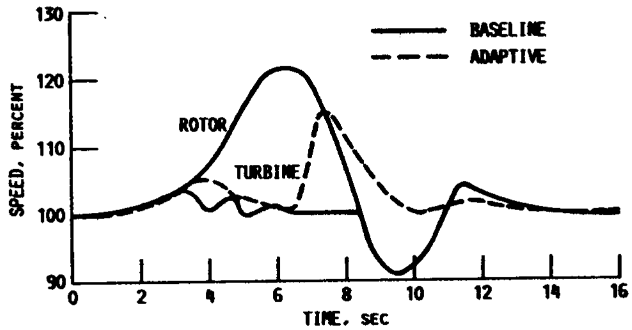

FIGURE 7. - QUICK-TURN MANEUVER FROM 120 KNOTS IN LEVEL FLIGHT WITH TWIN ENGINE CONFIGURATION.

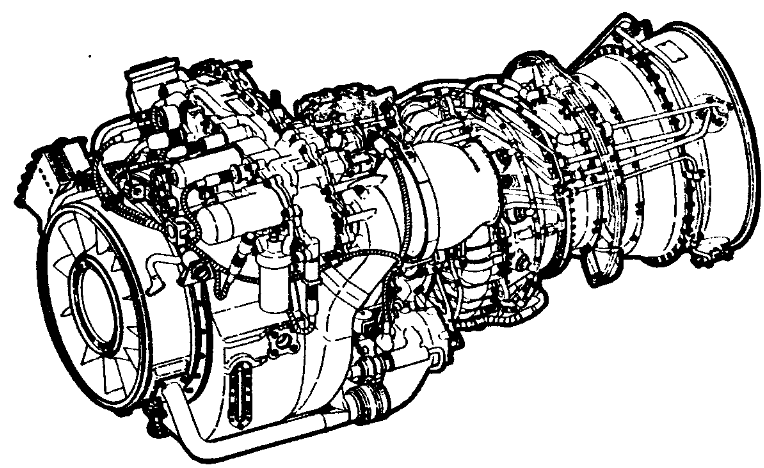

FIGURE 8. - GENERAL ELECTRIC T700-GE-701 TURBOSHAFT ENGINE.

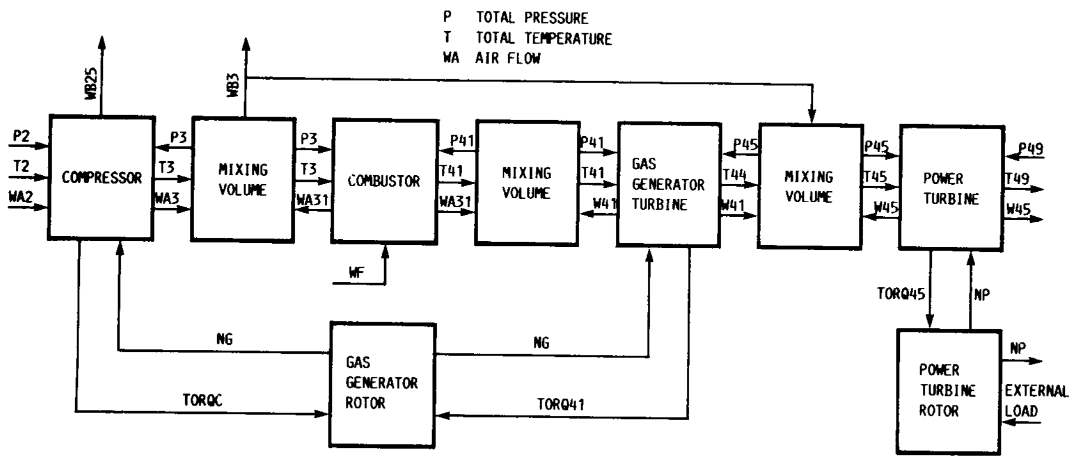

FIGURE 9. - BLOCK DIAGRAM OF SMALL TURBOSHAFT ENGINE MODEL.

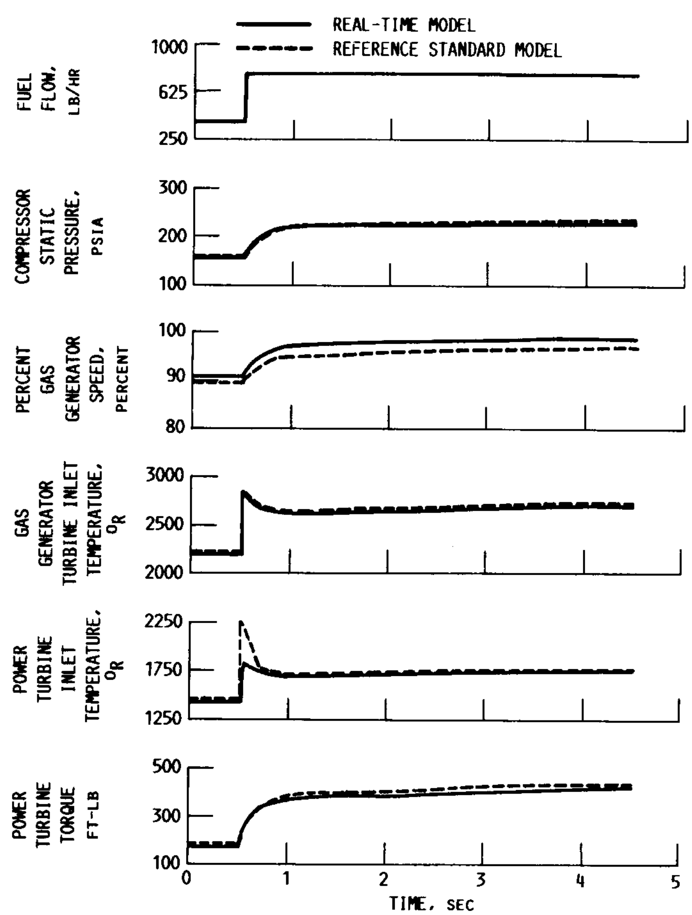

FIGURE 10. - STEP FUEL FLOW INCREASE FROM MID TO HIGH POWER.

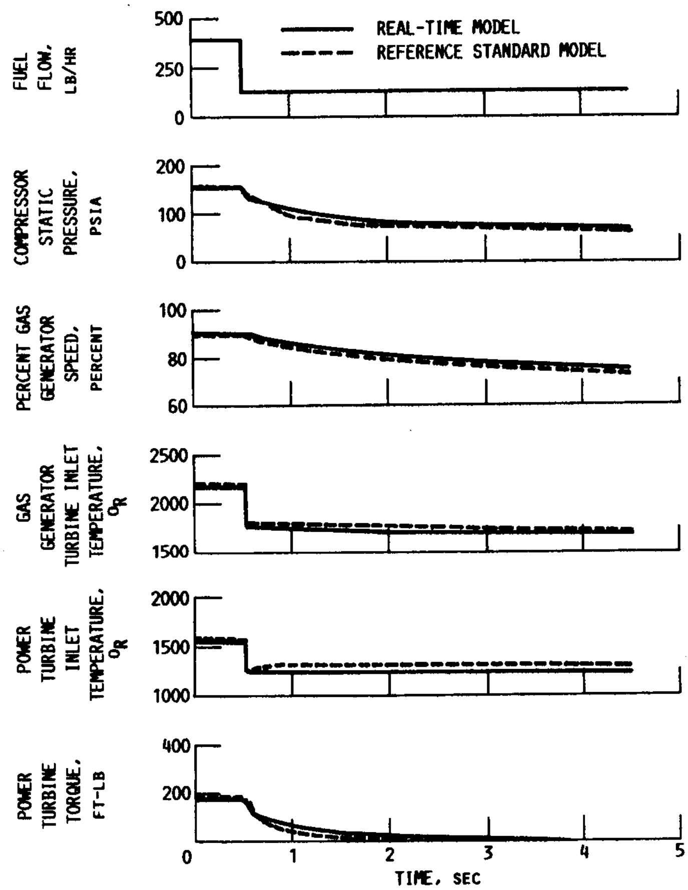

FIGURE 11. - STEP FUEL FLOW DECREASE FROM MID TO LOW POWER.

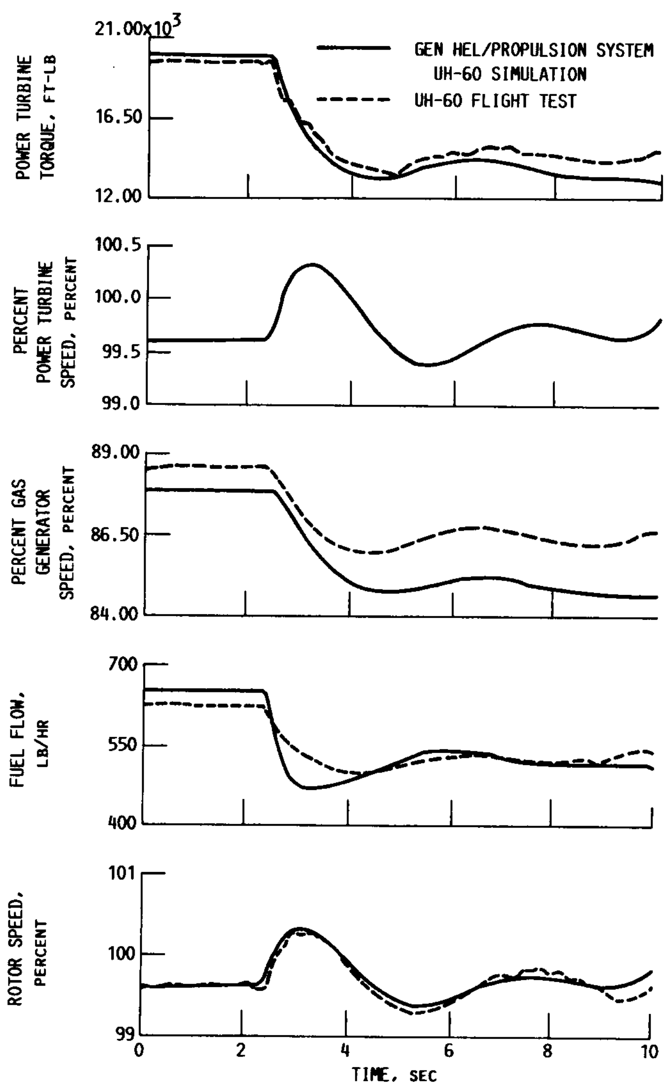

FIGURE 12. - PROPULSION SYSTEM RESPONSE WHEN USED IN CONJUNCTION WITH REAL-TIME ROTORCRAFT SIMULATION. (10 % DOWN COLLECTIVE INPUT, 60 KIAS.)

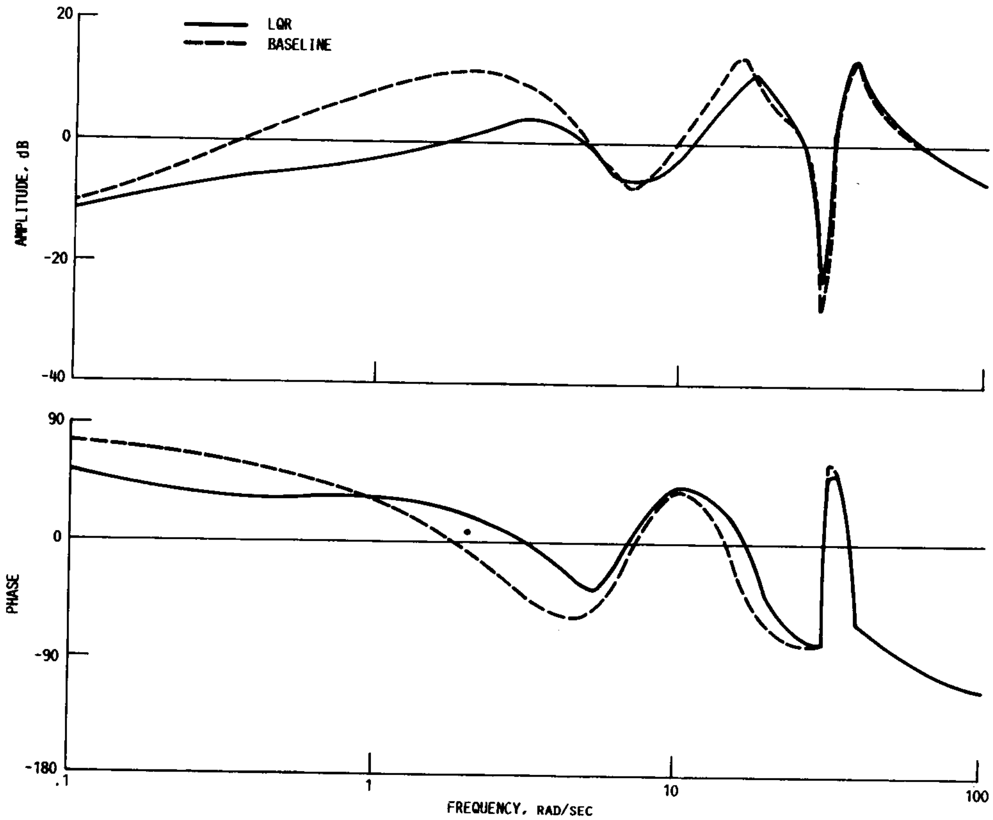

FIGURE 13. - BODE PLOT OF BASELINE AND LQR POWER TURBINE SPEED RESPONSE TO MAIN ROTOR TORQUE.

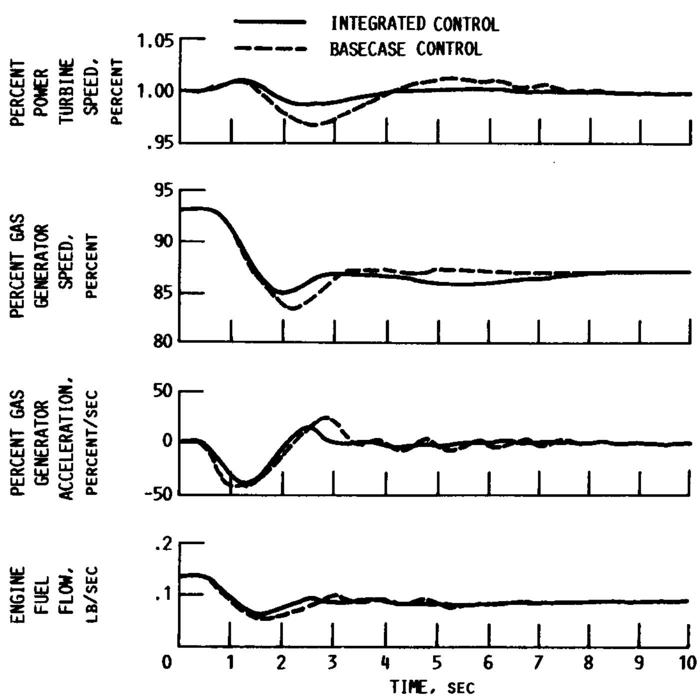

FIGURE 14. - SIMULATED DISCRETE GUST RESPONSE USING LQR CONTROLLER.

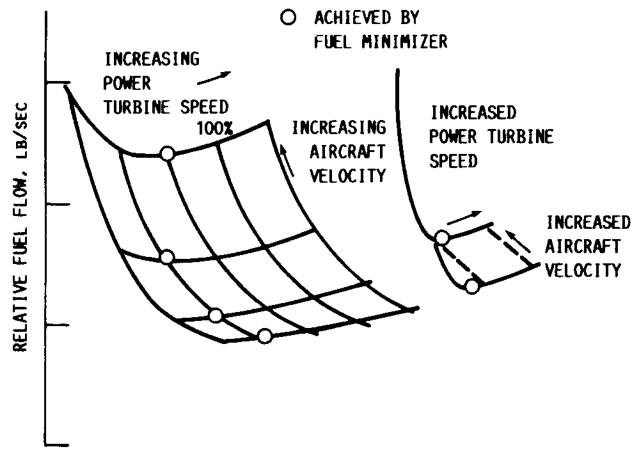

FIGURE 16. - RESULTS OF MINIMUM FUEL CONSUMPTION OPTIMIZER FOR VARIOUS STEADY CRUISE AIRCRAFT OPERATING CONDITIONS OF THE MGH BLACK HAWK SIMULATION.

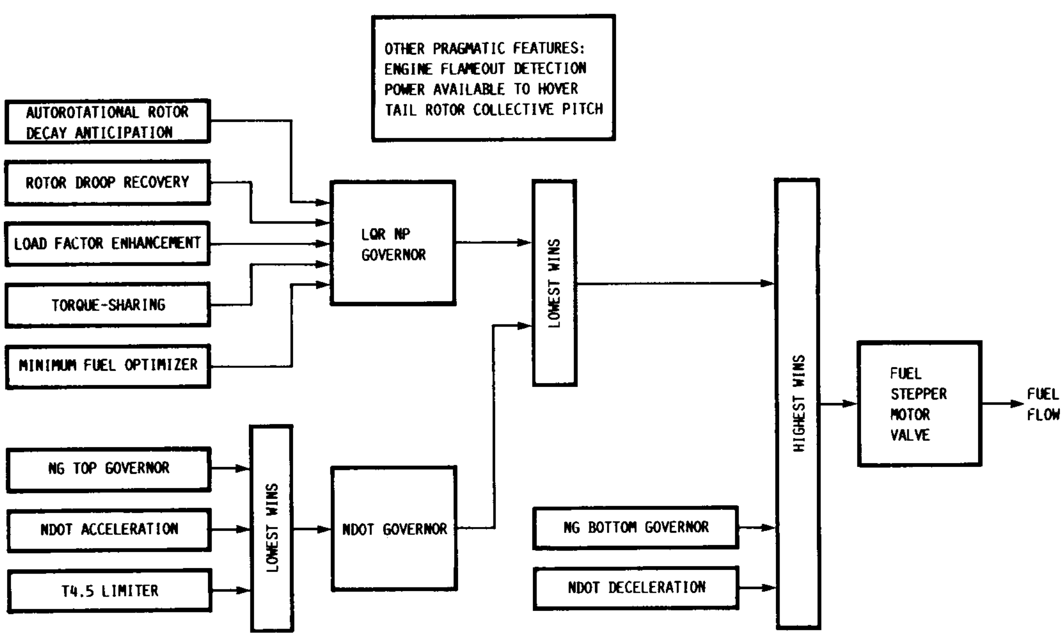

FIGURE 15. - BLOCK DIAGRAM OF INTEGRATED CONTROL.

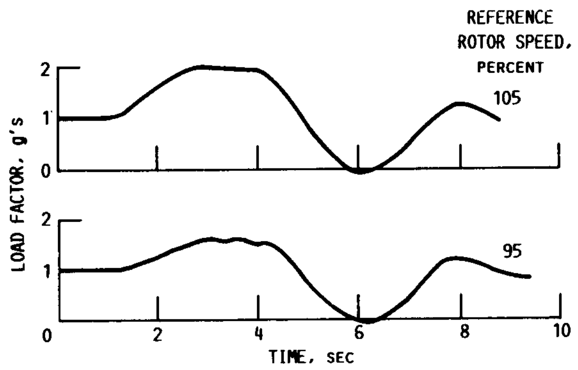

FIGURE 17. - EFFECT OF LOAD FACTOR ENHANCEMENT FEATURE DURING PULL-UP MANEUVER.

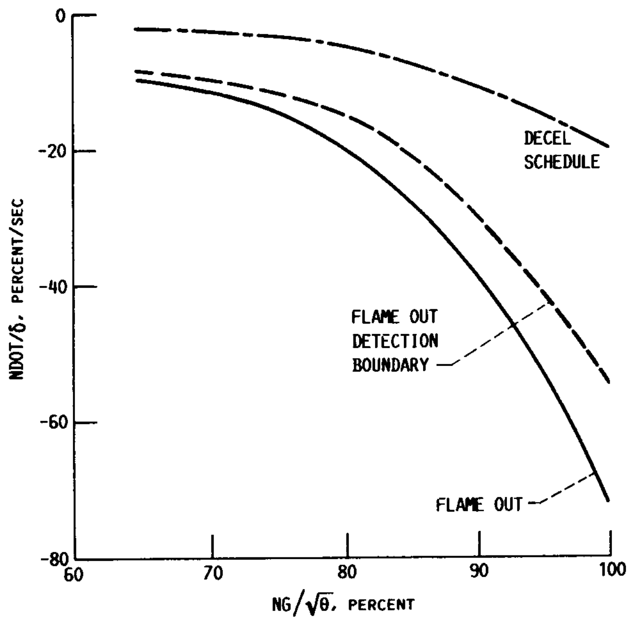

FIGURE 18. - FLAME OUT AND NORMAL ENGINE DECELERATION RATES.

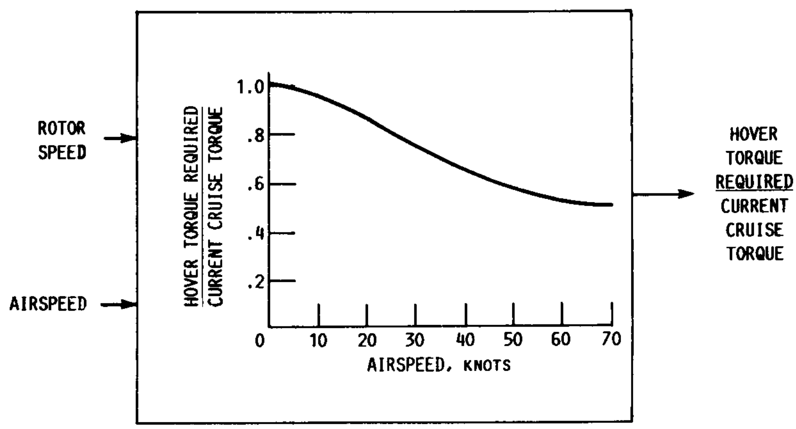

FIGURE 19. - PREDICTED TORQUE REQUIRED TO HOVER RATIOED TO CRUISE OPERATING TORQUE.

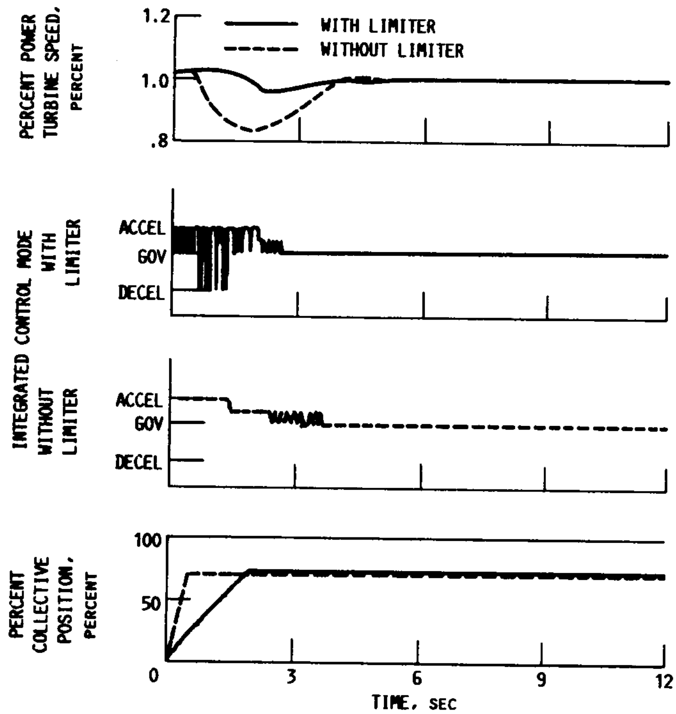

FIGURE 20. - SIMULATED AUTOROTATIONAL RECOVERY USING COLLECTIVE PITCH LEVER PULL LIMITER ON ACCELERATION SCHEDULE.

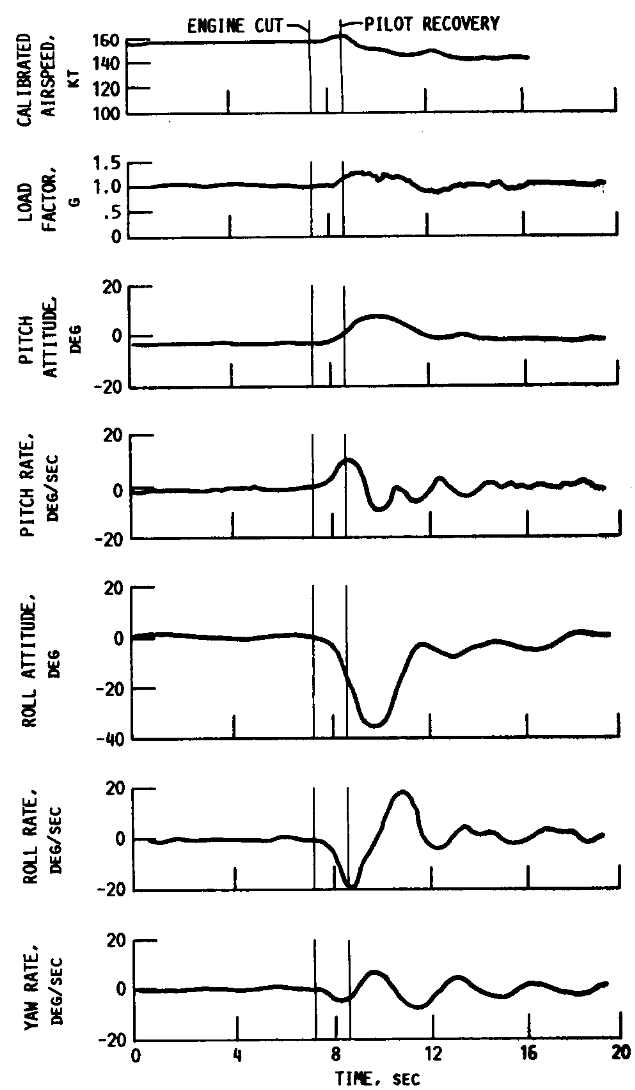

FIGURE 21. - RESPONSE OF A MODERN HELICOPTER TO A DUAL ENGINE FAILURE AT HIGH SPEED.