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ANALYSIS OF CONTROL CONCEPTS FOR GAS AND SHAFT-COUPLED V/STOL AIRCRAFT LIFT FAN SYSTEMS

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Abstract

V/STOL aircraft rely on their propulsion systems to provide lift and attitude control moments during hover and low-speed flight. For lift-fan powered V/STOL aircraft, two unconventional propulsion system types have been proposed. The first type uses fans connected by hot gas ducting, and the second type uses fans connected by cross shafting. This paper presents results of an analytical study which identifies the basic steady-state and dynamic characteristics for each type of system. For the gas-coupled system, the control concepts analyzed were variable-area fan turbines and throttling valves in the ducting. For the shaft-coupled system, the control concepts analyzed were variable-pitch fans and variable fan inlet guide vanes. All of these concepts are shown to be capable of meeting V/STOL aircraft control moment and transient response requirements when appropriate propulsion controls are used. Each type of system has unique problem areas which require an integrated approach to aircraft/propulsion control design.

Introduction

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V/STOL transport aircraft powered by high bypass ratio turbofan engines have shown promise for meeting the requirements of civil and military missions which call for long cruise range, large payloads, and independence from extensive ground-based airport facilities. Mission studies have shown that using a minimum number of propulsion units is important in reducing operating cost. To accomplish this, the same engines must be used for cruise propulsion, lift, and attitude control in hover. The requirement for attitude control, in particular, places new demands on the propulsion control system.

This paper discusses control concepts for two unconventional propulsion system types which have been proposed for the V/STOL application. The first type of system is referred to as a "gas-coupled" system and is shown in figure 1. The system consists of two or more gas generators and two or more lift/cruise fans connected by hot gas ducting. In this type of system, a "gas generator" is a single-spool turbojet engine which supplies hot gas to drive the fan turbines. The second type of system is referred to as a "shaft-coupled" system (figure 2) and consists of two or more turbofan engines connected by cross shafting.

Gas-coupled lift-fan systems were first investigated in the 1960's and several different control concepts have been proposed for them (refs 1-7). This study is confined to two of these concepts. The first concept employs variable-area fan turbines and the second employs throttling valves in the ducting system. Shaft-coupled turbofans are a recent innovation, and variable-pitch fans are the only control concept for the shaft-coupled system which has been investigated (refs 3,9). This paper analyzes both variable-pitch fans and variable fan inlet guide vanes.

STAR category 08

The objective of this study was to identify the basic steady-state and dynamic characteristics of the gas and shaft-coupled lift fan systems, and to assess their ability to meet V/STOL aircraft requirements. To meet the study objective, it was desirable to analyze the simplest propulsion configurations which still displayed the basic characteristics of each control concept. Therefore, only two-engine systems (figures 1 and 2) were analyzed. The two outputs were assumed to be lift (collective thrust) and control moment (thrust difference) about a single aircraft axis. The control moment could be a pitching or rolling moment depending on aircraft configuration.

The analysis for each system was performed using digital computer simulations which predict both dynamic and steady-state behavior of the propulsion systems under study. The analysis is confined to the hovering and low-speed flight envelope of V/STOL aircraft, since this is where the propulsion control requirements are unconventional. The analysis is also confined to normal operation. For completeness, failure-compensation aspects of each system are discussed qualitatively.

Figure 3 shows schematically the elements of a typical V/STOL aircraft/propulsion control system. In general, a complete analysis of the V/STOL control problem should include all of these elements at once, since they interact strongly. However, the scope of this paper is confined to the elements inside the dotted line in figure 3 - the propulsion system and its controls. Such a study is a necessary step toward understanding overall system behavior.

V/STOL Propulsion Control Requirements

Before discussing propulsion control requirements which are unique to the V/STOL application, it is worth noting the major requirements for any propulsion control system. Apart from regulating the output-thrust-of the engines at the requested level, a major function of a propulsion control system is to protect the engines from potentially damaging operating conditions. The most common protective functions performed by propulsion control systems are the prevention of compressor or fan surge, rotor overspeeds, and overtemperature of hot-section components such as combustors and turbines. As will be shown, these limits are usually critical in determining the ability of a given propulsion system to meet V/STOL requirements.

For V/STOL aircraft in hovering and low-speed flight, propulsion control requirements are more complex than for conventional aircraft. A V/STOL propulsion control system should generally be designed to meet the following goals:

1. Maximize available lift (collective thrust)

2. Maximize available moment (thrust difference)

3. Minimize response time for collective and differential thrust changes

The first goal is desirable since maximum lift implies maximum payload. Maximizing differential thrust capability is also desirable since it implies flexibility to meet the requirements of different aircraft configurations. Figure 4 shows estimated roll-axis differential thrust requirements for several aircraft of different gross weight (refs 9-12). For most aircraft configurations, roll-axis control requires more differential thrust than pitch-axis control, and therefore imposes the most demanding requirement. The band of typical requirements shown in figure 4 is used throughout this study as a guideline for assessing the moment-producing capability of V/STOL propulsion control concepts.

Minimum response times are also desirable since fast thrust response improves aircraft handling qualities. Current criteria (ref 13) indicate that differential thrust response should have a time constant less than .20 seconds, and collective thrust response should have a time constant less than .30 seconds. "Time constant" (τ) is defined as the time required to reach 63 per cent of a commanded step change in collective or differential thrust.

Analysis of Gas-Coupled Lift Fan System

Figure 1 identifies the essential elements of the gas-coupled lift fan system analyzed in this study. The system consists of two gas generators, two tip-turbine driven lift fans, and hot gas ducting to connect the gas generators and fans. The cross duct permits power transfer between the lift fans and thus enables the system to develop a thrust difference between the two fans for aircraft attitude control. Total (collective) thrust of the fans is determined by gas generator power output, and differential thrust is determined by the amount of flow transfer through the cross duct.

From the control designer's viewpoint, a significant feature of this system is its four separate rotors, which can and will run at four different speeds. Ideally, the two gas generator rotors will run at the same speed. The fans, however, must run at different speeds for the system to produce any differential thrust. The control problem, therefore, becomes one of finding the best way of transfering power from one fan to the other to induce a fan speed change. The dynamics of fan speed changes will tend to dominate the overall thrust response time, since the fans have a high polar moment of inertia and change speed at a relatively slow rate.

The gas-coupled system analyzed in this study consisted of two J97 gas generators and two LF460 lift fans. The J97 is an existing turbojet engine which has been successfully run in a gas-coupled system configuration (ref 3). The analytical model for the J97 has been verified by comparison with the experimental results of reference 3. The LF460 is a low-pressure ratio lift/cruise fan for which only performance predictions are available (ref 14). Table 1 summarizes the characteristics of the J97/LF460 system for the nominal takeoff condition selected for this study. The results of the analysis are normalized with respect to the values shown in table 1. Details of the analytical model are given in reference 5.

Variable-Area Fan Turbines. - One of the earliest control concepts proposed for gas-coupled lift fans is the variable-area turbine concept (ref 1). It was selected for analysis in this study because variable-area turbine technology is presently being developed under the Air Force/Navy Joint Technology Demonstrator Engine (JTDE) program. Present-day turbine technology may render this concept more attractive today than in the mid-1960's when it was first investigated.

A turbine consists of many small nozzles which accelerate the incoming flow before it impinges on the turbine rotor. The effective flow area of a turbine is roughly equal to the sum of all the individual nozzle areas. The effective flow area can be modulated in two ways, as shown in figure 5. The first method uses splitter vanes which can be rotated to block some of the individual nozzles. The second method involves rotating all of the stator vanes simultaneously to produce an area change in each of the individual nozzles. In principle, either method could be adapted to a tip-turbine lift fan. The first method was demonstrated in reference 1.

Variable-area turbines can be used to cause flow transfer between gas-coupled lift fans. The area of one fan turbine can be increased while the area of the opposite fan turbine is decreased by an equal amount, thus inducing flow transfer from the low-area side of the system to the high-area side. This principle insures that the gas generator operating points are not appreciably changed, since the total nozzle area seen by both gas generators remains roughly constant.

Figure 6 illustrates basic steady-state characteristics of the variable-area turbine concept. Fan thrust and speed, and gas generator exhaust gas temperature (EGT) are plotted against per cent modulation of fan turbine area. A modulation of 50 per cent means that one fan turbine is set to 150 per cent of its nominal area, while the opposite fan turbine is set to 50 per cent of its nominal area. Fan thrust and speed are seen to vary linearly with turbine area, while gas generator EGT increases by less than 6 per cent over the full modulation range. Gas generator EGT increases slightly more on the low-area side than on the high-area side. This is because excess pressure is required to induce flow through the cross duct, which acts as a pressure loss. The higher back pressure on the low-area side gas generator causes it to run at a higher EGT. The limit on differential thrust capability is set by the amount of area variation that can actually be realized with practical hardware. The $\pm$50 per cent modulation range assumed in this study is consistent with the experimental results of reference 1.

Figure 7 shows a plot of available control moment versus available lift for the variable-area turbine system. For a given aircraft configuration, the nominal lift level during hover will depend on gross weight, i.e., the amount of fuel or payload that the aircraft is carrying. A V/STOL propulsion system must be capable of supplying enough differential thrust to meet aircraft requirements over a normal range of gross weights. Figure 7 also shows a band of typical differential thrust requirements. For this study, it was assumed that aircraft moment of inertia is proportional to gross weight, a conservative assumption for most configurations. The reduction in moment of inertia at low gross weights causes a corresponding reduction in the differential thrust requirement at low gross weights, i.e., low lift levels. This explains the positive slope of the band of requirements shown in figure 7.

Figure 7 indicates that the variable-area turbine concept can exceed typical moment requirements. The positive slope of the moment versus lift characteristic can be explained by the method used to modulate total lift. For this study, lift was modulated by changing gas generator power setting at constant fan turbine area. At low power settings, the total flow available to both fan turbines is reduced. This causes a corresponding reduction in the amount of flow which can be transfered to produce differential thrust. The moment versus lift characteristic of the variable-area turbine system is not a problem, since it matches the trend of the requirements.

As noted earlier, the gas-coupled system requires a fan speed increase to generate differential thrust. Therefore, the fan must be designed to accommodate overspeeds relative to the zero-moment condition. The LF460 fan was designed for the V/STOL application and runs below its limiting speed even when generating maximum differential thrust. In general, the limiting speed for a tip-turbine lift fan should be chosen to match the maximum foreseeable differential thrust requirements for different aircraft configurations.

Throttling Valves. - The variable-area turbine concept requires complexity in the fan design. To surmount this difficulty, a more recent concept known as Energy Transfer and Control (ETaC) (ref 3) has been developed. As shown in figure 8, this concept employs throttling valves located in the ducting just upstream of the fan turbines. By partially closing the valve upstream of one fan turbine and leaving the opposite valve fully open, flow can be diverted through the cross duct to increase the speed and thrust of the fan on the unthrottled side.

Figure 9 shows the basic steady-state characteristics of the throttling-valve concept. As seen in figure 9, the thrust characteristic of the throttling-valve concept is asymmetric. This is due to the increase in gas generator EGT (about 12 per cent over the available throttling range). This partly compensates for the pressure drop across the throttling valve and tends to increase the gas power available to the throttled fan. To maintain total lift constant while control moments are being generated, the throttled fan must be "spoiled" to reduce its thrust level. Spoiling can be accomplished by louvers in the fan exhaust, or by venting flow out the side of the fan exhaust duct.

Moment capability of the throttling-valve concept is limited by the gas generator EGT limit. As gas generator power setting is reduced, EGT is also reduced. This implies that, at low power settings, more margin is available for increasing EGT before the limit is reached. Therefore, the throttling-valve concept can develop more control moment at low power settings, i.e., low lift levels. This fact is illustrated in figure 10, which shows available control moment versus available lift for the throttling-valve concept. Although available control moment is less at higher lift levels, it is still sufficient to meet most requirements.

Transient Response. - The transient response characteristics of the throttling-valve concept will be presented as typical for a gas-coupled lift fan system. Transient response of the variable-area turbine system is discussed in reference 1. As mentioned earlier, transient response of the gas-coupled system tends to be dominated by fan rotor dynamics. To get good moment response from such a system, it is necessary to supply excess gas power to the fan as quickly as possible. Gas power is a function of both flow rate and temperature. The throttling valve controls the amount of flow transfer to the increasing-thrust fan, and gas generator fuel flow determines gas temperature. Therefore, moment response time can be minimized by applying lead compensation to the throttling valve and by sending an anticipation signal to the gas generator fuel control.

Figure 11 shows a control system designed to take advantage of both effects. A "moment command" signal results in three kinds of action - movement of the throttling valve on one side (with lead compensation to cause an initial overshoot in valve position); an increase in fuel flow to both gas generators; and a change in spoiler position on the throttled side (with lag compensation to match the response of the spoiled fan to the fan on the opposite side). A "collective thrust command" causes a change in fuel flow to both gas generators as well as a transient reset of spoiler position, as will be discussed later.

Figure 12 shows moment response of the throttling-valve system with the control system of figure 11. The moment response time constant is .16 seconds, within the range of V/STOL requirements.

For the throttling-valve concept, collective thrust changes are made by changing gas generator power setting. The dynamics of the process are dominated by fan rotor dynamics. However, since spoilers are already required for generating moments, they can also be used to quicken the collective thrust response. This can be accomplished by presetting the spoilers to reduce the thrust of the fans by a small amount (10 per cent for this study). When a collective thrust increase is commanded, this spoiled thrust is made available to quicken the response. As fan speed rises to the requested level, the spoilers are reset to their original position. This function is labeled "transient reset" in the control schematic of figure 11. Figure 13 shows the collective thrust response with a control system of this type. The time constant is .09 seconds, well within the range of V/STOL requirements. For the upper 10 per cent of the available lift, where this technique cannot be used, the collective thrust response has a time constant of .25 seconds (ref 5), still within the required range. At lower lift levels the collective thrust response is marginal (ref 5) when the spoiling technique is not used. The spoiling technique involves a penalty in fuel consumption of about 10 per cent. This penalty is considered unimportant since hovering time is of short duration compared to overall mission time.

The above results show that a gas-coupled system can meet V/STOL thrust response requirements when appropriate propulsion controls are used. This conclusion should be considered preliminary until full-scale lift fans of the required size are built and tested. At present, only estimated values for fan polar moment of inertia are available, and these estimates might prove optimistic. Furthermore, fan polar moment of inertia increases with fan size. Therefore, the above results should be considered typical only for lift fans in the same thrust class (56,850N) as the LF460.

Comparison of Throttling-Valve and Variable-Area Turbine Concepts. - The throttling-valve and variable area turbine concepts both appear capable of meeting V/STOL requirements with appropriate propulsion control systems. The variable-area turbine concept has the ability to generate control moments at lower temper..ures than the throttling-valve concept. This is esirable since lower temperature implies longer engine life. Variable-area turbines might also provide flexibility for optimizing fuel consumption during mission segments other than hover (e.g., cruise, loiter), but that aspect of their performance was not covered in this study.

The variable-area turbine and throttling-valve concepts have noticeably different moment versus lift characteristics, as is evident from a comparison of figures 7 and 10. This difference is also due to the fact that the throttling-valve concept produces control moments at higher temperatures than the variable-area turbine concept. At low lift levels, the throttling-valve concept produces large control moments because of correspondingly large temperature increases. For the variable-area turbine concept, the reduction in available control moment at low lift levels is not likely to cause problems since the moment is still in excess of typical requirements.

The relative cost and performance of the two systems is difficult to assess without assuming specific aircraft configurations and mission requirements. Innovative designs for variable-area turbines, throttling valves, and thrust spoilers should be sought before a final conclusion is reached. Both systems are quite complex compared to conventional propulsion systems, and either one will require extensive development effort on unique components and overall system integration.

Analysis of Shaft-Coupled Lift Fan System

Figure 2 shows the elements of the shaft-coupled lift fan system analysed in this study. The two fans are connected to each other by a cross shaft and gearboxes. The fans can be either of the variable-pitch type or fixed-pitch type with variable fan inlet guide vanes (IGV's). In many important respects, the system resembles a tandem-rotor helicopter.

Usually the fans are run at constant speed. To maintain the constant fan speed, gas generator speed is varied to change the total gas power supplied to the fan turbines. To modulate thrust, either collectively or differentially, with the fan speed constant, a means of changing the fan pressure ratio is required. The fan pressure ratio is a function of blade angle of incidence. Figure 14 illustrates how fan blade angle of incidence can be varied by variable- tch blades or variable IGV's.

Collective thrust is modulated by collectively changing the pitch angles or IGV settings. Differential thrust changes are produced by differentially changing the pitch angles or IGV settings of opposed fans. The high-thrust fan absorbs power from the low-thrust fan, with the power transfer occurring through the cross shaft. Total power absorbed by both fans remains roughly constant.

The analytical model for the shaft-coupled system was based on the Quiet Clean Short-Haul Experimental Engine (QCSEE), a variable-pitch fan engine under development for NASA Lewis Research Center. The QCSEE was chosen for this study because of its similarity to a V/STOL lift/cruise turbofan configuration, and because the analytical model has been verified by comparison with core engine data and fan model data. Table 1 summarizes the characteristics of the QCSEE for the nominal takeoff condition assumed in this study. Analytical results are normalized with respect to the values shown in Table 1.

Figure 15 shows the steady-state characteristics of the variable-pitch fan concept. Fan thrust and gas generator EGT are plotted against differential pitch setting. The thrust characteristics of the opposed fans are symmetric, and control moment is produced at roughly constant gas generator temperature. The steady-state characteristics of the variable-IGV system are similar. For the variable-pitch and IGV concepts, available control moment is limited by the maximum fan blade angle of incidence that can be attained while still maintaining acceptable stall margin. For this study, the variable-pitch fan was limited to a blade pitch angle 10 degrees greater than the design value. For the IGV concept, the flow turning angle was limited to 10 degrees from the axial direction. Both of these limits apply only to the fan which is increasing in pressure ratio. A decrease in pressure ratio generally increases stall margin.

Figure 16 shows a comparisc of available control moment versus available l..t for the variable-pitch and variable-IGV concepts. In this analysis, fan speed and fan nozzle area were held constant over the moment versus lift range shown in figure 16. The variable-pitch and IGV concepts are seen to produce very similar performance. The reduction in available control moment at high lift levels is due to the limit on maximum blade pitch angle or IGV flow turning angle. The amount of thrust that can be produced on the high-thrust side is fixed regardless of total lift level. Therefore, as total lift increases, the available thrust increment (relative to the zero-moment condition) is reduced.

As shown by figure 16, the shaft-coupled system produces less differential thrust than may be required by some aircraft configurations. This is a characteristic of the particular engine cycle analyzed in this study, and is due to the relative size of the gas generator and fan. The QCSEE gas generator can supply enough power to drive both fans close to the upper limit of blade pitch angle or IGV setting; therefore, a relatively small amount of blade pitch or IGV angle is available for generating control moments. This situation could be altered by using a slightly larger fan, which would absorb more power at lower blade angles of incidence, thus leaving more margin available for generating control moments. As is also the case for a gas-coupled system, the optimum fan size for a shaft-coupled system will depend on the differential thrust requirements of specific aircraft configurations. If a given fan is intended for use in several different aircraft, it should be sized to meet the largest foreseeable differential thrust requirement.

Transient Response. - Since the fans in the shaft-coupled system can usually be assumed to run at constant speed, the transient response is fundamentally different from the response of a gas-coupled system. For small changes in fan thrust, the dynamics are primarily determined by the rate at which fan pitch or IGV setting can be changed. A significant factor in the dynamics of the shaft-coupled system is the torsional resonance of the cross shaft and fans. The cross shaft acts like a torsional spring, and the fans act like lumped inertias. The result is a lightly damped spring/mass type of resonance.

The transient response characteristics of the variable-pitch and variable-IGV concepts are virtually identical. Therefore, for illustrative purposes, only results for the variable-pitch concept will be presented.

Figure 17 shows the response of the shaft-coupled system to a step input of differential blade pitch angle. For the transient shown in figure 17, fuel flow to both gas generators was held constant to determine the basic system response without controls. The oscillation in fan thrust is due to the torsional resonance, which causes an oscillation in fan speed. This type of oscillation is unacceptable in a practical system. Similar problems occur in shaft-coupled helicopter propulsion systems (ref 15), and the technology for solving them is generally available.

The oscillation shown in figure 17 occurs at about 12 Hertz. Electronic filters can be designed which prevent inputs in that frequency range from being applied to the blade pitch actuators, thus preventing excitation of the resonance through the blade pitch input. Figure 18 shows a control system with such a filter in the fan pitch actuation system. Also shown is a speed control for the fans. Figure 19 shows the transient response of the shaft-coupled system with the controls of figure 18. The torsional resonance is suppressed, but the response time is noticeably increased by the presence of the filter. The time constant is .16 seconds, still within the range of V/STOL requirements. In this study, a simple second-order lowpass filter was used to prevent excitation of the resonance. A higher-order notch filter might succeed in improving the response time, but in this study a conservative approach was used since the simple second-order filter is adequate to meet the requirement. In general, the avoidance of torsional resonance should be approached as a problem in aircraft/propulsion control integration, since the fan pitch controller will be an element inside an overall aircraft attitude control loop.

Figure 20 shows the collective thrust response of the shaft-coupled system for a step input in collective pitch. The control system of figure 18 is applicable for this type of input. A collective pitch change requires a reset of gas generator speed demand, which is accomplished through the fan speed control. For very large collective pitch changes, gas generator surge and temperature limits could affect the transient response, but for typical V/STOL requirements (roughly ± 10 per cent lift modulation about a nominal lift level) this is not a problem. The time constant for the collective thrust change is .17 seconds, within the range of V/STOL requirements.

Since the fans in the shaft-coupled system run at constant speed, their polar moment of inertia does not have a primary effect on thrust response. As fan inertia increases, however, the torsional resonance will tend to occur at lower frequencies. A low-frequency resonance will generally complicate the problem of avoiding resonance while still meeting response requirements. An additional important effect for the shaft-coupled system concerns the number of interconnected fans. Unlike the two-fan system analyzed in this study, a three-fan system will have more than one resonant frequency to be avoided. These problems can be overcome provided they are appreciated at an early stage of development, and provided that an integrated approach is used in the design of an aircraft/propulsion control system.

Comparison of Variable-Pitch and Variable-IGV Concepts. - The results of this study indicate that variable-pitch and variable IGV's give similar performance in a shaft-coupled turbofan system. In general, variable IGV's offer less overall range in modulating fan thrust (a variable-pitch fan can produce reverse thrust), but for the V/STOL control application variable IGV's appear promising. Compared to variable-pitch, variable IGV's offer a simplified actuation system since the moving parts need not be packaged inside a rotating fan hub. A fixed-pitch fan also offers more design options than a variable-pitch fan, since features such as blade mid-span dampers can be incorporated. In this study, the analysis for the variable-IGV concept was based on scaled experimental data and simplified fan performance prediction methods. Therefore, additional fan aerodynamic design studies and experiments are needed to substantiate the analysis performed in this study.

Compensation for Gas Generator Failures

A V/STOL lift fan system must be capable of providing balanced lift after a gas generator failure. For completeness, the propulsion control aspects of gas generator failure compensation will be discussed qualitatively for both the gas and shaft-coupled systems.

In a gas-coupled system of the type analyzed in this study, two gas generators drive two fans through a common ducting system. Each fan turbine is nominally sized to accept the flow from one gas generator. If one gas generator fails, the effective flow area of each fan turbine must be reduced by half to compensate for the loss of half the original flow. This is most readily accomplished by a fan turbine design which provides for shutting off half of the available turbine admission arc. The LF460, for example, has its turbine inlet scroll separated into two isolated 180-degree admission arcs. Half of the scroll can be shut off by closing a valve. Therefore, when a gas generator failure occurs, the control system must sense the failure and close two valves, one for each fan. The failed gas generator must also be isolated to prevent hot gas from escaping through it in the reverse direction. This is done by shutting a third valve (possibly a passive check valve) just downstream of the gas generator exhaust. Once the valve is closed, the gas generator cannot be restarted until after the aircraft lands or transitions to conventional flight.

In summary, the gas-coupled system requires controls which are capable of sensing a gas generator failure and closing the appropriate valves. Analytical results for system performance with a failed gas generator are presented in reference 4. Experimental results are presented in reference 16.

Gas generator failure compensation for the shaft-coupled system is simpler, and resembles current practice for shaft-coupled helicopter propulsion systems. Each fan is connected to its fan turbine through an overrunning clutch. If a gas generator fails, the fan turbine stops producing power, and the overrunning clutch disengages. Power is transferred through the cross shaft to the fan on the failed side. Since the total power available to each fan is cut in half, blade pitch or IGV setting must be collectively reduced. This action can probably be left up to the pilot, as is usually the case with helicopters. An automatic reset of fan speed and nozzle area might be desirable to maximize thrust at the new fan operating point. If the gas generator failure is temporary (e.g., a compressor stall), restart can be attempted.

In summary, the shaft-coupled system does not require automatic controls to successfully compensate for a gas generator failure, although pilot action to reduce collective blade pitch or IGV angle is required.

Conclusions

For the gas-coupled lift fan system, the major conclusions of this study are:

1. Assuming proper fan sizing, both the variable-area turbine and throttling-valve concepts are capable of producing control moments in excess of typical V/STOL requirements.

2. As a typical gas-coupled system, the throttling-valve concept appears capable of meeting V/STOL thrust response requirements when appropriate propulsion controls are used.

3. The variable-area turbine concept is capable of producing control moments at lower temperatures than the throttling-valve concept.

For the shaft-coupled lift fan system, the major conclusions are:

1. Assuming proper fan sizing, both the variable-pitch and variable-IGV concepts are capable of producing control moments in excess of typical V/STOL requirements.

2. On the basis of scaled experimental data and simplified fan aerodynamic calculations, variable-pitch fans and variable-IGV's give similar performance over the thrust modulation range required for the V/STOL application.

3. As a typical shaft-coupled system, the variable-pitch fan concept appears capable of meeting V/STOL thrust response requirements.

4. The shaft-coupled system exhibits a torsional resonance which must be avoided through careful aircraft/propulsion control integration.

The above conclusions are based on an analytical study and should be considered preliminary until full-scale hardware experience is gained. It is worthwhile to note some of the potential problem areas that were not covered in this study but which should be investigated in the future.

1. Mismatched engines - Usually, any two engines of the same model will show some difference in actual performance as a result of manufacturing tolerances and component deterioration. For both gas and shaft-coupled systems, the performance variations and control problems resulting from such mismatches should be investigated.

2. Component nonlinearities - Since V/STOL propulsion systems will be elements of an overall aircraft control system, it is essential that fundamental nonlinearities (e.g., hysteresis, deadband) be minimized. Specialized components such as variable-pitch actuators and throttling valves must be designed with this problem in mind.

3. Pilot/aircraft/propulsion interactions - Although propulsion dynamics are an essential part of overall system dynamics, all the elements shown in figure 3 must be interconnected before integrated system behavior can be explored. To a great extent, this can be accomplished with piloted flight simulators incorporating realistic aircraft/propulsion analytical models.

4. Reliability/maintainability/cost - Due to the large number of sensors, actuators, and interconnections required in a V/STOL aircraft/propulsion control system, effort must be devoted to developing the components and redundancy architectures needed for a safe, reasonably-priced system.

Although the results of this analytical study are encouraging, most of the development work on V/STOL integrated aircraft/propulsion controls still remains to be done. Before V/STOL aircraft can become cost-effective operational systems, a broad-spectrum controls technology effort must be undertaken to demonstrate solutions to the potential problems noted above.

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Table 1 Characteristics of VTOL lift fan systems at nominal takeoff condition

	Gas-Coupled (J97/LF460)	Shaft-Coupled (QCSEE)
Fan Thrust (F_n)	56,850 N (12,780 lbf)	77,980 N (17,530 lbf)
Fan Speed (NF_n)	3967 rpm	3082 rpm
Fan Pressure Ratio	1.29	1.27
Fan Airflow	257 kg/sec (566 lbm/sec)	396 kg/sec (874 lbm/sec)
Gas Generator Speed	13,855 rpm	13,104 rpm
Gas Generator Airflow	31.4 kg/sec (69.2 lbm/sec)	31.0 kg/sec (68.3 lbm/sec)
Gas Generator Exhaust Gas Temperature (EGT_n)	1019 °K (1835 °R)	1182 °K (2128 °R)

(1) Sea level static, standard day
(2) Characteristics shown are for a single engine

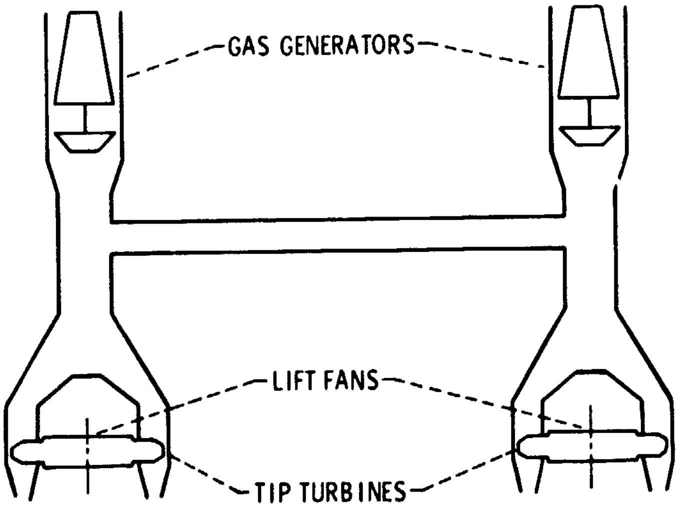

Figure 1. - Gas-coupled lift fan system.

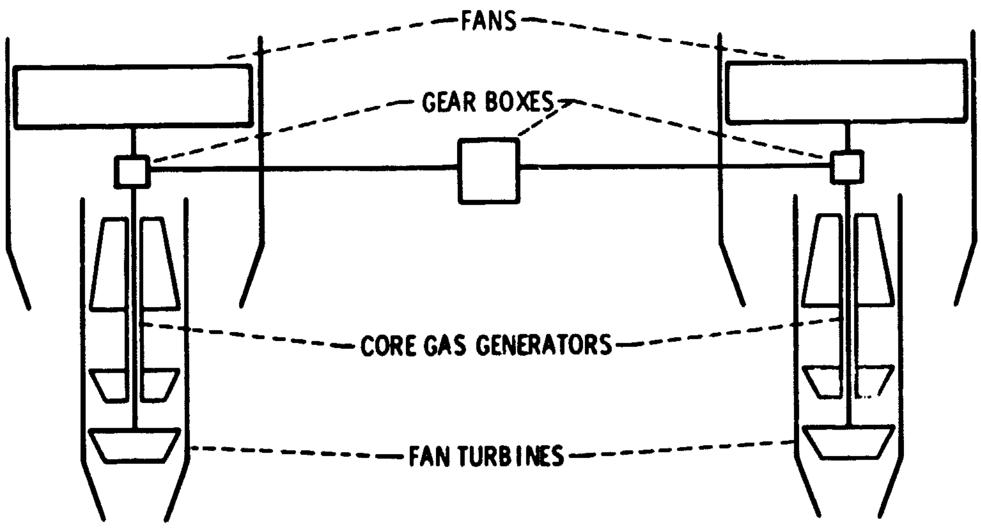

Figure 2. - Shaft-coupled lift fan system.

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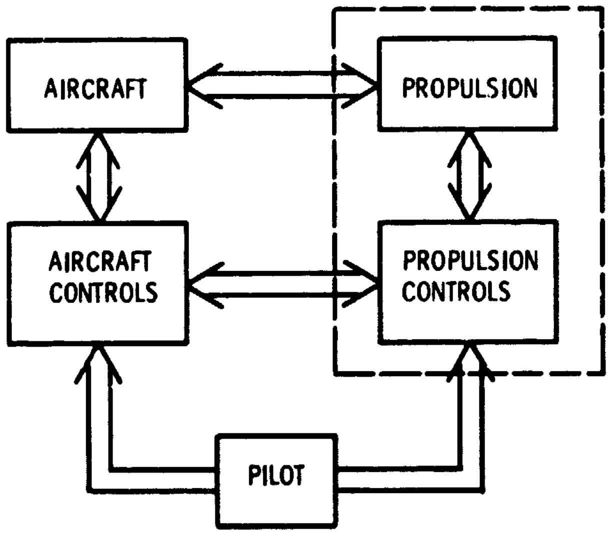

Figure 3. - Elements of a V/STOL aircraft/propulsion control system.

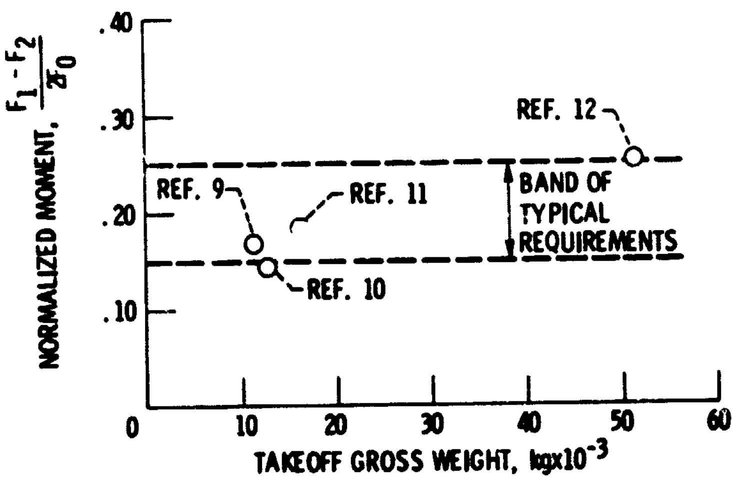

Figure 4. - VTOL aircraft differential thrust requirements for roll control.

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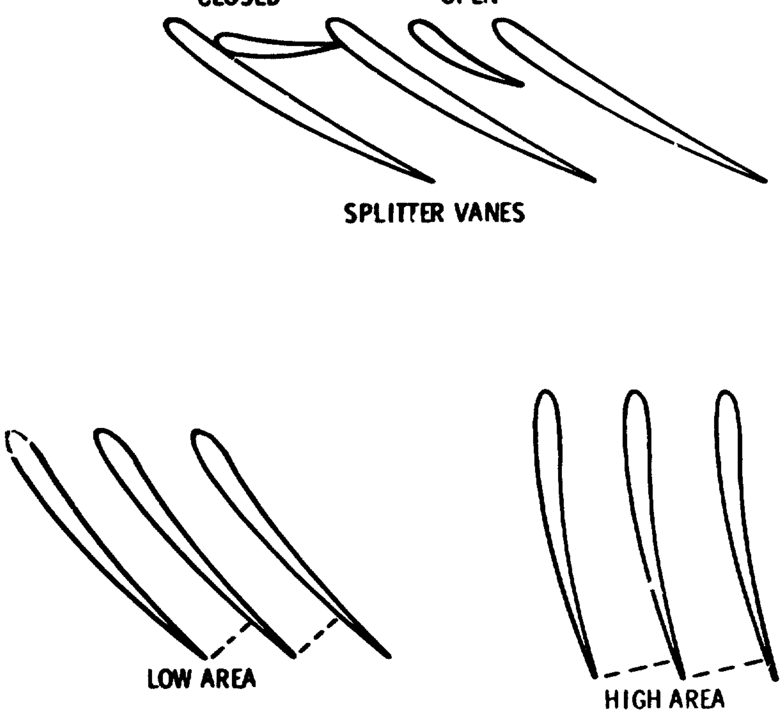

Figure 5. - Methods of obtaining turbine area modulation.

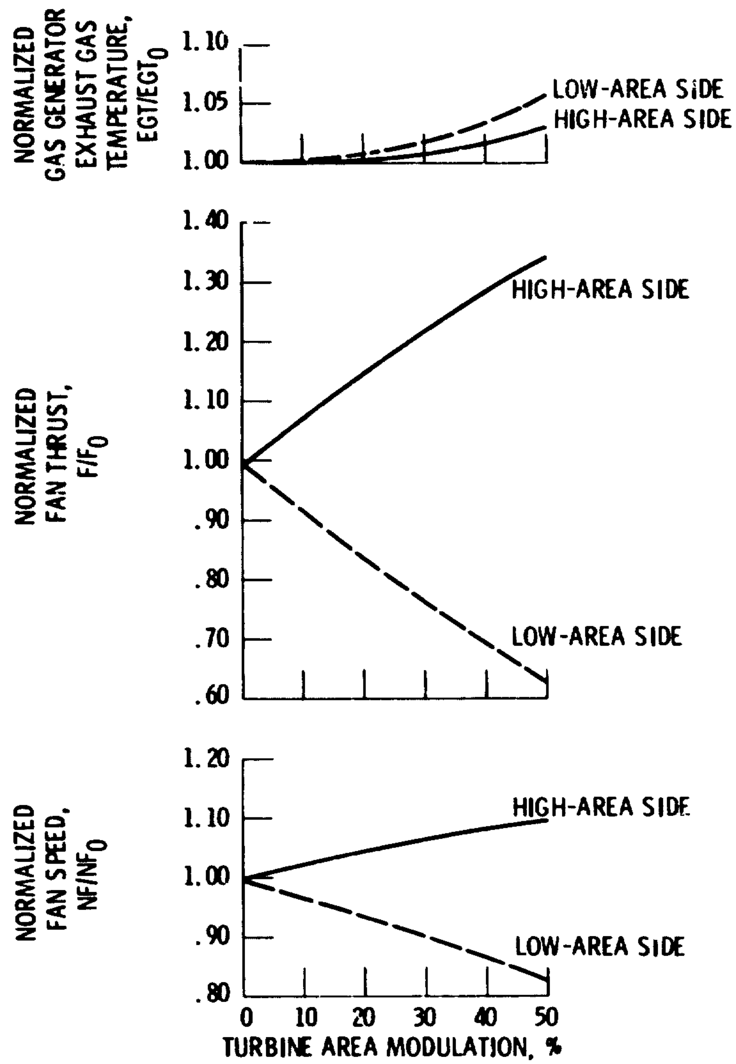

Figure 6. - Steady-state characteristics of the gas-coupled system with variable-area fan turbines.

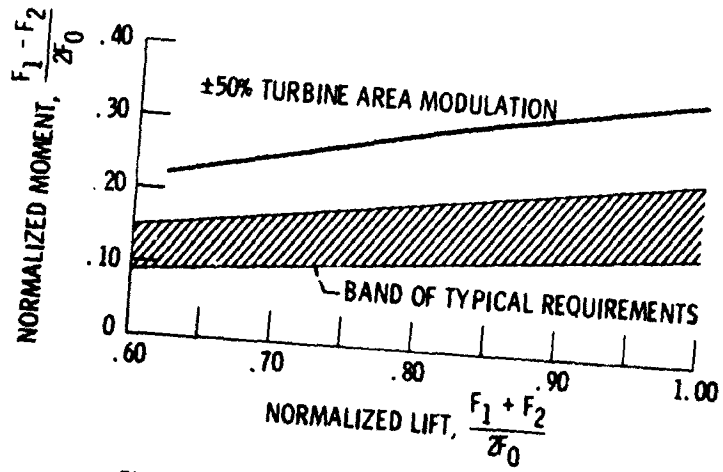

Figure 7. - Available control moment versus available lift for the gas-coupled system with variable-area turbines.

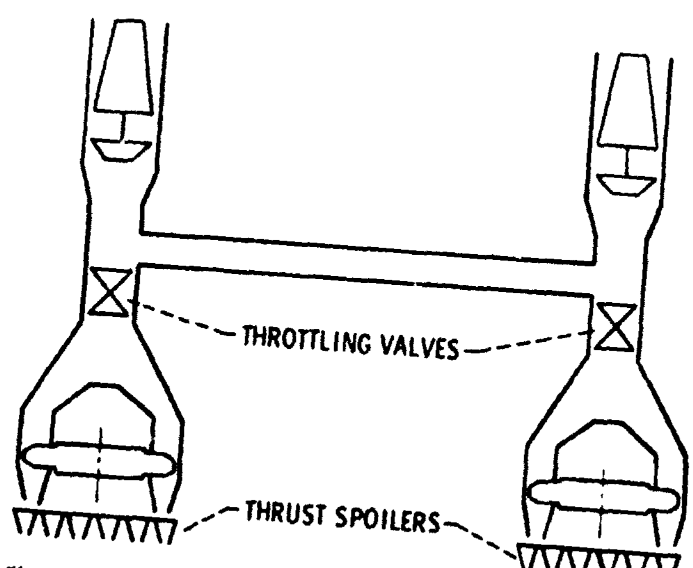

Figure 8. - Gas-coupled lift fans with throttling valves for flow transfer.

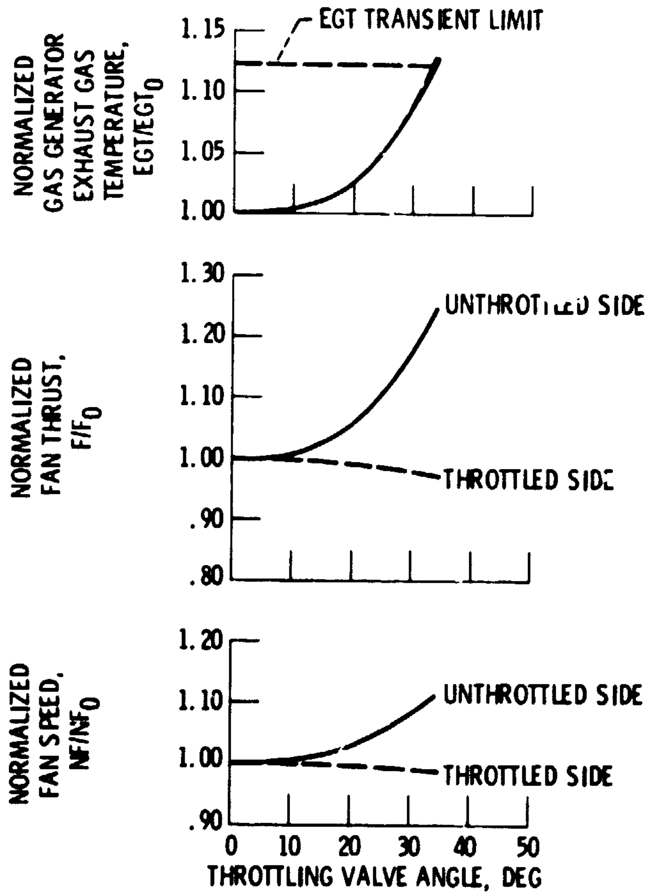

Figure 9. - Steady-state characteristics of the gas-coupled system with throttling valves.

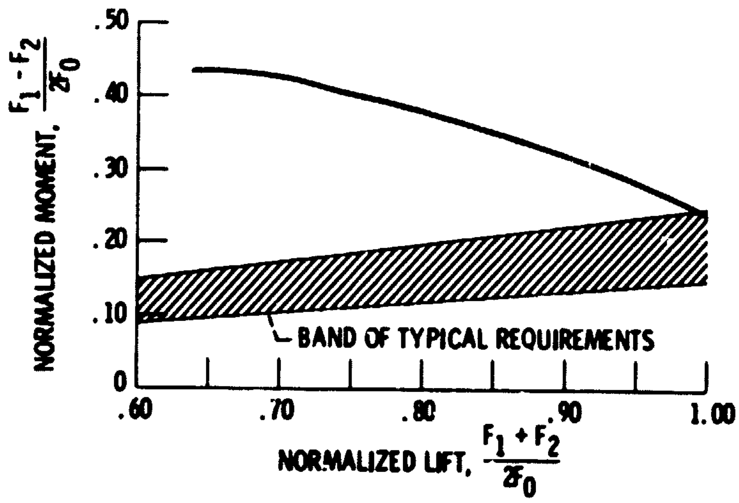

Figure 10. - Available control moment versus available lift for the gas-coupled system with throttling valves.

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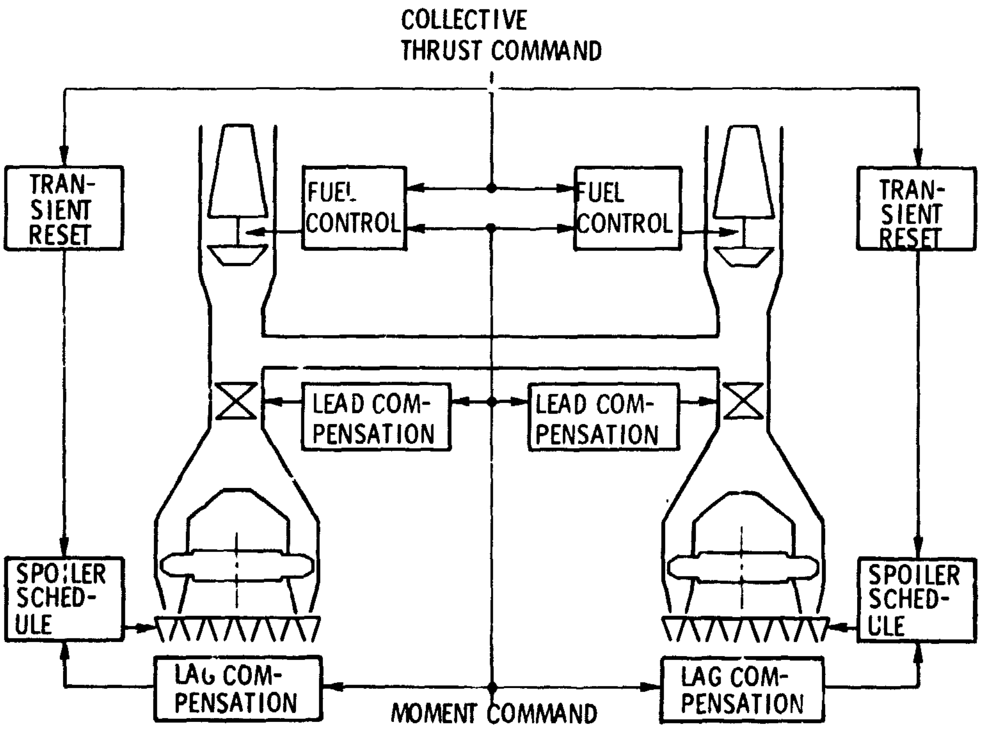

Figure 11. - Control system for gas-coupled lift fans with throttling valves.

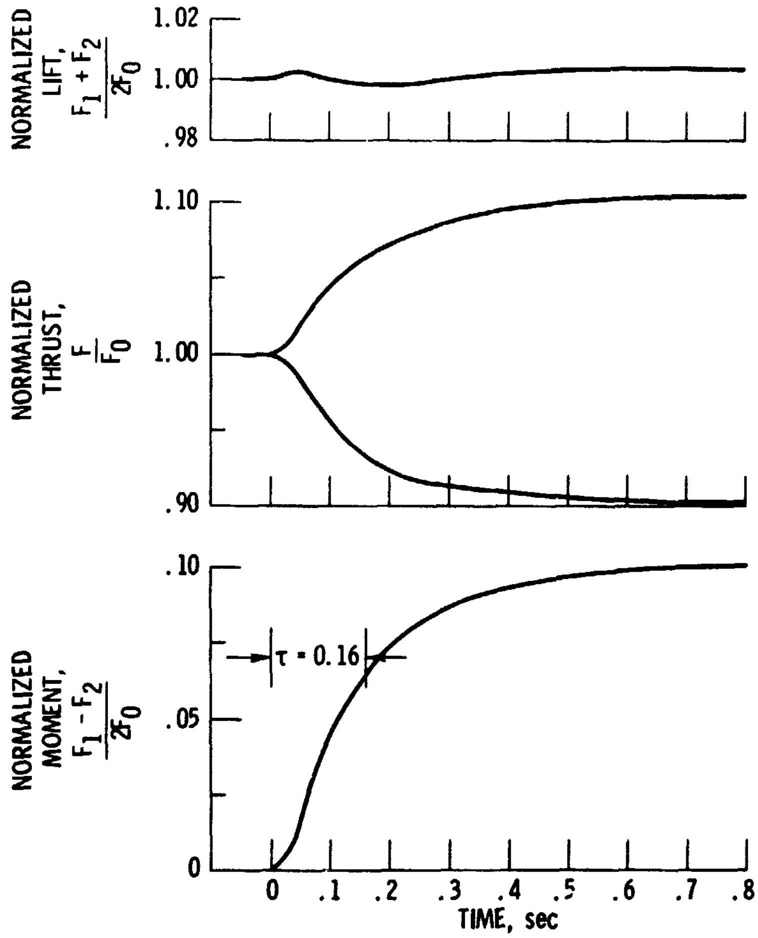

Figure 12. - Response of gas-coupled system with throttling valves to a step in moment request.

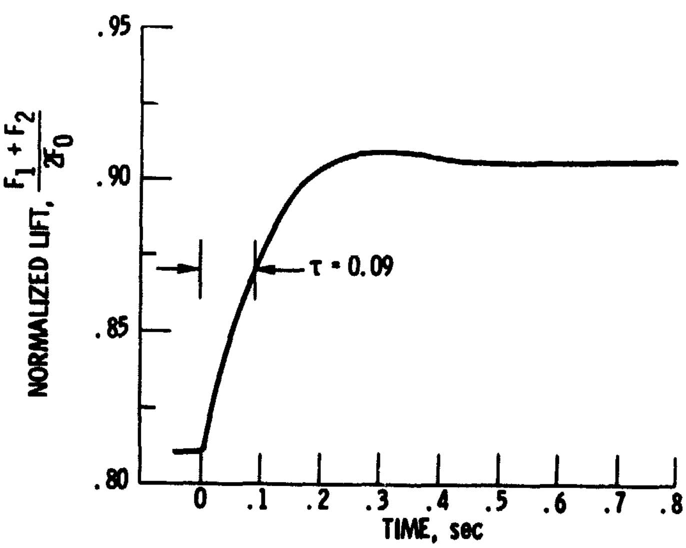

Figure 13. - Response of gas-coupled system to a step in collective thrust request. (Spoilers used to improve response.)

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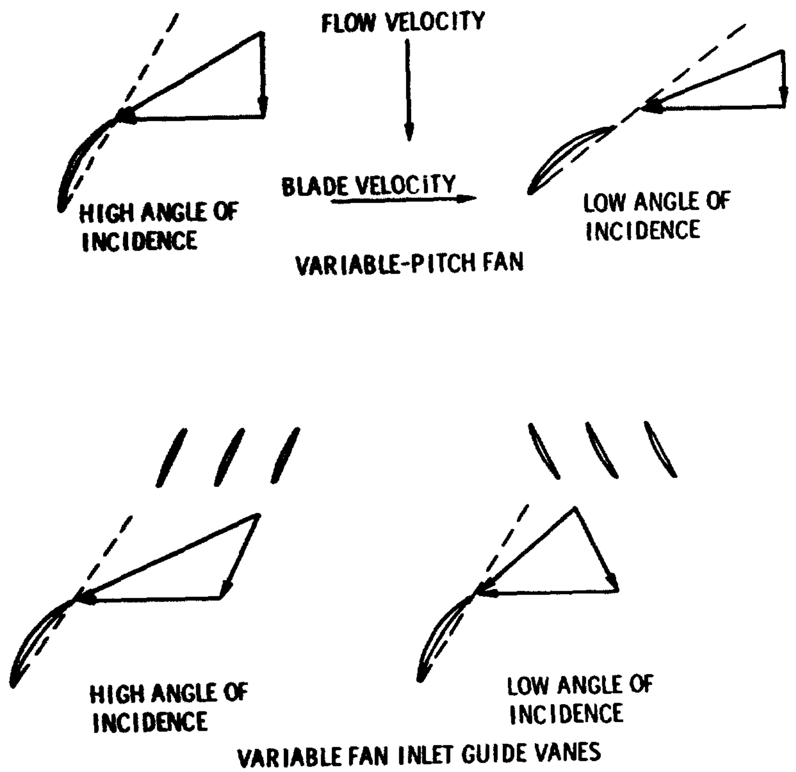

Figure 14. - Methods of changing fan blade angle of incidence at constant speed.

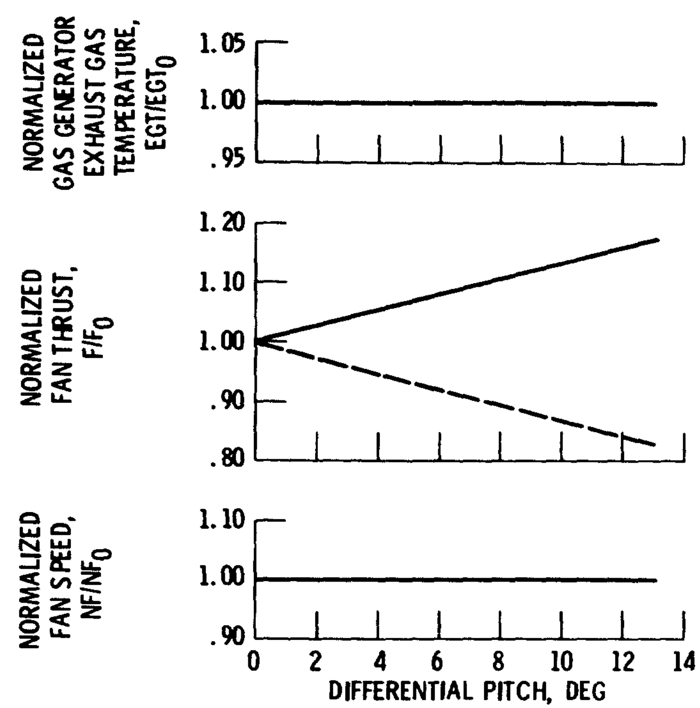

Figure 15. - Steady-state characteristics of the shaft-coupled system with variable-pitch fans.

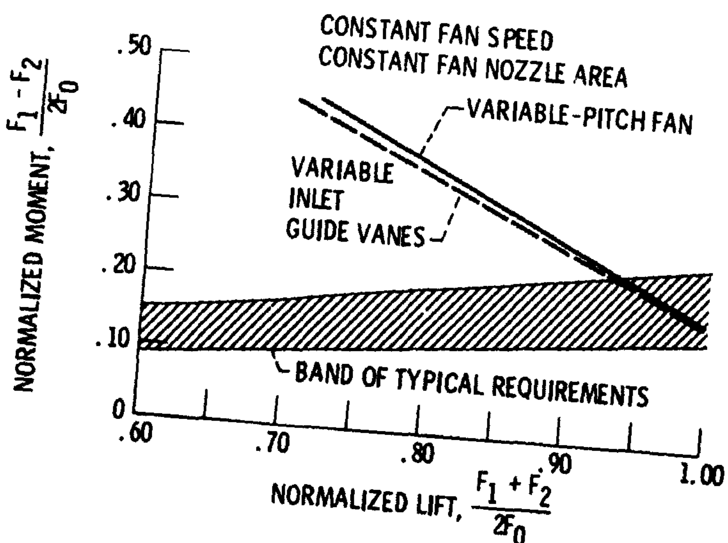

Figure 16. - Available control moment versus available lift for shaft-coupled lift fans.

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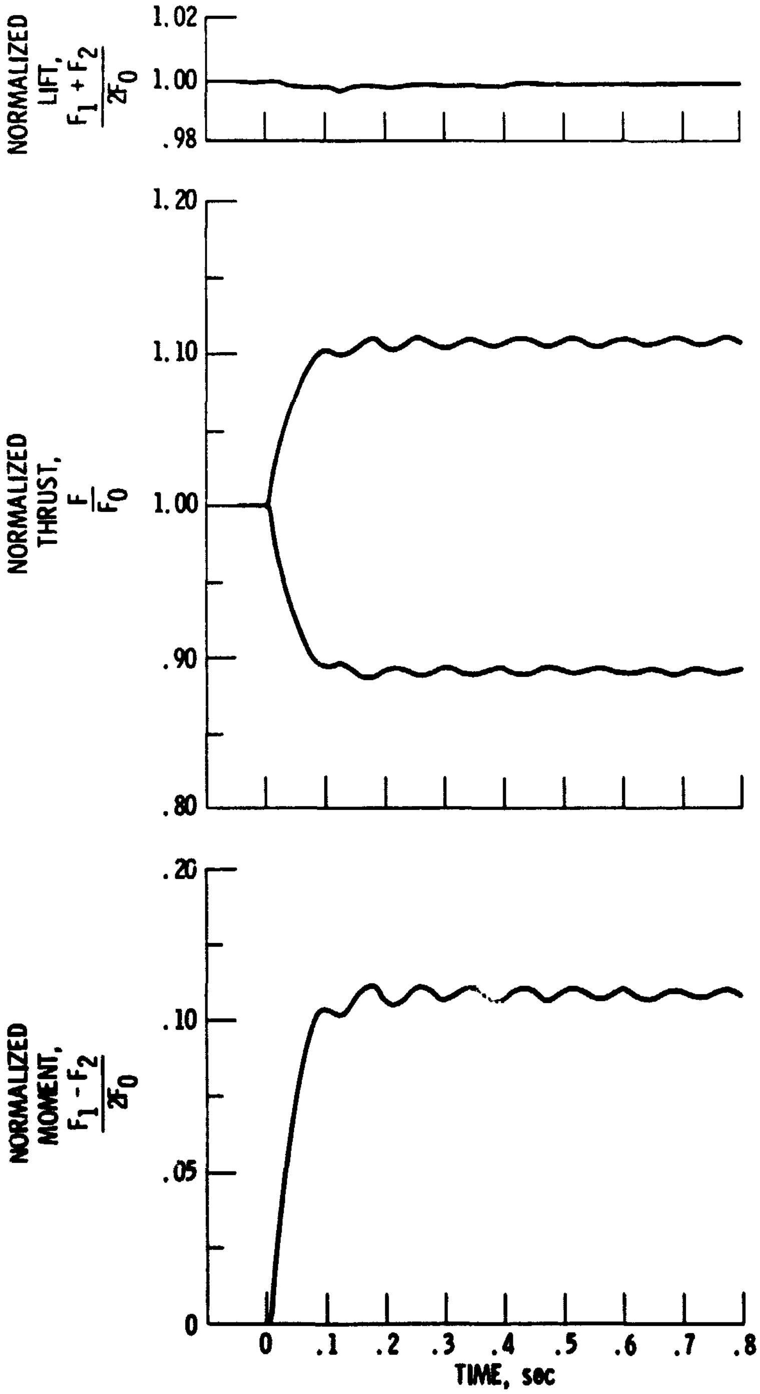

Figure 17. - Response of shaft-coupled system to a step in differential pitch (no controls).

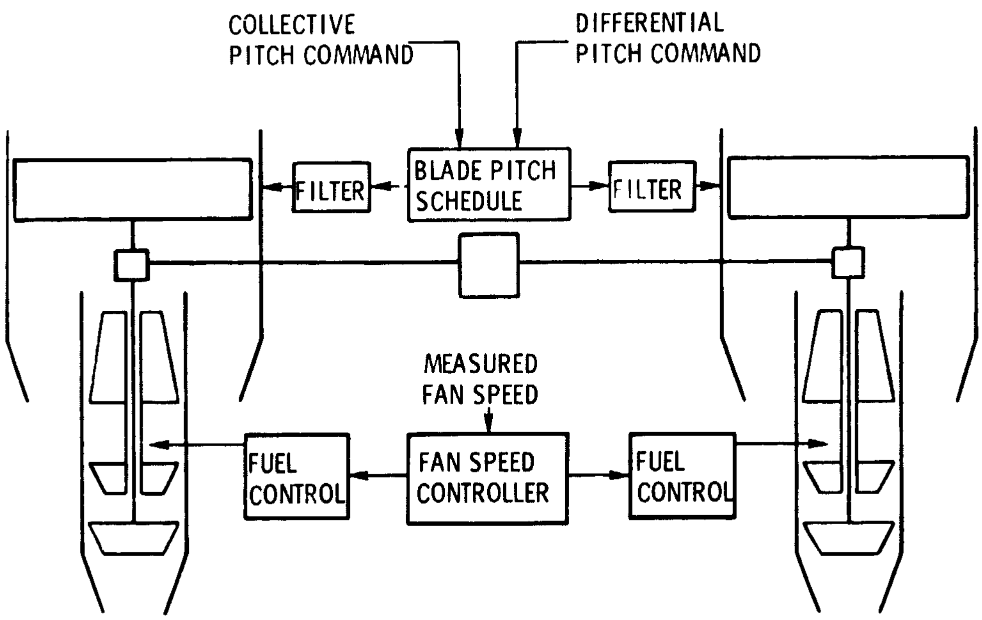

Figure 18. - Controls for shaft-coupled system.

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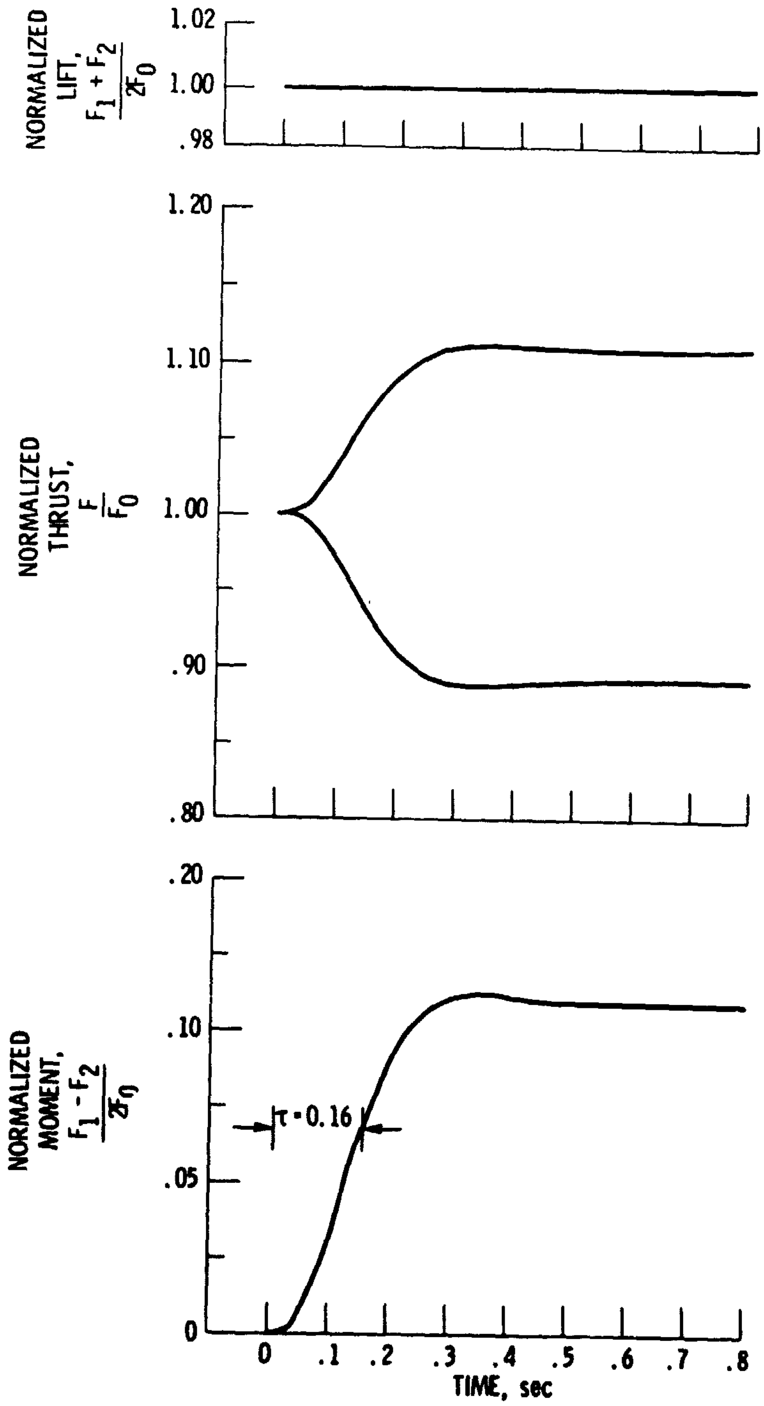

Figure 19. - Response of shaft-coupled system to a step in differential pitch request (filtered inpu').

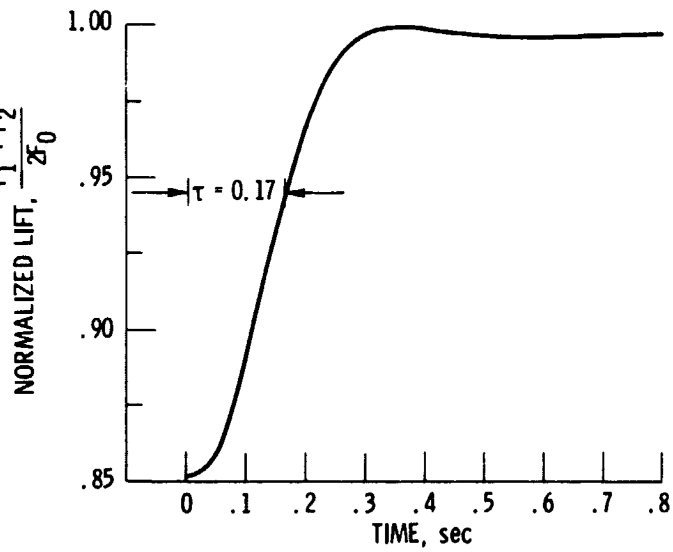

Figure 20. - Response of shaft-coupled system to a step in collective pitch request (filtered input).

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