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CONTROL OF TURBOFAN LIFT ENGINES FOR VTOL AIRCRAFT

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FOR VTOL AIRCRAFT

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ABSTRACT

The use of turbofan engines as lift units for VTOL aircraft poses new engine control problems. At low flight speeds, the lift units must provide the fast thrust response needed for aircraft attitude and height control. This paper presents the results of an analytical study of the dynamics and control of turbofan lift engines, and proposes methods of meeting the response requirements imposed by the VTOL aircraft application.

Two types of lift fan engines are discussed: the integral and remote. The integral engine is a conventional two-spool, high bypass ratio turbofan designed for low noise and short length. The remote engine employs a gas generator and a lift fan which are separated by a duct, and which need not be coaxial. For the integral engine, a control system design is presented which satisfies the VTOL response requirements. For the remote engine, two unconventional methods of control involving flow transfer between lift units are discussed. Both methods are shown to have thrust response near the required levels.

INTRODUCTION

VTOL transport aircraft powered by high bypass ratio turbofan engines have shown promise in meeting the criteria for a quiet, clean, transportation system which is not dependent upon large airport facilities.

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Aircraft studies have shown that using a minimum number of propulsion units is important in minimizing operating cost (ref. 1). To accomplish this, the same engines are used for cruise propulsion, lift, and attitude control in hover. The requirement of attitude control, in particular, places new demands on the engine control system. This paper discusses the ability of turbofan engine control systems to meet these new requirements. The conclusions presented are the result of an analytical study using detailed dynamic system models programmed for the hybrid and digital computers.

For a hovering VTOL aircraft, height control is accomplished by collectively modulating the thrust of the lift engines. The aircraft vertical acceleration is approximately proportional to the amount of thrust in excess of the aircraft gross weight. For attitude control, the angular acceleration about a given axis is proportional to the moment provided by the lift engines. For example, an aircraft with a lift engine at each wing tip would obtain roll control by developing a thrust difference between the two wing tip mounted engines. Ideally, one engine should increase in thrust while the opposite engine decreases its thrust by an equal amount, thus keeping total lift constant.

Extensive VTOL handling qualities studies (ref. 2) have resulted in criteria for the transient response of lift engines in terms of the thrust response "time constant". Consistent with reference 2, the time constant, τ, of a given reponse shall be defined in this paper as the time to reach 63 percent of a commanded step change. The time constant for collective thrust changes (height control) must be less than 0.50 second to be considered satisfactory. The magnitude of thrust changes for height control can be as much as ±10 percent of the nominal thrust level, in order to provide vertical accelerations of ±0.10 g (ref. 2). The time constant for moment response (attitude control), should be less than 0.20 second. The thrust modulation requirements for attitude control can be 15 to 25 percent of the nominal thrust level, depending upon aircraft size and geometry. While the same fans must provide the modulation for height <u>and</u> attitude control, ±25 percent modulation for combined inputs was chosen as a typical maximum requirement for this study. The VTOL transient thrust reponse requirements are quite severe in view of previous turbofan experience.

The principal objective of this study was to predict the transient performance of two types of turbofan engines designed for the VTOL aircraft application, and to determine their ability to meet the VTOL transient response requirements. The two types of engines discussed are the "integral" and "remote" turbofans (ref. 3). An integral engine is a typical high bypass ratio turbofan designed for short overall length. This reduces aircraft frontal area when the engine is vertically mounted. The results presented in this paper are for an advanced technology integral engine designed by the General Electric Company under contract to NASA. The engine is designated the ILF1A1 and has a projected thrust of 12 500 lbf (55 500 N). To date, only preliminary design has been completed for the ILF1A1. The transient analysis of the ILF1A1 included an engine control system designed by the General Electric Company. This control system was designed for fast thrust response in the VTOL application.

A remote fan system is somewhat unconventional, compared to the integral engine. The gas generator and fan need not be coaxial, and they are separated by a hot gas duct which supplies gas generator exhaust flow to the fan turbine (ref. 3). The remote fan system discussed in this paper is the YJ97-GE-100 gas generator driving the LF460 lift fan. The YJ97 is an existing turbojet (ref. 4). The LF460 (ref. 5) is a tip turbine driven fan of 60 in. (152 cm) diameter. The General Electric Company has completed preliminary design of the LF460 under contract to NASA. The YJ97 and LF460, when connected by a duct, form a remote drive turbofan producing about 12 500 lbf (55 500 N) thrust.

Two unconventional methods of control involving flow transfer between separate lift engines were analyzed in connection with the YJ97/LF460 turbofan. The first of these methods was developed by the McDonnell Aircraft Company and is known as Energy Transfer Control

(ETC), (ref. 6). The ETC concept involves the transfer of gas generator exhaust gas between opposite lift engines. The second concept discussed involves the transfer of compressor bleed air between opposite lift engines. These two concepts were analyzed in connection with the existing YJ97 gas generator control system, which was originally designed for a more conventional application. However, the YJ97 control system was modeled in its current form to establish the need, if any, for specific improvements.

INTEGRAL DRIVE FAN SYSTEM

A cross sectional view of the ILF1A1 integral drive turbofan is shown in figure 1. Design details for this engine are given in reference 3. The design thrust of the ILF1A1 is 12 500 lbf (55 500 N), but for study purposes the takeoff thrust was assumed to be 10 000 lbf (44 500 N). This allows ±25 percent thrust modulation for height and attitude control. The analysis of the ILF1A1 engine and control system was performed using the Lewis Research Center's hybrid computer. A detailed analytical model was used, employing dynamic analysis techniques developed at Lewis. Engine information and the design of the engine control system were provided by the General Electric Company. Accuracy of the analysis was verified by comparison with an independent study done at General Electric.

In order to explain the response limitations of the ILF1A1, a brief discussion of the engine control system will be given. Transient performance of the engine will then be discussed in connection with the design concept of the controls.

Control System

The primary function of the ILF1A1 control system is to regulate fuel flow, $\dot{W}_F$, to the combustor in order to maintain fan speed, N_f, at a desired level $N_{f,dem}$. This function is illustrated in figure 2, which shows closed loop control of fan speed. The controls designer can select the fan speed error gain, K_1, the limit functions, and the fuel system dynamics to combine the desired characteristics of fast response, stability, and engine protection.

The limit functions are primarily to prevent overspeeds, overtemperatures, compressor stall, and combustor blow-out. However, these limits only enter the picture during severe transients, i.e., when the fan speed error $N_{f,dem} - N_f$ is large. Under these circumstances, the fan speed loop is temporarily disconnected and the fuel flow signal is computed from other parameters. The limit functions are important for this study, since severe transients are the main subject of investigation.

Figure 3 gives additional detail on the limits incorporated in the ILF1A1 fuel control. Two parameters, high pressure (HP) spool speed, N_c, and HP turbine inlet temperature, T_4, are limited to maximum values $N_{c,max}$ and $T_{4,max}$. In addition, fuel flow is limited according to the acceleration and deceleration schedules. These schedules compute maximum and minimum fuel flow as a function of HP spool speed, N_c, fan inlet temperature, T_2, and HP compressor discharge pressure, P_3. The acceleration schedule limits maximum fuel flow to prevent compressor stall, while the deceleration schedule limits minimum fuel flow to prevent combustor blow-out.

The limit functions of the ILF1A1 control system operate by means of MAX and MIN circuits. The output of a MAX circuit is the largest of its inputs; the output of a MIN circuit is the smallest of its inputs.

In figure 3, the fan speed error signal $K_1 (N_{f,dem} - N_f)$ is compared with the temperature error signal $K_2 (T_{4,max} - T_4)$ in the first MIN circuit. In the steady state condition, fan speed error will be essentially zero; but the temperature error should have a positive value since T_4 will be less than $T_{4,max}$. As a result, the MIN circuit will select fan speed error as its output.

During an acceleration transient, $N_{f,dem}$ will exceed N_f so the fan speed error will be positive. However, if T_4 exceeds $T_{4,max}$, the temperature error will be negative, and the MIN circuit will select $K_2(T_4 - T_{4,max})$ as its output. Similar reasoning holds for the remaining limits. The gains K_1, K_2, and K_3 are selected to result in the desired switching characteristics among the limiting control modes.

Control gains and schedules selected by the General Electric Company were used in the analysis of the ILF1A1 control system. These parameters were chosen by General Electric to produce good transient performance for the VTOL application.

Calculated Transient Performance

The previous discussion of the ILF1A1 fuel control system showed that demand fan speed was the primary control input. In flight, this single input is varied to provide thrust modulation for both height and attitude control.

The assumed response goal for the ILF1A1 in this discussion shall be a thrust time constant, τ, of less than 0.20 second. If the ILF1A1 can meet this requirement it is also satisfactory for the height control requirement of τ less than 0.50 second.

Since a VTOL transport will be required to hover at a variety of different gross weights, the time constant of the lift engines at different nominal thrust levels is of interest. Also, the time constant as a function of commanded thrust increment is of interest, since in flight the amount of modulation required will vary.

Figure 4 shows the variation of the ILF1A1's thrust time constant as a function of thrust level and commanded increment. The input is a step in demand fan speed. The size of the resulting thrust change is expressed as a percentage of the design thrust of 12 500 lbf (55 500 N). A negative step indicates a thrust decrease, while a positive step means an increase. Figure 4 is for sea level, standard day conditions.

Figure 4 shows that for the standard day condition, the ILF1A1 has satisfactory attitude control response for thrust increments of ±10 percent and for a wide range of initial thrust levels. For larger thrust increments the response was unsatisfactory. This slow thrust response is the result of two effects: the basic characteristics of the ILF1A1, and the acceleration and deceleration fuel flow schedules. The T_4 and N_c limits had no effect on the responses shown in figure 4. The only apparent way to improve the response for large thrust increments is to alter the acceleration and deceleration fuel schedules. However, this type of control modification was not attempted in this study.

In order to assess the effect of temperature limiting, large thrust increments were analyzed for the hot day (550° R, 305 K) condition. Thrust demand was stepped from the nominal takeoff thrust of 10 000 lbf (44 500 N) to the design thrust of 12 500 lbf (55 500 N). This is a thrust increase of 25 percent of the nominal level, the maximum increment for this study.

Figures 5(a) and (b) show the time histories of thrust and T_4 for this step size at sea level static, hot day conditions. Thrust and T_4 are expressed in percent of design value. For the ILF1A1, $T_{4,des}$ was 2960° R (1640 K). The parameter $T_{4,max}$ used in the limit functions (fig. 3) was varied from $T_{4,des}$ to 1.1 $T_{4,des}$ to determine the effect of this limit on the thrust response. With $T_{4,max}$ set to 1.1 $T_{4,des}$, the temperature limit had no effect on the thrust response; the only active limit function was the acceleration schedule. The response time constant was 0.285 second for this case, but the peak value of T_4 was 3120° R (1730 K), 160° R (90 K) in excess of $T_{4,des}$.

Thrust response is degraded as the temperature limit begins to have an effect, as shown by figure 5. With $T_{4,max}$ equal to $T_{4,des}$, the thrust response has a time constant of 0.735 second. The tradeoff illustrated by figure 5 must be taken into account in the design of fast-response integral drive lift fans. In flight, thrust modulation for attitude and height control will occur continuously, so thermal cycling effects introduced by the control system will require close attention.

The preceding discussion has shown the ILF1A1 integral engine to have satisfactory attitude control response (τ less than 0.20 sec) for thrust increments less than 10 percent of design. Thrust response for larger increments was limited by the acceleration schedule, and possibly by transient over temperatures on hot days. Height control response was satisfactory (τ less than 0.50 sec) for practically all cases studied.

An additional possibility exists for improving the attitude control response of the integral engine if thrust spoiling is used. For attitude control, one fan must lose thrust while the opposite fan gains. Thrust can be spoiled very quickly through the use of louvers which are pinched partly closed when a thrust reduction is needed. This method trades fast moment response for a transient lift loss, since the low side (spoiled) fan loses lift more quickly than the high side fan can regain it. Spoiling is a vital part of the control of remote drive fans, and will be discussed more fully in the following section.

REMOTE-DRIVE FAN SYSTEMS

A typical remote fan system employing two YJ97 gas generators and two LF460 lift fans is shown in figure 6. A cross duct is also shown, which permits the two fans to share unequally the exhaust gas of the two YJ97 gas generators. The two fans are viewed along their axes of rotation; they are not coaxial with the gas generators. The LF460 fan is driven by turbine buckets mounted around the circumference of the fan; hot gas from the YJ97 reaches the turbine by means of a scroll which entirely surrounds the fan. The flow transfer capability of remote fan systems is one of their most useful features for the VTOL aircraft application.

For example, consider the two fans of figure 6, one mounted at each wing tip of a large aircraft, with the cross duct passing through the wings. When a rolling moment is required, a thrust difference must be developed between these two fans. Ideally, the fan on the low side should lose the same amount of thrust that the high side gains, in order to keep the total lift constant. Taking flow away from the low side fan and transferring it to the high side fan is an obvious method of realizing this ideal situation.

Two systems of flow transfer, the Variable Area Scroll and Turbine

Energy Modulation systems, are discussed in the literature (refs. 7 and 8) and will not be covered in this paper. Instead, two more recent systems will be discussed. One is known as Energy Transfer Control (ETC), and involves the transfer of gas generator exhaust gas between lift units. The other system employs gas generator compressor bleed air as the only transfer gas.

The ETC system has been proposed for use in a VTOL research aircraft employing YJ97/LF460 lift units (ref. 9). Both the ETC system and the compressor bleed system have unique capabilities for lift recovery in various failure modes, but in this paper only their normal operation will be discussed. A brief description of each system will be given to aid in the discussion of results.

Energy Transfer Control System

The ETC system is shown schematically in figure 6. Two butterfly valves are mounted upstream of each LF460 turbine scroll inlet. Both YJ97's are run at the same throttle setting; when the valves are wide open, no cross flow occurs and both fans produce the same thrust.

When a control moment is needed, the two valves on the low side are rotated to a partly closed position. This restriction upstream of the low side LF460 turbine causes flow to cross over to the high side, where the valves remain fully open. Furthermore, closing the valves has the effect of reducing the effective discharge area for the two YJ97's. The response of the YJ97's to this backpressuring effect depends upon the design of their fuel controls. Since the YJ97 has a constant-speed governor, the speed drop resulting from the high backpressure is quickly corrected by a fuel flow increase. Hence, with the valves on the low side partly closed, the system reaches a new equilibrium condition with higher duct pressures and temperatures, and unequal flow passing to the two LF460 turbines. The high side LF460 receives more flow at a higher temperature and pressure, and its speed and thrust increase. The low side LF460 receives less flow, but at a higher temperature. The pressure loss due to the valves is partly offset by the increase in duct pressure. The net result of these effects on the low side LF460 is a small thrust loss, but not enough to equalize the thrust increase on the high side. Fan thrust spoiling is used to bring the low side thrust down to the desired level. This is usually accomplished by the partial closing (pinching) of louvers mounted in the fan exhaust stream.

The method outlined above can be employed even when the YJ97's are run at full military power (101.5 percent speed). Applying moment control in this condition results in transient overtemperatures to the YJ97. The total amount of moment capability is restricted by transient temperature limits, reduced stall margin, and fan overspeed limits.

Compressor Bleed System

The compressor bleed system of flow transfer is shown schematically in figure 7. Each YJ97 is equipped with a compressor bleed manifold. A three-way valve at each end of the cross duct controls the amount of bleed air entering the cross duct. The same valves also permit bleed flow from the cross duct to be injected into the hot stream between the YJ97 and LF460. As in the ETC system, both YJ97's are run at the same throttle setting. When the valves are in the neutral position, no bleed or cross flow occurs and both fans produce the same thrust.

When a control moment is needed, the valves are positioned so that bleed flow from the low side YJ97 passes through the cross duct and is injected into the YJ97 discharge stream on the high side. This increases the flow rate through the high side LF460 turbine, and increases the back-pressure on the YJ97. Again, the YJ97 fuel control adds fuel flow to prevent a speed drop so the duct temperature rises. On the low side, the bleed from the compressor results in less flow through the YJ97 turbine, and hence less work done by the turbine. The YJ97 governor compensates for this by adding fuel flow in order to maintain constant speed, so turbine inlet and exhaust temperature both rise. As a result, the low side LF460 sees a flow and pressure decrease, but a temperature increase. As in the ETC system, the low side LF460 needs spoiling to balance the thrust increase on the high side.

Steady-State Performance

Although moment demands are only of short time duration in flight, the steady state performance of the ETC and compressor bleed systems is still of interest since it identifies the limits on moment production.

Table I summarizes the moment-generating capabilities of both systems, at the sea level standard day condition with the YJ97's running at full military power. The results shown are from a transient simulation of the YJ97/LF460 system programmed for a digital computer. Steady-state accuracy of the simulation is within 1 percent, compared to data from a computer program provided by the General Electric Company, which gives estimated performance of the YJ97-GE-100 turbojet.

When there is no cross flow (trim condition), each fan produces 12 780 lbf (56 860 N) of thrust, and YJ97 exhaust gas temperature is 1835° R (1019 K). Maximum cross flow, and hence attitude control moment, is set by the transient YJ97 exhaust gas temperature limit of 2060° R (1144 K). At this condition, the high side fan produces a thrust 24 percent greater than at trim, and the low side fan is spoiled to a thrust 24 percent less than at trim. This is equivalent to a thrust difference of 6140 lbf (27 300 N) between the high and low sides. For both systems, YJ97 compressor stall margin is cut to 15.8 percent at maximum control moment, compared to 21.4 percent at trim.

The two systems are quite similar except for the amount of cross flow required to obtain maximum moment: 6.84 lbm/sec (3.10 kg/sec) for the ETC system and 8.86 lbm/sec (4.02 kg/sec) for the compressor bleed system. This difference is due to the higher cross flow temperature (2060° R, 1144 K) for the ETC system, as compared to 1200° R (667 K) for the bleed system. For the bleed system, the high side LF460 turbine inlet temperature is less than the YJ97 exhaust gas temperature, due to the addition of relatively cool compressor bleed air. As a result, slightly more flow is required to drive the LF460 to its maximum thrust. Pressure in the cross duct is lower for the ETC system (62 psia, 4.2 atm) than for the bleed system (210 psia, 14.3 atm).

Due to the lower temperature and higher pressure, the cross ducts for the bleed system can be smaller in diameter than for the ETC system, but they must be stronger to withstand the pressure. In return for the disadvantages of hot ducts, the ETC system offers certain benefits in failure mode performance (ref. 9).

Both systems, of course, can provide varying amounts of control moment up to the limiting case shown in table I. They are also capable of producing the same amount of moment at lower YJ97 power settings, where overall thrust and temperature levels are lower.

Control System

Figure 8 gives a schematic representation of the control system used in the analysis of the YJ97/LF460 system. Unlike the integral-drive turbofan, remote fan systems employing flow transfer have two control inputs: a gas generator speed demand for collective thrust modulation (height control), and a valve position demand for generating attitude control moments. As discussed earlier, both YJ97's receive the same speed demand. For this study, spoiler pinch angle was scheduled as a function of demand valve position and demand YJ97 speed, in order to keep steady state total lift constant regardless of the amount of moment being generated. The transient analytical model for this study included all major effects, including two interconnected YJ97/LF460 units with duct and actuator dynamics.

Figure 9 gives a schematic representation of the model used for the YJ97 gas generator fuel control system, as provided by the General Electric Company. The primary function of the control system is to maintain YJ97 rotor speed, N_c, at a commanded level $N_{c,dem}$. The model used for the YJ97 control system did not have temperature limiting, but acceleration and deceleration schedules were included.

The control system shown in figure 9 was originally designed for a military application, but it was modeled in its current form to determine if modifications were required for use in flow transfer systems.

Calculated Transient Performance

Since the ETC and compressor bleed systems have separate inputs for height and attitude control, the responses for these inputs will be discussed separately. All thrust data are normalized with respect to F_0, (12 780 lbf, 56 860 N), which is the thrust produced by one YJ97/LF460 unit at military power with no cross flow ("trim" column of table I). For study purposes, takeoff thrust (100 percent of F_0) was assumed to occur at 101.5 percent YJ97 speed, while landing thrust (56.5 percent of F_0), was assumed to occur at 92 percent YJ97 speed.

Height control. - Figure 10 summarizes the transient response of the YJ97/LF460 turbofan for step changes in YJ97 demand speed. Figure 10 applies to both the ETC and compressor bleed systems, since no cross flow is involved; that is, no moment demand accompanies the height control input. The step sizes for figure 10 are for aircraft vertical accelerations and decelerations between the maximum levels of ±0.10 g, at the nominal takeoff and landing conditions.

The major conclusion evident from figure 10 is that thrust response for height control varies with initial thrust level. For the takeoff condition, the time constants of 0.23 and 0.34 second are well below the required value of $\tau = 0.50$ second. For the landing condition, with thrust levels near 60 percent of F_0, the time constants of 0.50 and 0.52 second are near the limiting value. Although the responses shown are for the maximum step size that would be required in flight, the results are typical of those for smaller step sizes as well.

The acceleration and deceleration fuel flow limits in the YJ97 control system had no effect on the responses shown in figure 10. This is encouraging, since it means engine protective limits are not encountered. A modified YJ97 fuel control would probably produce better thrust response by increasing or decreasing fuel flow until the limits were reached. Even with the existing fuel control, height control response is very nearly satisfactory.

Attitude control. - Figure 11 shows a typical attitude control response for the ETC system at the takeoff condition (101.5 percent YJ97 speed). The thrust of each of the two LF460's is shown, as well as the sum and difference of the two thrusts. The input is a step in demand valve position.

Figure 12 shows a similar transient for the compressor bleed system. The two systems are qualitatively similar but the time constants are different. For the ETC system, the high side fan responds with a time constant of 0.42 second, while the low side response has a time constant of 0.09 second. The fast response of the low side fan is due to the effect of spoiling.

The moment response ($\tau = 0.18$ sec) is satisfactory according to the attitude control criterion (τ less than 0.20 sec). However, the total thrust experiences a noticeable transient drop. This situation is the one mentioned earlier in connection with thrust spoiling for the integral engine, and illustrates the penalty associated with obtaining fast moment response through spoiling. The aircraft height loss associated with this total lift drop is negligible, however (ref. 6). Fan thrust spoiling appears to be a plausible way of obtaining satisfactory moment response in spite of the fact that the high side thrust response has a time constant above 0.20 seconds.

For the bleed system, figure 12 shows that $\tau = 0.30$ seconds for the high side thrust response, and $\tau = 0.12$ seconds for the low side. The moment response ($\tau = 0.23$ sec) is slower than for the ETC system, despite the fact that the high side thrust responds faster. This is reflected in the fact that total lift experiences less transient drop for the bleed system than for the ETC system. The bleed system moment response could be made satisfactory for this case by adding lead compensation to the spoiler control system.

Like the height control response, the attitude control response of the YJ97/LF460 system is slower at the landing condition. For example purposes, only the compressor bleed system will be discussed for this case, but the conclusions for the ETC system are similar.

Figure 13 shows the attitude control response of the compressor bleed system at 92 percent YJ97 speed. The moment response (τ = 0.28 sec) is unsatisfactory for this case. The slow response of the high side fan (τ = 0.50 sec) is the primary cause of this result. This, in turn, is due to the design concept of the YJ97 fuel control, which is not ideal for this application. The YJ97 has no way of sensing increased back pressure except through the resulting transient speed drop. Hence, the necessary fuel flow and exhaust temperature increase is governed by YJ97 fuel control and rotor dynamics, which are fairly slow at 92 percent speed. The attitude control response of the ETC system was also found to be unsatisfactory at 92 percent YJ97 speed.

Improved fuel control system. - One obvious method of improving the response of both systems is to alter the YJ97 fuel control so that valve position changes can be anticipated. This modification is illustrated in figure 14. The modified fuel control is identical to the original one except that an extra input signal proportional to demand valve position has been added. In this analysis, the gain of the anticipation signal, K_2, was chosen on the basis of steady state fuel flow against valve position requirements at 101.5 percent YJ97 speed:

$$K_2 = \frac{\dot{W}_{F,max} - \dot{W}_{F_o}}{X_{max}}$$

where $\dot{W}_{F_o}$ is the fuel flow corresponding to 101.5 percent speed and no cross flow; $\dot{W}_{F,max}$ is the fuel flow for maximum control moment; and X_{max} the valve position for maximum control moment.

The calculated results for this modification were encouraging, as shown by figure 15, which gives compressor bleed system response at 92 percent YJ97 speed with the modified control system. High side thrust response is markedly improved (τ = 0.23 sec), while moment response is now satisfactory (τ = 0.19). The ETC system showed similar improvement as a result of the modification.

CONCLUSIONS

Results from the analysis of the ILF1A1 integral-drive turbofan and its control system indicated that:

1. The thrust response for height control was satisfactory (time constant less than 0.50 sec) for nearly all cases studied. The thrust response for attitude control was satisfactory (time constant less than 0.20 sec) for thrust changes less than 10 percent of the design thrust.

2. Response for changes greater than 10 percent was limited by the acceleration fuel flow schedule, and, for hot days, by transient turbine overtemperatures.

3. Attitude control response can be made satisfactory for all step sizes if thrust spoiling is used.

Similar results from the analysis of the YJ97/LF460 remote-drive turbofan system indicated that:

1. The ETC and compressor bleed systems of flow transfer can produce up to a 24 percent thrust increase for attitude control.

2. With the existing YJ97 control system, thrust response for height control was generally satisfactory, but was degraded at YJ97 speeds near 92 percent. However, attitude control response at 92 percent YJ97 speed was definitely unsatisfactory using this control system.

3. One possible control modification was demonstrated which results in satisfactory attitude control response at 92 percent YJ97 speed.

The most significant overall conclusion of this study is that high bypass ratio turbofan engines in the 12 500 lbf (55 500 N) thrust category can, with certain restrictions, be made to meet the stringent VTOL thrust response requirements.

APPENDIX - NOMENCLATURE

F	thrust
HP	high pressure
K_i	control gain
N_c	high pressure rotor speed
N_f	fan speed
P_3	compressor discharge pressure
T_2	fan inlet temperature
T_4	high pressure turbine inlet temperature
$\dot{W}_F$	fuel flow
X	valve position
τ	time constant

Subscripts:

dem	demand
des	design
HIGH	increasing thrust
LOW	decreasing thrust
max	maximum
0	value at trim, military power

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TABLE I. - MAXIMUM MOMENT GENERATING CAPABILITY

Sea level static, standard day conditions; Both YJ97's at military power (101.5 percent speed)

Energy Transfer Control (ETC) System

Cross Flow - 6.84 lbm/sec (3.10 kg/sec) at 2060° R (1144 K)

	Trim	High side	Low side
LF460 thrust, lbf (N)	12 780 (56 860)	15 850 (70 510)	9710* (43 200)
YJ97 exhaust gas temperature, °R (K)	1835 (1019)	2057 (1143)	2060 (1144)
LF460 turbine inlet temperature, °R (K)	1835 (1019)	2058 (1143)	2060 (1144)
YJ97 compressor stall margin, percent	21.4	15.9	15.8

Compressor Bleed System

Cross Flow - 8.86 lbm/sec (4.02 kg/sec) at 1200° R (667 K)

	Trim	High side	Low side
LF460 thrust, lbf (N)	12 780 (56 860)	15 850 (70 510)	9710* (43 200)
YJ97 exhaust gas temperature, °R (K)	1835 (1019)	2060 (1144)	2023 (1124)
LF460 turbine inlet temperature, °R (K)	1835 (1019)	2022 (1123)	2023 (1124)
YJ97 compressor stall margin, percent	21.4	15.8	33.0

*Includes effect of thrust spoiling.

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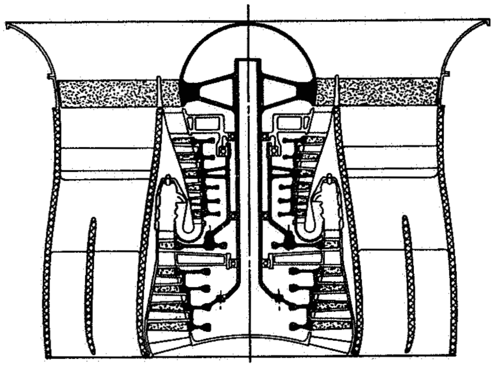

Figure 1. - Cross-section of integral-drive fan engine.

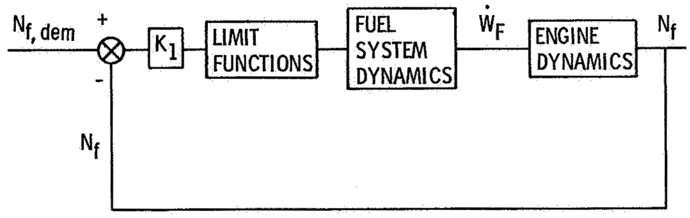

Figure 2. - Integral-drive fan engine primary control loop - fan speed control.

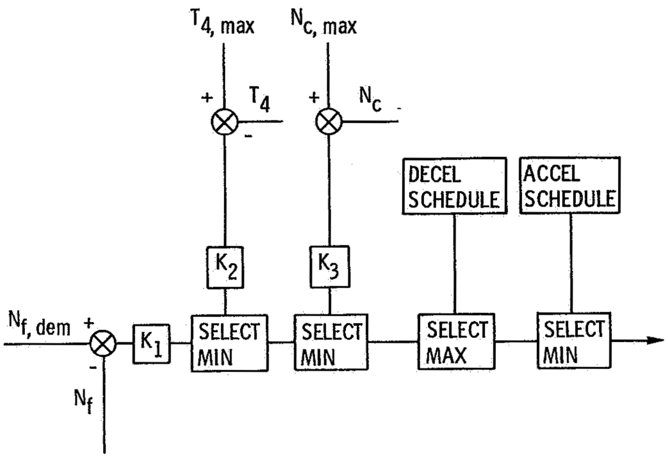

Figure 3. - Integral-drive fan engine control limit functions.

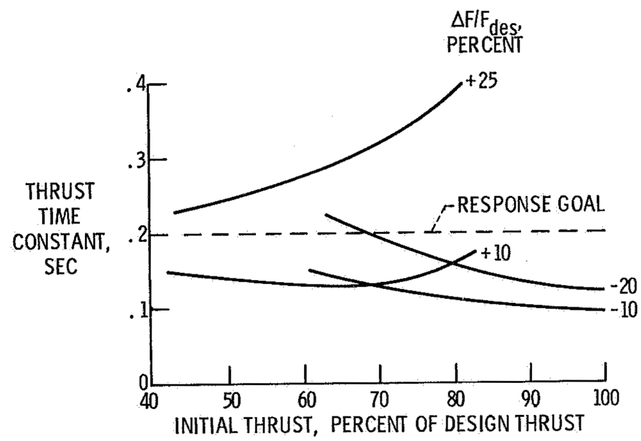

Figure 4. - Integral-drive fan engine. Effect of initial thrust and thrust increment on thrust time constant; standard day conditions.

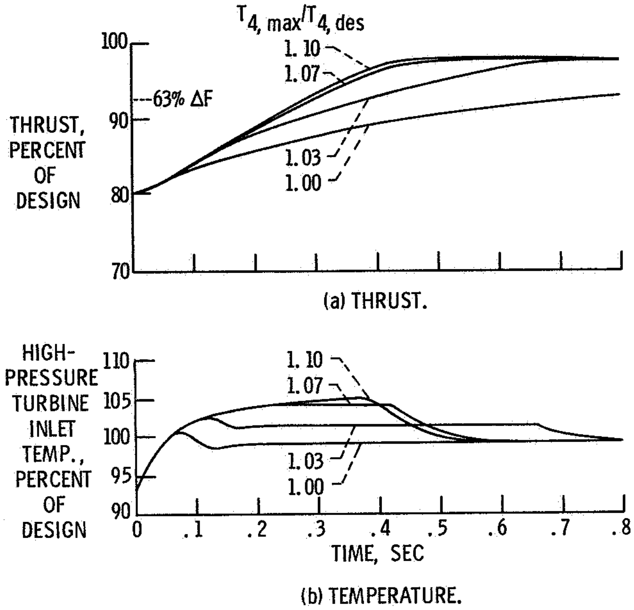

Figure 5. - Effect of temperature limit on integral-drive fan engine response; acceleration from takeoff to design thrust; hot-day, sea level static conditions.

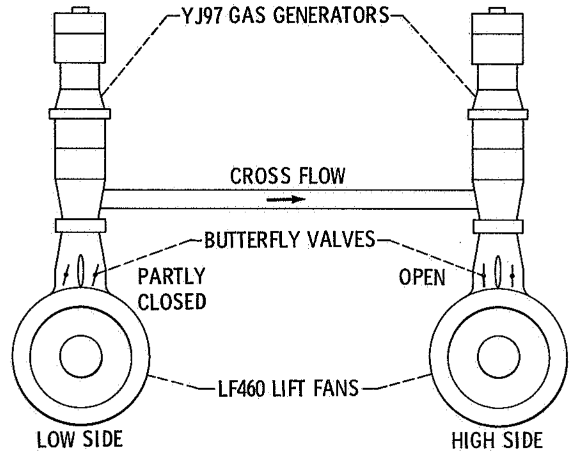

Figure 6. - Energy transfer control (ETC) system schematic.

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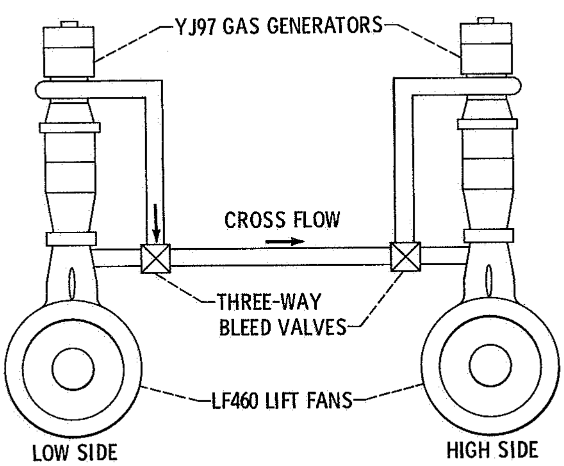

Figure 7. - Compressor bleed transfer system schematic.

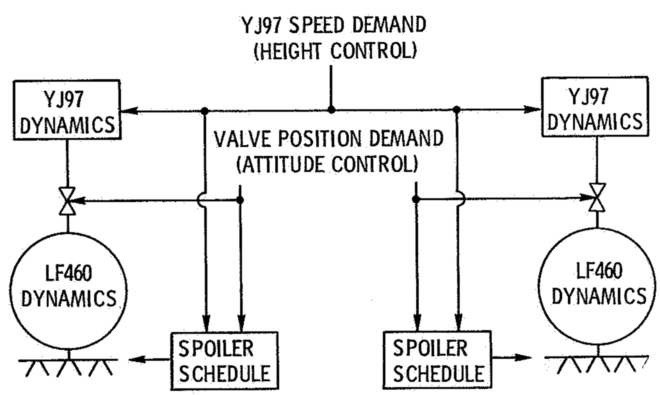

Figure 8. - YJ97/LF460 remote-drive fan system control schematic.

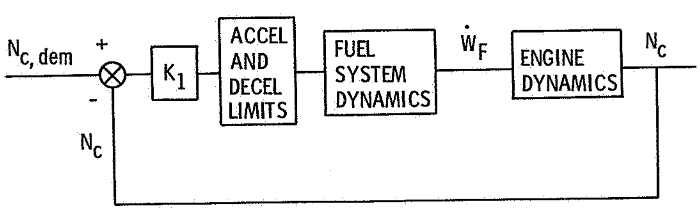

Figure 9. - YJ97 gas generator control system.

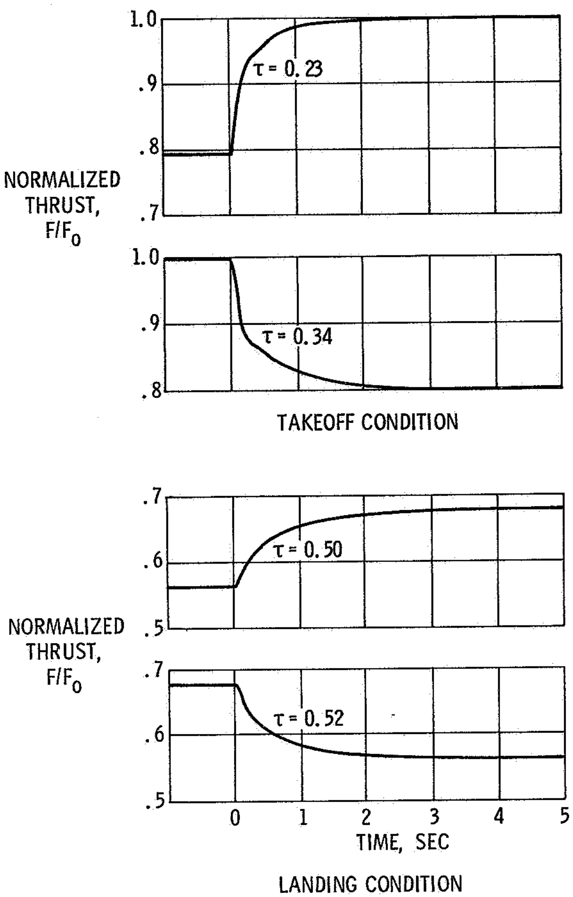

Figure 10. - Effect of initial thrust level on YJ97/LF460 height control response.

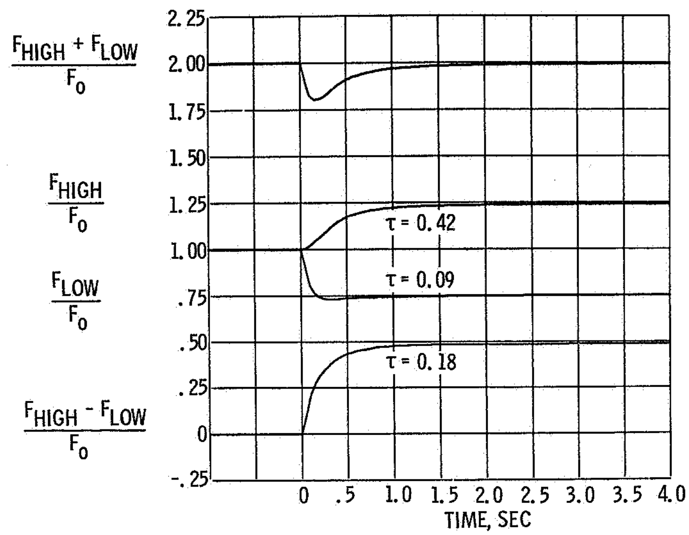

Figure 11. - ETC system attitude control response Takeoff condition, 101.5 percent YJ97 speed.

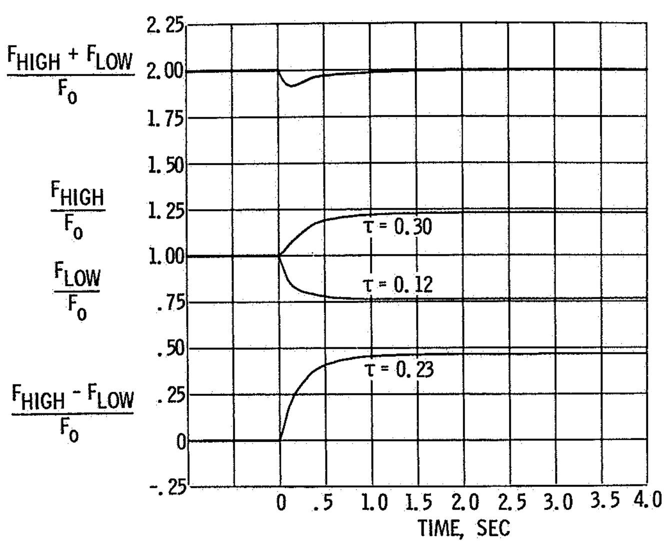

Figure 12. - Compressor bleed system attitude control response. Takeoff condition, 101.5 percent YJ97 speed.

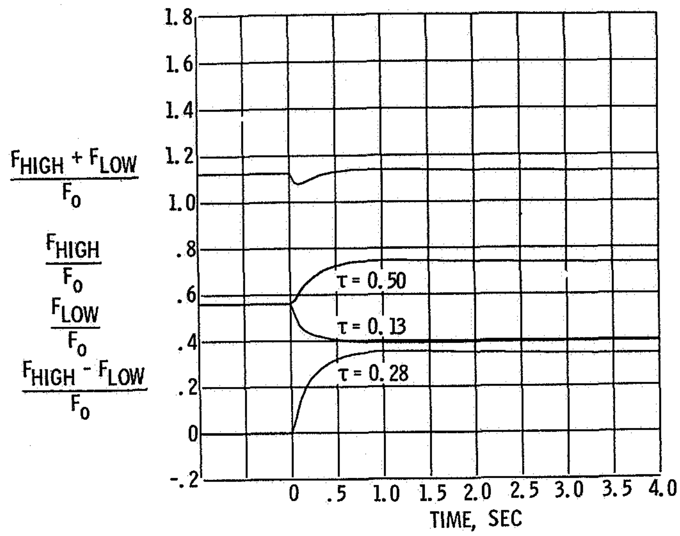

Figure 13. - Compressor bleed system attitude control response. Landing condition, 92 percent YJ97 speed.

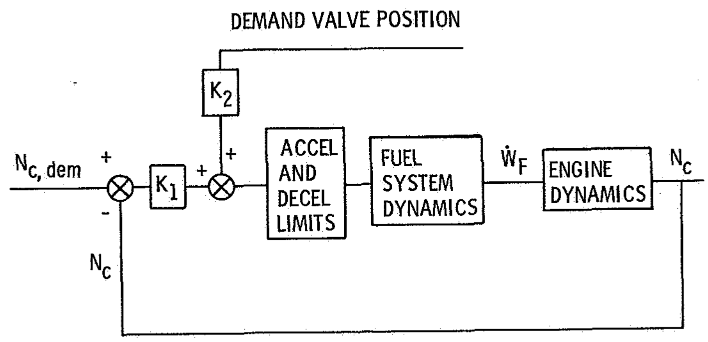

Figure 14. - Improved YJ97 gas generator control system.

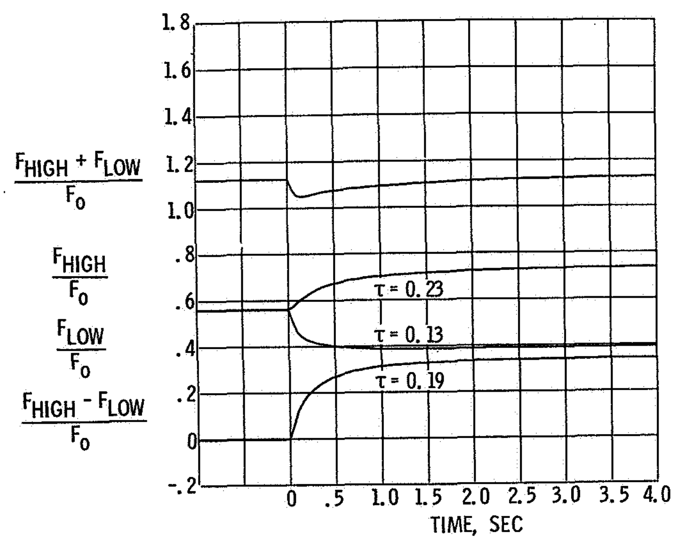

Figure 15. - Compressor bleed system attitude control response. Landing condition, 92 percent YJ97 speed. Improved YJ97 control system.

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