N76-31135 PART 2

N76-31155

DESCRIPTION AND TEST RESULTS OF A DIGITAL SUPERSONIC PROPULSION SYSTEM INTEGRATED CONTROL

Peter G. Batterton, Dale J. Arpasi, and Robert J. Baumbick
NASA Lewis Research Center

SUMMARY

A digitally implemented integrated inlet/engine control system was developed and tested on a mixed-compression, Mach 2.5, supersonic inlet and augmented turbofan engine. The control matched engine airflow to available inlet airflow so that in steady state, the shock would be at the desired location and the overboard bypass doors would be closed. During engine induced transients, such as augmentor lights and cutoffs, the inlet operating point was momentarily changed to a more supercritical point to minimize unstarts. The digital control also provided automatic inlet restart.

INTRODUCTION

Advanced propulsion systems such as those found in the B-1, F-14, and F-15 are quite complex. As future supersonic transport aircraft are designed, the propulsion systems of those aircraft will require control systems even more complex than those found in current aircraft. Some aspects of these supersonic propulsion system control problems are discussed in references 1 to 4. This increase in complexity has led to an upsurge in interest in digital controls for advanced propulsion systems because of the inherent flexability of the digital computer.

There has been little actual experience with the combination of a turbofan engine and mixed-compression supersonic inlet. This is the first experimental test in the United States to study the interactions of such a system, and to determine its controlability. Several difficulties can arise from the use of such combinations in the area of overall reliability and efficiency, and in providing sufficient stable operating range for the inlet while minimizing the probability of engine stall.

There are several inter-related control problems for this engine and inlet. Any changes in augmentor operation will result in temporary changes in fan airflow. An example of an airflow disturbance for an augmentor light-off is shown in figure 1. This is a result of the fact that, at the high Mach numbers, the fan operating point is generally at a low corrected speed on the fan operating map. Relatively large airflow changes can therefore result from small changes in fan pressure ratio. These airflow changes can cause inlet unstarts if of sufficient magnitude and if the rate of change is outside the control bandwidth of the inlet terminal shock control system. An inlet unstart that was caused by an augmentor light-off transient is shown in figure 2. The unstart causes a rapid dropoff in the fan inlet pressure with a corresponding drop in propulsion system thrust. This occurs while the terminal shock is being expelled from the inlet. The engine compressor is also stalled by this pressure disturbance. Also shown in figure 2 is the indicated turbine inlet temperature. This temperature shows approximately 15 percent increase over the initial value with the inlet unstart and engine stall. This could possibly overtemperature the engine in actual flight, but that did not occur during testing because of low engine inlet temperatures. During the restart of the inlet, high distortion is generated. This may cause a second engine stall and this is shown in the figure. The unstart problem would be less apt to occur if the inlet terminal shock could be positioned further downstream in the inlet throat providing greater margin against an unstart. But this results in poor inlet pressure recovery (poor efficiency) and greater distortion at the engine.

This project was undertaken to determine the nature of a control system such that the aforementioned problems could be avoided or at least minimized and at the same time minimize overboard spillage of inlet capture air. The approach taken was to tie together the inlet, engine, and augmentor control systems in an appropriate manner so as to: first, in steady state, monitor inlet shock position and overboard bypass door command and adjust engine airflow to match available inlet airflow; second, for augmentor induced transients, provide information to the inlet and engine control systems which can be used to prevent inlet unstart and/or engine stall; and third, provide automatic restart should the inlet unstart. Since there was considerable logic involved in this type of control system and since much experience has already been gained in the use of digital computer control of supersonic inlets (ref. 5) and of an augmented engine (ref. 6), it was decided that this control would be implemented on a digital computer. This is the first attempt at simultaneously controlling both a supersonic inlet and engine with the same digital computer. It was also felt that this choice would provide support material for the Air Force-NASA cooperative digital integrated control flight program (ref. 7) now under contract.

SYMBOLS

N_H high rotor speed, rpm

N_L low rotor speed, rpm

P total pressure, N/cm^2

p static pressure, N/cm^2

T total temperature, ^oC

W_f fuel flow, kg/sec

θ (T + 273.15)/288.15

Subscripts

eng main engine

zone1 zone 1

zone2 zone 2

0.5 inlet cowl lip station

1 inlet geometric throat station

1.1 inlet throat exit station

2 engine fan inlet station

2.2 engine low-pressure compressor discharge station

3 engine high-pressure compressor discharge station

4 engine high-pressure turbine inlet station

5 engine low-pressure turbine discharge station

APPARATUS AND PROCEDURE

Testing of the digital integrated control was conducted in the Lewis 10- by 10-Foot Supersonic Wind Tunnel. The propulsion system was composed of a mixed-compression inlet coupled to a dual rotor turbofan engine. Figure 3 shows the system installed in 10- by 10-Foot Supersonic Wind Tunnel. Table I lists the average tunnel free stream conditions. A brief description of the inlet, engine, and computer are provided in the following sections. Complete descriptions of the inlet, engine, and computer are provided in reference 8.

Inlet

The Lewis designed inlet is an axisymmetric, mixed-compression inlet with translating centerbody and 45 percent internal supersonic area contraction. The inlet is designed for Mach 2.5 operation with a TF30 engine. The inlet has a capture area of 0.707 square meters and measures 180 centimeters from the cowl lip to the fan face. The inlet is equipped with eight slotted plate bypass doors which are used to position the inlet terminal shock.

Engine

The engine used in this investigation is a Pratt and Whitney TF30-P-3. The TF30-P-3 is an axial, mixed-flow, augmented, twin spool, low bypass ratio turbofan engine with a variable area convergent primary nozzle. The engine includes a three-stage axial-flow fan mounted on the same shaft with a six-stage axial-flow low-pressure compressor. This unit is driven by a three-stage low-pressure turbine. A seven-stage axial-flow compressor driven by a single-stage, air-cooled turbine makes up the high-pressure spool. The compressor is equipped with 7th stage (low-pressure compressor) and 12th stage (high-pressure compressor) bleeds. The 7th stage bleed is operated by aircraft systems and the 12th stage is normally operated automatically by the engine control system. The 12th stage bleed was set closed for this test.

The augmentor consists of a diffuser section, five concentric ring fuel manifolds (zones), three V-gutter ring flame holders, a combustion chamber liner, and a fully modulating flap-type convergent primary nozzle. Variable thrust augmentation is accomplished by adjusting fuel through the fuel manifolds. Augmentor ignition is by means of two "slugs" of fuel injected into the engine gas stream, one upstream of each turbine. This "hot streak" continues aft and ignites the augmentor fuel. The augmentor zones are turned on sequentially, each reaching a predetermined level before proceeding to the next. Note that only the first two zones of the augmentor were actually used for this test program.

The standard TF30-P-3 fuel control systems consist of a hydromechanical main fuel control (MFC) and a hydromechanical combined augmentor and exhaust nozzle control (A/B-ENC). A single power level commands the MFC and A/B-ENC. However, to provide access to the augmentor at the nonstandard wind tunnel conditions, the A/B-ENC was completely removed from the engine and replaced with servocontrolled throttles for fuel flow control, a position servo for the exhaust nozzle, and solenoid valves for generation of the logic signals used by the augmentor ignitor.

Integral with the MFC is a so-called "Weapons Derichment Port" to which for some engine installations an electrically operated valve is connected to allow derichment of fuel during the firing of aircraft weapons. A servocontrolled throttling valve was attached to this port to allow the bypassing of fuel. By setting the power lever angle (PLA) to a high enough value, the MFC computer would provide acceleration fuel flow. The excess fuel could then be bypassed and engine speed regulation obtained externally of the MFC. The hydromechanical control could then be used for startup as well as emergency procedures during the tunnel operation.

Instrumentation

Sixteen steady-state transducers were used to measure the inlet terminal shock position. These transducers start at a distance of 23 centimeters from the cowl lip and extend to a point 66 centimeters from the cowl lip. The last two transducers were located 5.08 centimeters apart while the others were located 2.54 centimeters apart. The dynamic pressures were measured with strain-gage-type transducers connected to the cowl with short tubes. The frequency response of this pressure measuring system had negligible dynamics in the range covered in these tests (0.1 to 100.0 Hz).

There are four dynamic transducers located 66 centimeters from the cowl lip and positioned 90° apart circumferentially around the cowl. These static pressure signals were electrically averaged and identified as $p_{1.1}$. In addition to these transducers, dynamic transducers were included to measure total and static pressure at the geometric throat (P_1 and p_1, respectively), and static pressure near the cowl lip $p_{0.5}$.

All engine pressures used engine supplied probes; that is, the p_3 signal comes from the pressure signal tube going to the MFC. All pressure signals were sensed by strain-gage-type pressure transducers. The fan inlet temperature T_2 was sensed by a thermocouple, but the high-pressure turbine inlet temperature T_4 is the Pratt and Whitney supplied signal which is based on the temperature rise across the compressors and the low-pressure turbine discharge temperature. The low-pressure rotor speed was sensed by a magnetic pickup and gear located in the "bullet nose". The high-pressure rotor speed was sensed by a magnetic pickup and gear located on the gear box. All fuel flows were measured by turbine flowmeters. The two speeds and the fuel flows were converted to high level analog signals for use by the digital integrated control and recording equipment. The nozzle exit area and the compressor bleed positions were obtained from potentiometers.

Digital Computer

The digital integrated control was implemented on a digital computer, located at the analog computer facility in a building approximately 500 meters from the test facility. It was connected to the test facility via land lines with ground isolation amplifiers at the receiving end of each line. A small desk-top-size 10-volt general purpose analog computer was also used for signal conditioning and biasing of both sensed model parameters and returned control commands. The analog computer was located at the test facility. The digital system consists of four major units.

(1) A digital computer with 16 384 words of memory, a read-restore memory cycle of 750 nanoseconds, and a word length of 16 bits.

(2) A digital interface capable of converting both analog and frequency signals to computer compatible digital words and converting computer generated words to analog and logical outputs.

(3) A signal processing unit which provides signal conditioning and monitoring capability between the digital interface and the propulsion system to be controlled.

(4) Programming peripherals consisting of a high-speed paper-tape reader and punch, and a teletype.

The capabilities of the system are given in table II and a comprehensive description is available in reference 9.

Procedure

The inlet, engine, and control system were tested at zero angle-of-attack. No angle-of-attack data were obtained. At angle-of-attack the inlet control requires more shock position instrumentation than was provided in this inlet. The mass flow delivered to the engine was varied by adjusting the amount of airflow bypassed by the disturbance doors of the inlet. This would allow the observance of the behavior of the system to steady-state, step, and sinusoidal disturbances in airflow. The inlet was unstarted by momentarily reducing the inlet throat bleed until the throat Mach number dropped low enough for the inlet to unstart. Behavior of the control to unstarts could then be determined. For testing of the augmentor control, the primary method of disturbing the control was the PLA. Step changes in the PLA were used. To get in condition for these tests, the engine would be started with the hydromechanical MFC while the inlet was controlled using an electronic analog control.

CONTROL DESCRIPTION

The goals of the integrated control are summarized as follows. By matching engine airflow to available inlet airflow, inlet pressure recovery is maximized and spillage airflow is minimized, and both these effects usually maximize inlet performance. This is the primary goal of the digital integrated control and is our definition of an airflow match between the engine and inlet. The TF30-P-3 is a turbofan engine, and the bypass ratio of the fan varies, depending on conditions, from about one to two. Augmentor transients such as zone lights and cutoffs disturb the fan airflow directly and these disturbances propagate up into the inlet relatively unimpeded when compared to turbojets. Therefore, the second goal of the control is to provide a more stable operating point while attempting augmentor transients. The last goal for the control is to provide automatic inlet restart should an unstart occur.

A description of the basic inlet and engine control systems is provided in the next section followed by a brief description of the integration of these controls to achieve the aforementioned goals. A more detailed description of the integrated control is provided in reference 8.

Basic Control Functions

There are three basic control functions for this mixed-compression inlet and augmented turbofan propulsion system. These are: (1) inlet terminal shock and restart control, (2) engine rotor speed regulation and fuel flow limiting control, and (3) augmentor and exhaust nozzle control. A brief explanation of each of these control functions follows.

The basic control problem of a mixed-compression supersonic inlet is that of maintaining the terminal shock in the throat to maximize inlet pressure recovery but not allowing the inlet to unstart (allowing the terminal shock to be expelled from the inlet). The usual method of control is to manipulate overboard bypass doors to bypass inlet airflow which in turn positions the terminal shock. By increasing bypass airflow, the shock is pulled downstream in the inlet throat and the reverse occurs if bypass airflow is decreased. Thus a control which senses shock position is used to drive the overboard bypass doors.

The second part of the inlet control is that of starting the inlet. Starting is defined as causing the externally located terminal shock to enter the throat region of the inlet. (The inlet is unstarted when the terminal shock is located forward of the cowl lip.) Starting is accomplished by increasing the ratio of throat area to capture area until the throat goes supersonic, and extending the spike increases ratio of the throat area to capture area for this inlet. Once started, the spike returns to its design position. The started (or unstarted) condition is detected by the presence of supersonic (or subsonic) airflow at the cowl lip.

For the TF30-P-3, speed regulation is obtained normally by using PLA to schedule a high rotor speed reference in the MFC. The speed reference and actual speed are used in a droop governor to provide a ratio of fuel flow to burner pressure which, when multiplied by burner pressure, determines fuel flow to the engine. Speed regulation is obtained in that manner. The MFC also limits maximum fuel flow during acceleration to avoid turbine inlet overtemperature and/or compressor stall, and limits minimum fuel flow during deceleration to avoid combustor blowout and/or compressor stall. The MFC also provides operating point information (high rotor corrected speed) to the augmentor/exhaust nozzle control, and a signal from the augmentor control indicating that an augmentor blowout has occurred. The augmentor blowout signal causes the MFC to switch from the speed governor to a special fuel flow schedule. This fuel flow schedule reduces fuel flow to the engine to avoid overspeeding the low rotor.

The augmentor control uses PLA to command a level of augmentor fuel flow and to determine which zones should be lit. The zone fuel flow schedules are also ratios of fuel flow to burner pressure schedules because burner pressure is used as a measure of engine core airflow. Thus changes in engine bypass ratio are taken into account to bias those augmentor zones which are in the fan duct airstream. The exhaust nozzle is positioned to drive the error in the MFC determined fan operating point to zero. The fan operating point schedule is a ratio of burner pressure to turbine discharge total pressure p_3/P_5 as a function of high rotor corrected speed. The rate of change in P_5 is used to indicate that the first zone of the augmentor is lit or that an augmentor blowout occurred.

Control Integration

The inlet and engine are defined as being matched when the shock is at the desired location and the bypass doors are closed. Therefore a signal can be generated which could tell the engine to increase speed (and thus airflow) if more airflow is available and conversely if less airflow is available. It is this type of scheme which was developed to satisfy the primary goal for the integrated control. The overall integration loops are shown in figure 4. The nonaugmented engine operation will be discussed first. The airflow match signal is defined as the bypass door command signal, or, if the bypass door command is zero, the shock position error signal. This signal is used to drive a proportional plus integral control which produces a shift in the high rotor speed demand to the engine speed governor. Note, PLA normally generates the base speed demand schedule.

During augmentation, the exhaust nozzle is also available to adjust engine airflow. Therefore, during augmented operation, the airflow match error signal biases the fan operating point schedule. This is done in such a manner as to cause the exhaust nozzle to open more than normal if the bypass doors are open or to close more than normal if shock is supercritical. This action was made proportional to allow the integrator in the speed demand shift logic to reset the airflow match signal to zero by adjusting engine speed. This allows the nozzle to return to its normal schedule, which is desirable since significant changes in the fan operating point can lead to engine stall.

The aforementioned scheme will operate successfully except during augmentor transients and inlet unstart-restart. Therefore, additional logic signals were used for these special cases.

Augmentor transient signals are generated by the augmentor/exhaust nozzle control to tell the engine and inlet controls that engine induced airflow transients can be expected. The signals are simply logic signals that indicate whether or not the augmentation level has reached that commanded by PLA. One augmentor transient signal sets the airflow match signal to zero which causes the speed demand control to hold its present value until the transient is over.

Since the response of the bypass door control may not be capable of handling the augmentor induced airflow transient, another augmentor transient signal is used by the inlet control to command the shock to a more supercritical location appropriate to the expected airflow transient. Because the speed demand is held constant, the engine speed will not change and the bypass doors will open to move the shock to the more supercritical location. Having both the shock positioned supercritically and the bypass doors partially open is desirable when large airflow transients are expected from the engine.

The augmentor blowout signal causes the MFC to switch from the speed governor to a special fuel flow schedule. Thus, during this time, the speed demand is placed in the hold mode.

The unstart-restart signal for the engine is the unstart-restart signal used by the inlet control except that, as far as the engine is concerned, the restart is not complete until the spike has returned to its design point. The unstart-restart signal causes the value of the shift in speed demand to be reset to zero. The augmentor/exhaust nozzle control uses the unstart portion of this signal to cause an automatic shutdown of the augmentor. This is based on the assumption that the engine will stall when the inlet unstarts and it is felt that the augmentor should be turned off with engine stalls.

The digital integrated control briefly described here and more completely in reference 8 used no additional sensed inlet or engine variables than would be used for the conventional controls.

RESULTS AND DISCUSSION

The control described in this report was tested with three inlet configurations. The results presented here are for the inlet configured with 10-hertz bandwidth inlet overboard bypass doors. By 10-hertz bandwidth, we mean that the position servo frequency response of the overboard bypass doors exhibited a first-order rolloff at approximately 10 hertz. Two other configurations were tested. These were one with 80-hertz bandwidth bypass doors and one with 10-hertz bandwidth bypass doors and with a controlled variable bleed at the inlet throat. The results of these latter two configurations may be found in reference 8. In discussing the results of the 10-hertz bandwidth bypass doors, the major differences in the results of the other configurations will be mentioned.

The digital control sampled the inlet variables and calculated the inlet control output commands once every 5 milleseconds. The engine variables were sampled and the engine control output commands calculated once every 50 milleseconds. These sample times are representative of the differences in the dynamics of the inlet and engine. Details of how the computer functioned with the different time steps and shared the same multiplexer are described in reference 8.

Inlet terminal shock position could not be dynamically measured directly in the inlet. Therefore, a throat exit static pressure signal was obtained which could be used as a dynamic measure of shock position for feedback to the control. The relation of this pressure $p_{1.1}$ to shock position is shown in figure 5.

Figure 6 shows the action of the control to a square-wave-type disturbance of inlet airflow. The magnitude of this disturbance was 0.85 percent peak-to-peak of the engine total corrected airflow of 68 kilograms per second. At the step closing of the disturbance bypass doors, the control bypass doors step open to correct for the error in shock position $p_{1.1}$. Closing the disturbance bypass doors increases the airflow available to the engine. The engine speeds then increase to allow the control bypass doors to close. With the control gains that were used, this process was underdamped and the speeds would overshoot momentarily pulling the shock to a slightly supercritical position. When the disturbance bypass doors open, the available airflow to the engine is reduced. Thus at the step opening of the disturbance bypass doors, the shock was pulled to a slightly supercritical position. Engine speeds then reduce allowing the shock to return to the desired position. The system is still underdamped, but less than for the step closing of the disturbance bypass door transient. The control thus was able to match engine airflow to available inlet airflow and achieve the result of no overboard bypass airflow in steady state while maintaining the shock at the desired position. This was the first goal of the integrated control.

The second goal of the control was to minimize inlet unstarts during augmentor transients. Figure 7 is an augmentor transient from light-off to maximum zone 2. As the PLA is advanced into augmention, the control commands the shock to a more supercritical position (lower $p_{1.1}$) in anticipation of the augmentor light-off disturbance. In this case, $p_{1.1}$ was reduced from 5.50 to 4.97 newtons per square centimeter. This positions the shock 17.5 centimeters downstream of the throat instead of the 3 centimeters during normal operation. The control bypass doors open to achieve this result. The engine speeds were not allowed to reset the control bypass doors during the augmentor transient. Total fuel flow shows the increase in fuel flow as the first augmentor zone starts flowing. The augmentor does not light-off right away since the fuel is filling the manifolds. The large jump in the turbine discharge pressure P_5 indicates that the augmentor has lit-off and the exhaust nozzle is released. The exhaust nozzle slews open to reduce the error in the ratio of p_3 to P_5 and thus maintains the engine at the desired operating condition. As the error in p_3/P_5 is reduced, the augmentor fuel flow is allowed to increase to maximum zone 1. The second step on the total fuel flow trace is the fuel flow for the second zone turning on. After a manifold fill delay, the second zone is allowed to increase to its maximum. After the augmentor has reached the desired level of operation, the shock command is returned to its nominal value and the bypass doors are closed again. Thus by pulling the shock back to a more supercritical position, the additional inlet stability margin could be obtained to avoid an inlet unstart due to an augmentor light-off transient.

Figure 8 is an augmentor transient where the augmentor is turned off from maximum zone 2. Again the shock is positioned to a more supercritical value during the transient. As PLA is reduced out of augmentation, the control reduces the fuel flow first in zone 2 then zone 1. The exhaust nozzle area decreases to maintain the desired ratio of p_3 to P_5. At the minimum fuel flow for zone 1, the fuel flow is cut off abruptly. This is shown in the figure as the drop off of fuel flow. The exhaust nozzle then returns to its nominal area. However, the shock is pulled to a more supercritical position while the nozzle is closing. Once the nozzle has returned, the shock is returned to its nominal position and the control returns the control bypass doors to their closed position. Again the control achieves the desired results of no unstarts during augmentor transients and in steady state the engine airflow is matched to the available inlet airflow.

As mentioned earlier, the control was also tested with 80-hertz bandwidth bypass doors and with 10-hertz bypass doors with a throat bleed control. The response of the 80-hertz bandwidth bypass door control to the square-wave disturbance was essentially the same. However, because of the greater response capability of the door servos, the inlet terminal shock control was better able to handle the augmentor transient airflow disturbances. The net result was that it was not necessary to position the shock to such a supercritical value. For the 80-hertz bandwidth bypass door control, the value of the $p_{1.1}$ command was reduced to only 5.40 newtons per square centimeter instead of 4.97. This positioned the shock 6.5 centimeters downstream of the inlet throat instead of 17.5 centimeters as was required for the 10-hertz bandwidth bypass door case.

The throat bleed for this inlet consisted of a slot just upstream of the geometric throat. This slot dumped into a volume which was bled overboard through four servo controlled butterfly valves. This bleed was used as a "shock trap" by monitoring the inlet throat Mach number and opening the valves if the throat Mach number dropped too low. By including this control with the 10-hertz bandwidth bypass door control, it was also possible to reduce the supercritical value of shock position during the augmentor transient. The value of $p_{1.1}$ command of this control was reduced to only 5.35 newtons per square centimeter. This positioned the shock 8.5 centimeters downstream of the throat. During normal operation, the shock is positioned 3 centimeters downstream of the throat.

The last goal of the integrated control was to provide automatic inlet restart should an inlet unstart occur. Figure 9 shows an inlet unstart with the engine at the maximum zone 2 condition. Immediately following the unstart the augmentor control portion of the integrated control starts to close the exhaust nozzle and to shut off the augmentor fuel flows. The inlet control portion of the integrated control starts extending the spike to increase the ratio of throat area to capture area until the throat goes supersonic again and the inlet restarts. The $p_{1.1}$ command is adjusted to maintain a choked condition in the inlet throat to avoid inlet buzz. Just before the inlet is restarted the $p_{1.1}$ command is reduced considerably. The reason for this is that this inlet generates considerable distortion under restart conditions and this was an attempt to avoid a second engine stall. A second engine stall occurs anyway just after the inlet restarts. This causes a second unstart, but the inlet again restarts without further engine stalls. This characteristic of the second engine stall during restart when unstart occurred during augmented engine operation is not understood at this time. The augmentor is shut down during the inlet restart sequence and does not relight without removing the PLA from augmentation and then returning it to augmentation. The control, however, does bring the inlet and engine back to the match condition after the spike has been returned to its design position.

SUMMARY OF RESULTS

The general problems associated with the mixed-compression inlet and augmented turbofan engine should be similar to those experienced with this particular combination. The results of this test program indicate that the problems of control of an augmented turbofan engine and mixed-compression inlet can be minimized by integrating the engine and inlet control systems. This integration required no additional instrumentation than that normally required for this combination of engine and inlet.

The digital integrated control demonstrated an on-line digital control that provided integration of both augmented turbofan engine and mixed-compression supersonic inlet control systems. The control matched engine mass flow to available inlet mass flow. By monitoring inlet terminal shock position and overboard bypass door command, the control adjusted engine speed so that in steady state, the shock would be at the desired location and the overboard bypass doors would be closed. The control thus obtained maximum mass flow recovery as well as maximum pressure recovery consistent with inlet stability. During engine induced transients, such as augmentor lights and cutoff, the inlet operating point was changed to a more supercritical point and thus minimized unstarts. The digital control also provided automatic restart of the inlet should an unstart occur, and provided automatic augmentor operation.

For the system tested here, an improvement in response and damping could be expected with further effort and could also lead to additional sensed parameters. Also, some of the areas not investigated for this control system were the effects of including a turbine inlet temperature limit, and of a mechanical limit on either rotor of the engine. However, these areas are details that could be included in the next effort on applying digital integrated control to the mixed-compression inlet and augmented turbofan engine. In addition, the control tested in this study matched engine airflow to available inlet airflow while maximizing inlet recovery. Other approaches to the integration might be to maximize thrust specific fuel consumption or overall thrust subject to the appropriate restrictions. It is possible that these approaches would result in a different match between the inlet and engine than in the control described in this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 3, 1974

REFERENCES

1. Flanders, Theodore A.: The Inlet/Engine Control Vector. Paper 70-696, AIAA, June 1970.

2. Bayati, J. E.; and Tyson, R. M.: Propulsion Flow Transient Accommodation Control. Paper 70-694, AIAA, June 1970.

3. Cole, Gary L.; Neiner, George H.; and Wallhagen, Robert E.: Coupled Supersonic Inlet-Engine Control Using Overboard Bypass Doors and Engine Speed to Control Normal Shock Position. NASA TN D-6019, 1970.

4. Paulovich, Francis J.; Neiner George H.; and Hagedorn, Ralph E.: A Supersonic Inlet-Engine Control Using Engine Speed as a Primary Variable for Controlling Normal Shock Position. NASA TN D-6021, 1971.

5. Neiner, George H.; Cole, Gary L.; and Arpasi, Dale J.: Digital-Computer Normal-Shock-Position and Restart Control of a Mach 2.5 Axisymmetric Mixed-Compression Inlet. NASA TN D-6880, 1972.

6. Arpasi, Dale J.; Cwynar, David S.; and Wallhagen, Robert E.: Sea-Level Evaluation of Digitally Implemented Turbojet Engine Control Functions. NASA TN D-6936, 1972.

7. Bentz, Charles E.; and Zeller, John R.: Integrated Propulsion Control System Program. Paper 730359, SAE, Apr. 1973.

8. Batterton, Peter G.; Arpasi, Dale J.; and Baumbick, Robert J.: Digital Integrated Control of a Mach 2.5 Mixed-Compression Supersonic Inlet and Augmented Mixed-Flow Turbofan Engine. NASA TM X-3075, 1974.

9. Arpasi, Dale J.; Zeller, John R.; and Batterton, Peter G.: A General Purpose Digital System for On-Line Control of Airbreathing Propulsion Systems. NASA TM X-2168, 1971.

TABLE I. - TEST CONDITIONS

Mach number	2.5
Free stream total pressure, N/cm^2	9.3
Free stream total temperature, K[a]	297
Specific heat ratio	1.4
Reynold's number index[b]	.86
Engine total corrected airflow, kg/sec	70.8

[a]Standard day free stream total temperature at 20 000-meter altitude would be 488 K.

[b]Ratio of Reynold's number at station 2 to Reynold's number at sea-level static.

TABLE II. - DIGITAL CONTROL COMPUTER SYSTEM CAPABILITIES

Digital computer	
Magnetic core memory size, words	16 384
Word length, bits plus parity	16
Memory cycle time, nsec	750
Add time, μsec	1.5
Multiply time, μsec	4.5
Divide time, μsec	8.25
Load time, μsec	1.5
Indirect addressing	Infinite
Indexing	Total memory
Priority interrupts	28 Separate levels
Index registers	2
Interval timers	2
Analog acquisition unit	
Overall sample rate (maximum), kHz	20
Resolution of digital data, bits	12 (plus sign)
Output code	Two's complement
Number of channels	64
Input range, V full scale	±10
Conversion time, μsec	38
Total error with calibration, percent	0.073
Analog output unit	
Total number of digital-to-analog conversion channels (DAC)	26
Resolution (13 bit DAC; 10 channels), bits	12 (plus sign)
Accuracy (13 bit DAC), percent of full scale	±0.05
Resolution (12 bit DAC; 16 channels), bits	11 (plus sign)
Accuracy (12 bit DAC), percent of full scale	±0.1
Output voltage range, V full scale	±10
Slew rate, V/μsec	1
Priority interrupt processor	
Number of channels	10
Input voltage range, V	±10
Computer switching	Trigger on rise or fall
Comparator hysteresis, mV	Adjustable from 35 to 650
Comparator output, V	7

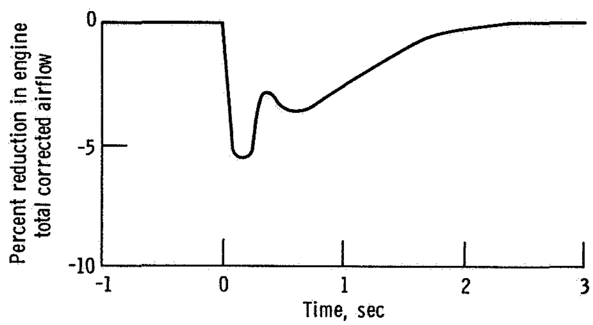

Figure 1. - Typical augmentor light-off airflow disturbance as seen at inlet.

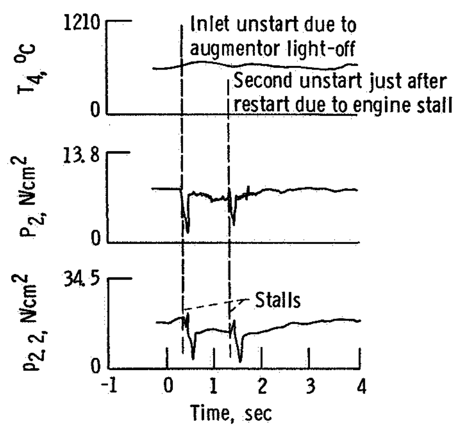

Figure 2. - Augmentor light-off induced inlet unstart and subsequent inlet restart and second engine stall.

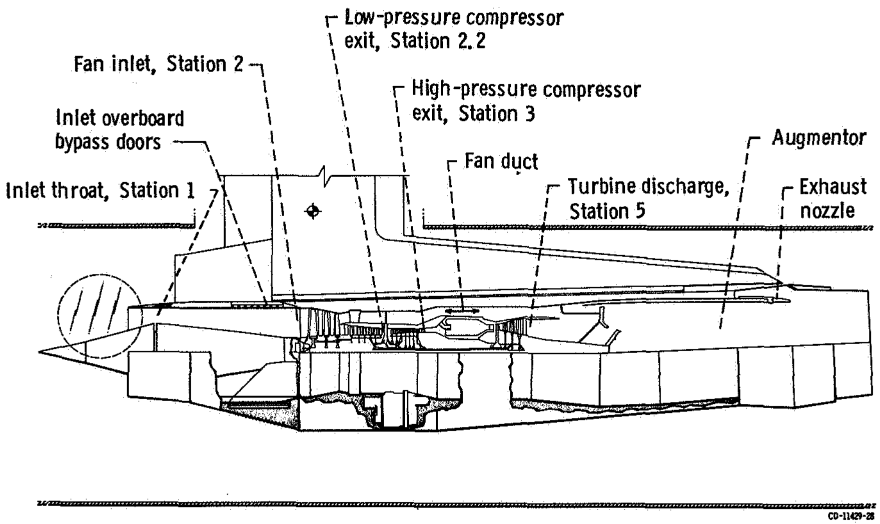

Figure 3. - Cross section of 55-45 axisymmetric mixed-compression inlet and TF30-P-3 turbofan engine.

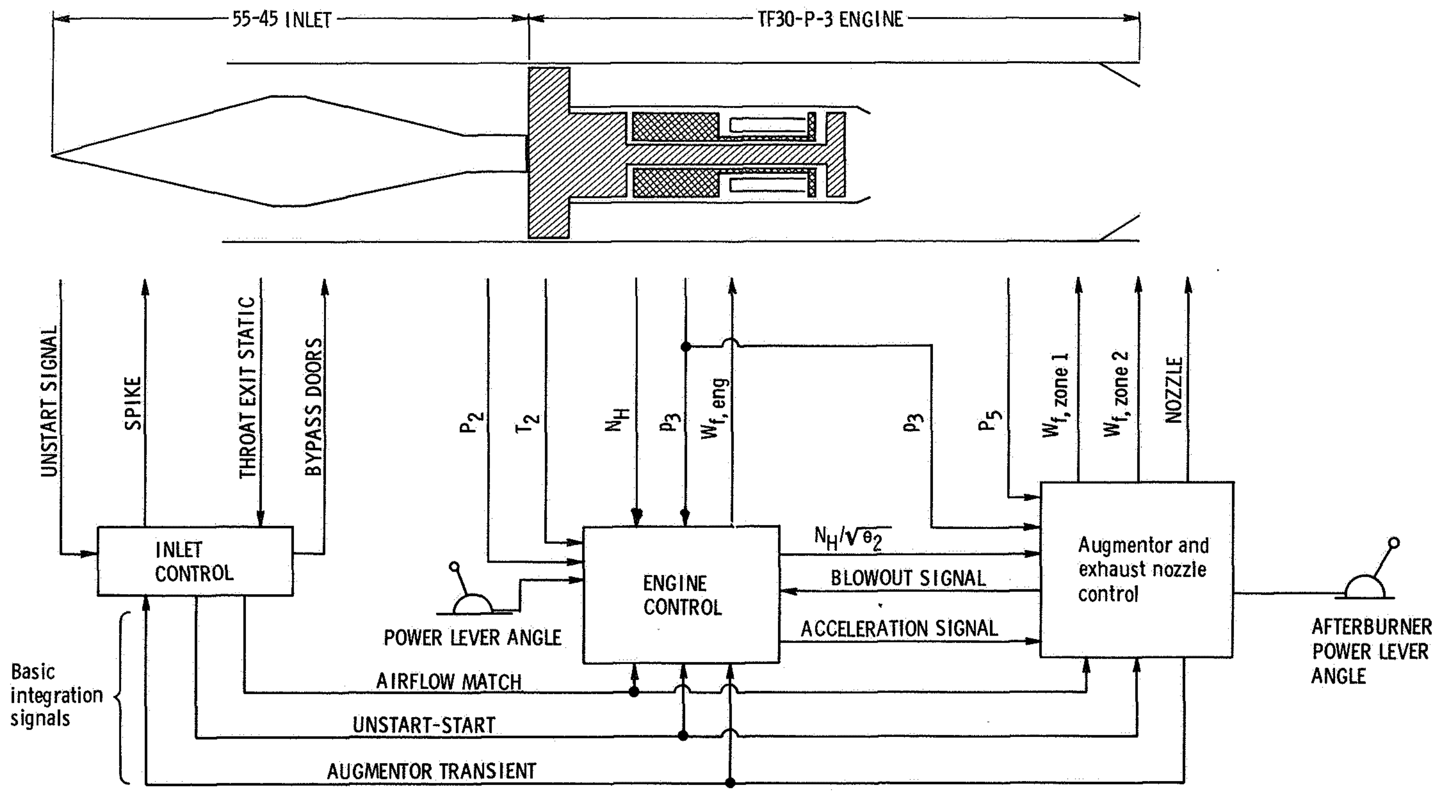

Figure 4. - Overview of digital integrated control.

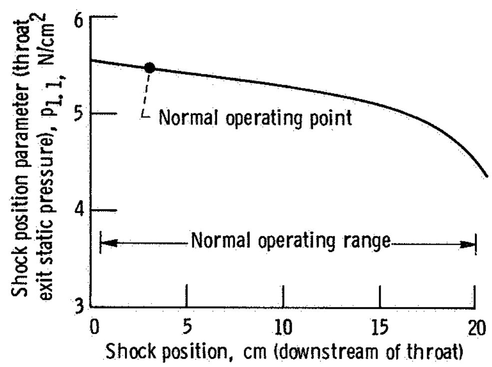

Figure 5. - Relation of throat exit static to shock position.

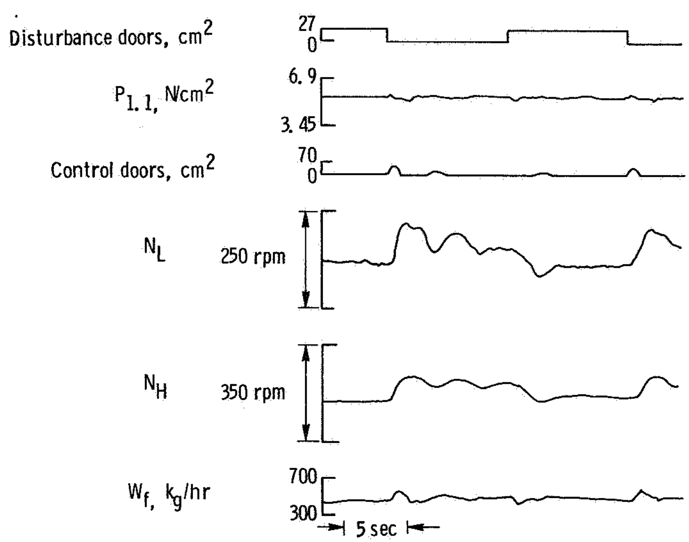

Figure 6. - Square wave airflow disturbance.

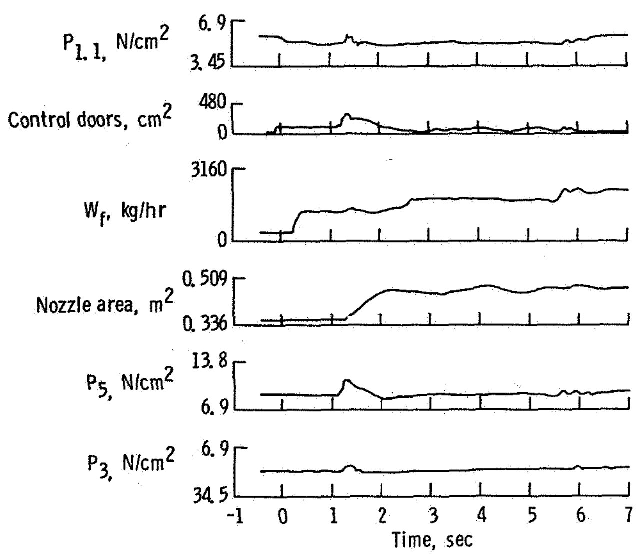

Figure 7. - Augmentor transient, light-off to maximum zone 2.

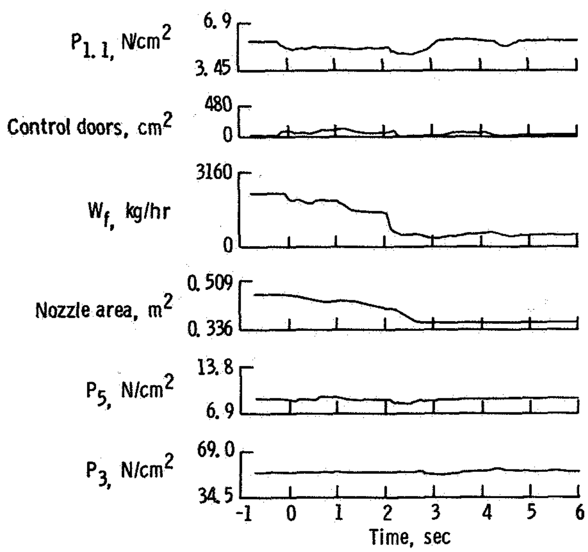

Figure 8. - Augmentor transient, turn-off from maximum zone 2.

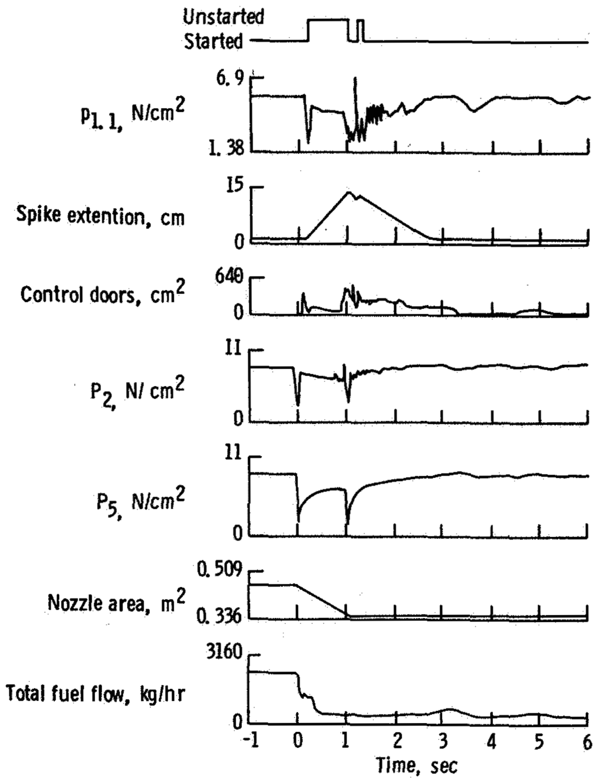

Figure 9. - Inlet unstart and automatic restart with unstart occurring at maximum zone 2 augmentation.