NASA TECHNICAL MEMORANDUM

NASA TM X-73647

NASA TM X-73647

(NASA-TM-X-73647) ATMOSPHERIC EFFECTS ON INLETS FOR SUPERSONIC CRUISE AIRCRAFT (NASA) 14 p HC A02/MF A01 CSCL 01A

N78-10026

Unclas

G3/02 52343

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TECHNICAL PAPER to be presented at the
Thirteenth Propulsion Conference
cosponsored by the American Institute of Aeronautics
and Astronautics and the Society of Automotive Engineers
Orlando, Florida, July 11-13, 1977

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Abstract

An analysis, that realistically simulates mixed-compression inlet dynamic behavior in the vicinity of unstart, was used to investigate time response of an inlet's normal shock to independent disturbances in ambient temperature and pressure and relative velocity (longitudinal gust), with and without inlet controls active. The results indicate that atmospheric disturbances may be more important than internal disturbances in setting inlet controls requirements. This is because they are usually not anticipated and because normal shock response to rapid atmospheric disturbances is not attenuated by the inlet, as it is for engine induced disturbances. However, before inlet control requirements can be fully assessed, more statistics on extreme atmospheric disturbances are needed.

Introduction

An efficient propulsion system will be a key factor in the development of an economically viable supersonic cruise aircraft. New engine concepts known as variable cycle engines are being defined by studies under contract to NASA.[1] A balanced program requires attention to the problems of inlets, especially since they are quite important for cruise Mach numbers in the range of 2.2 to 2.7. To minimize cowl drag and provide efficient propulsion system performance at those Mach numbers requires the use of a mixed-compression inlet (i.e., an inlet with internal supersonic area contraction). Unfortunately, when such an inlet operates at its peak performance it is also on the verge of an instability termed unstart. The unstart transient can be accompanied by many adverse effects on the inlet and engine, which can also seriously affect aircraft stability. Such an event would be unacceptable on a commercial transport. Therefore, the problem of maximizing inlet performance while minimizing or eliminating the unstart problem is of concern.

An inlet can encounter both internal (e.g., engine induced) or external (e.g., atmospheric induced) disturbances that can cause unstart. Engine transients, such as a throttle change or afterburner light are usually anticipated, and appropriate control action can be initiated to prevent a potential unstart. Also, such transients can be investigated in wind tunnel tests. Numerous experimental programs have been conducted at Lewis Research Center and elsewhere to investigate inlet response to internal disturbances and appropriate control actions. A recent wind-tunnel program at Lewis was conducted to investigate a mixed-compression inlet/turbofan engine combination.[2]

Atmospheric type disturbances are of greater concern because they are generally unexpected, giving less time for controls to respond. Very little information relating to atmospheric effects on mixed-compression inlets in flight has been acquired. And furthermore, simulation of atmospheric disturbances in a wind tunnel is difficult. One recent paper does cite flight experience of supersonic cruise aircraft indicating that severe atmospheric transients can have serious effects on the flight path and propulsion system.[3] Some inlet normal-shock responses to simulated gusts have been obtained in wind tunnels by oscillating wedges and flat plates upstream of the inlet.[4,5] An analytical procedure for predicting frequency of unstarts using a linear inlet model and a power spectral density representation of atmospheric perturbations is given by Barry.[6]

This paper is aimed at directing attention to time response effects of atmospheric-type disturbances on inlets and some implications regarding inlet controls. Results are presented from a study that used a linear dynamic analysis[7,8] modified for a significant nonlinearity to simulate a mixed-compression inlet. Transient disturbances in ambient temperature and pressure and wind gusts are considered independently at the inlet cruise Mach number of 2.5.

A brief description of the inlet simulation and a discussion of modifications and limitations for this study are followed by a description of the assumed inlet characteristics and operating conditions. Results are presented showing the maximum amplitude of a triangular-wave disturbance, that does not cause inlet unstart, as a function of disturbance pulse width. Unstarts initiated by normal shock excursions upstream of the inlet throat and by throat choking (reduction in throat Mach number) with and without inlet control, were investigated.

Inlet Analysis

Only a brief description of the analysis, selected for simulating the mixed-compression inlet, will be given because it is described in detail elsewhere.[7,8] Instead, the validity of the simulation and its limitations will be given greater attention.

The simulation is based on a linear (small perturbation) one-dimensional mathematical analysis. The analysis was initially derived for application to internal airflow perturbations[7] and later modified for application to flow-field perturbations upstream of the normal shock.[8] The analysis time dependent variables are total pressure, mass-flow rate, entropy and a moving normal shock that separates the supersonic and subsonic flow regions. The inlet geometric-flow-area variation is approximated by constant-area cylindrical sections which result in one-dimensional wave equations. Wave equations are used to represent both the subsonic and supersonic flow regions. Hence, discontinuities and losses in total pressure due to oblique shock waves in the supersonic portion are neglected.

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The analysis was previously verified for small perturbation results with the normal shock operating point at a supercritical position (away from unstart) where shock position is reasonably linear with perturbation amplitude. Frequency responses of the inlet normal shock and subsonic duct static pressures to internal airflow variations calculated with the analysis[7] have been shown to give good agreement with published[5] and unpublished experimental results. Good agreement was also demonstrated with a limited amount of experimental data for external airflow perturbations.[8] For frequency response data it was generally found that phase angle agreement was better than that for amplitude. Amplitude agreement was improved by factoring steady-state experimental data into the analysis.[7,8] This provides a means of compensating for boundary-layer effects not accounted for when the duct geometric-flow-area variation is used.

To further evaluate the merit of the linear analysis for external perturbations, it was compared[8] to frequency response results obtained from a one-dimensional method-of-characteristics solution.[6] Phase angle and amplitude agreement was perfect over the frequency range of 5 to 40 Hz for which method-of-characteristic data were calculated. Of course neither analysis includes viscous effects and the problem is not simply one-dimensional.

In order to provide a more realistic simulation of inlet operation in the vicinity of unstart, the basic analysis[7,8] was modified by adding a nonlinearity that is associated with the rate-of-change of duct flow area ($\Delta A/\Delta x$). This can be explained with the aid of Fig. 1. The linear analysis assumes that the normalized rate-of-change of duct flow area $(\Delta A/A)/(\Delta x/R_c)$ is constant and equal to the value at the shock operating point. Actually, the value of that parameter changes with shock position, primarily because of the change in $\Delta A/\Delta x$. As the shock moves forward $\Delta A/\Delta x$ varies from a positive value at the shock operating point to zero at the throat and then negative upstream of the throat where the shock is unstable, resulting in unstart. The variation of $(\Delta A/A)/(\Delta x/R_c)$ is significant because the shock position gain to any perturbation is inversely proportional to $(\Delta A/A)/(\Delta x/R_c)$. This nonlinear effect is included in the analysis for this study by making $(\Delta A/A)/(\Delta x/R_c)$ a continuous function of shock position measured from the throat station. This was easier to implement in the analysis and more accurate than using several $(\Delta A/A)/(\Delta x/R_c)$ segments each having a different but constant value.

The nonlinear version of the analysis is compared in Fig. 2 with data obtained during a wind tunnel program[9] that used an inlet from a YF-12 aircraft. The disturbance, composed of a single triangular wave pulse, caused a decrease in diffuser exit corrected airflow, simulating an engine-induced disturbance. The pulse amplitude was increased until the maximum value the inlet could tolerate without unstart was found. Analysis results were obtained from an analog computer version of the inlet simulation. The nonlinear analysis results were obtained in the same manner as the experimental results, where the simulated inlet steady-state corrected-airflow-margin from unstart was the same as for the experimental inlet. The nonlinear analysis predicts unstart by the onset of a rapid upstream excursion of the normal shock, sending the simulation into saturation. The linear analysis results are based on the assumption that the inlet unstarts when the normal shock reaches the throat. The maximum disturbance amplitude without unstart is plotted as a function of pulse zero-to-peak time in Fig. 2. As pulse width decreases, the nonlinear analysis, which shows better agreement with the data, predicts that the amplitude required to unstart the inlet is greater than for the linear analysis. One reason why the nonlinear analysis agrees better is because it predicts that the normal shock can move further upstream without unstart as pulse duration decreases. This phenomenon is exhibited in Fig. 3, which shows time histories of the disturbance and normal shock position for two pulse widths; the maximum amplitude case is shown for both transients. Note that for the longer duration pulse, the shock only reaches the throat, whereas for the shorter pulse it actually travels upstream of the throat. The conclusion that an inlet will unstart when the normal shock moves upstream of the throat is drawn from steady-state aerodynamics. The analysis shows that, under transient conditions, the shock can make a momentary excursion upstream of the throat without unstart. The occurrence of this phenomenon was observed from transient static-pressure measurements that were obtained during the wind tunnel program of Ref. 9.

Before investigating external disturbances, additional modifications were made to the analysis reported in Ref. 8. The modifications include terms to account for changes in supersonic spillage due to changes in free-stream Mach number and in centerbody position, as well as an effect of centerbody position on normal shock position.

There were no experimental data, comparable to those for internal disturbances, to verify the external analysis results. One source of error in the analysis is that interaction of the normal shock with the boundary layer is not modeled. Shock/boundary-layer interaction is important because it can affect conditions upstream of the shock. The interaction could induce unstart due to local choking upstream of the shock or by shifting the location of the aerodynamic throat, which is assumed fixed in the analysis. Another source of analysis error is a set of constant coefficients that affect the gain of normal shock position to a disturbance. The coefficients are functions of Mach number just upstream of the shock, and are based on the value at the shock operating point. However, the Mach number can change significantly due to ambient temperature and gust disturbances. Although absolute levels predicted by the analysis may not be exact, the transient-response trends are believed to be realistic.

The fact that the analysis is one-dimensional limits it to the investigation of longitudinal disturbances. Therefore, consideration of other effects which might contribute to unstart is eliminated, including (1) angle of attack changes due to gusts, (2) angle of attack changes and throat choking due to atmospheric induced flight path changes and structural motion of the centerbody relative to the cowl.

Inlet Characteristics and Operating Point Conditions

Supersonic cruise aircraft studies for NASA indicate a cruise Mach number in the range of 2.2

to 2.7. The inlet selected for this study was a mixed-compression-type with a design Mach number of 2.5. Aerodynamic and geometric characteristics of the inlet are shown in Fig. 4. The inlet is based on a NASA design,[10] but with a slightly shorter subsonic diffuser. Also, for this analysis, it was scaled up by a factor of about 3.3 to make it comparable to inlets being sized for current variable-cycle-engine designs. This resulted in a capture radius of 79 cm. The inlet has a translating centerbody to accommodate off-design operation and an overboard bypass system near the diffuser exit to allow matching of inlet airflow to engine airflow demand.

The inlet was assumed to have the following operating point conditions with the centerbody at the cruise position and the overboard bypass closed: Spillage at the cowl-lip, 0; throat boundary-layer bleed mass-flow ratio, 0.06; compressor-face total-pressure recovery, 0.92; engine corrected airflow, 184.4 kg/sec; and engine corrected airflow margin from unstart, 3.5 percent.

In all cases the simulated inlet was disturbed with single triangular wave pulses of varying time durations at inlet cruise conditions, which were Mach 2.5 at an altitude of 16,764 meters. The corresponding ambient conditions were 0.91 N/cm^2 and 216.7 K.

Model of Inlet and Control System

The inlet model was based on the idealized inlet schematic of Fig. 5. The disturbance was assumed to occur at centerbody tip conditions but delay times between the centerbody tip and cowl lip were neglected. Supersonic spillage at the cowl lip varies with the corresponding change in Mach number at the centerbody tip. The inlet duct was modeled by one supersonic and two subsonic sections. Transport delay times, used in the wave equations that govern those sections, were calculated by using the average Mach number in each section. Average Mach numbers were found from Fig. 4. A choked boundary-layer bleed region was assumed to occur across zero length upstream of the normal shock. The amount of bleed could vary with changes in upstream conditions. A term is included in the analysis[8] that allows bleed airflow to vary with shock position according to the equation

$$\left(\frac{\Delta W_{bl}}{W_c}\right) \Bigg/ \left(\frac{\Delta X_s}{R_c}\right) = -0.108 \qquad (1)$$

where a positive shock displacement occurs in the downstream direction. The value is based on experimental data.[10]

Using the diffuser area variation curve of Fig. 4, it was found that the normalized rate-of-change of duct flow-area $(\Delta A/A)/(\Delta x/R_c)$ in the vicinity of the throat varies linearly with distance. Therefore the analysis was modified to make $(\Delta A/A)/(\Delta x/R_c)$ vary directly with shock position measured from the throat, making the analysis nonlinear, rather than being constant as in the linear analysis. Finally, the overboard bypass was assumed to occur across zero length at the diffuser exit.

A schematic of the inlet control system is given in Fig. 6. The system, which manipulates the overboard bypass and the centerbody, is representative of a conventional control for mixed-compression type inlets.

The overboard bypass control is a closed-loop system, the purpose of which is to maintain the position of the normal shock at a high performance condition without allowing unstart. The control senses shock position by means of the duct pressure ratio PR, which is the ratio of an internal duct static pressure p_d to an external Pitot pressure P_t. The desired or commanded value PR_{com} is scheduled as a function of Mach number. Mach number is calculated from Pitot-static probe measurements near the cowl lip. When the shock moves, it causes an error $(PR_{com} - PR)$, which is sensed by the controller. The resulting control action is an increase or decrease in bypass flow until the error is driven to zero. An upstream movement of the normal shock causes the bypass to open, and vice versa.

The centerbody position control is an open-loop or scheduled system. It merely positions the centerbody as a function of Mach number. The centerbody is moved to keep the throat Mach number approximately constant by varying throat area and supersonic spillage. Throat area and supersonic spillage increase when the spike extends, due to a decrease in sensed Mach number, and vice versa.

The response of sensors and actuators selected for the control system was based on the assumption that, in the future, actuation hardware will limit control response to a much greater extent than the sensors. This is basically true because of the massive hardware that must be moved. Therefore, the responses of the Mach and duct pressure ratio sensors were assumed to be instantaneous relative to the actuators, which would be true of close-coupled transducers. Obviously, long line lengths between sensing ports and the transducers would introduce pneumatic lags. In addition, a mismatch of lag times could cause problems. For example, an erroneous indication of Mach number would result in a wrong reaction of the control system.

The frequency dependent portion of the transfer functions governing the response of the bypass and centerbody positions to position commands, as well as for the bypass controller, are given in Fig. 6. The centerbody is characterized by a second order lag, and the bypass by a first order lag. Bypasses with two different corner frequencies ω_{bp} were investigated. A proportional-plus-integral type controller was chosen to manipulate the bypass.

The functions enclosed by the dashed line in the schematic would be performed by a computer in a flight application. For this study, they were programmed on the analog computer along with the inlet analysis.

Results and Discussion

Unstarts initiated by excursions of the normal shock upstream of the throat and by throat choking were investigated analytically with and without inlet control. The normal-shock type unstarts will be discussed first.

Normal Shock Unstarts

With inlet controls inactive. A comparison of linear and nonlinear analysis results is shown in

Fig. 7 for independent disturbances in ambient temperature, relative velocity (longitudinal gust), ambient pressure, and engine corrected airflow. The disturbance pulses are also illustrated. Plus and minus signs on the ordinate indicate whether the disturbance variable increased or decreased from its operating point value. The choice of sign was dictated by the requirement for the normal shock to move upstream toward unstart. The inlet was assumed to be connected to an engine whose corrected airflow changes due to changes in air total temperature. The results show that in all cases the nonlinear analysis predicts greater tolerance to unstart than does the linear analysis as pulse duration decreases. Hence, a linear analysis would predict a greater frequency of inlet unstarts for a given atmospheric model, indicating a possible need to operate the inlet more supercritically (less efficiently) than necessary. Figure 7 also shows that inlet tolerance to unstart remains about the same or decreases with decreasing pulse duration for the external disturbances, whereas it increases for the engine disturbance. Thus, besides being unexpected, the external disturbances represent a potentially greater control problem because the inlet has less natural immunity to fast disturbances, which conventional controls are less apt to respond to. The ambient pressure disturbance results are interesting because it does not affect flight Mach number and has little or no effect on steady-state shock position. However, a rapid change in ambient pressure, that could be caused by a passing aircraft for example, does result in significant normal shock displacements (Fig. 7(c)). Of course, combinations of the external disturbances are likely to occur, which could act to reinforce or cancel each other. Finally, it was found that inlet tolerance to unstart was essentially proportional to engine corrected airflow margin from unstart for all pulse widths, although it is not shown in Fig. 7.

Study results were found to be significantly effected by engine corrected airflow sensitivity to total temperature. The inlet is most sensitive to changes in ambient temperature and gusts because they cause the greatest changes in total temperature. Therefore, results will be shown only for those two disturbances. However, all disturbances that induce a normal shock excursion cause some change in total temperature that is proportional to the change in shock velocity but this is generally less significant. Figure 8 shows a comparison of results obtained ignoring the change in engine corrected airflow with temperature ($K_T = 0$) to the results of Fig. 7 for which a representative value of $K_T = -1$ was used. When ambient temperature is the disturbance (Fig. 8(a)), the results are about the same for short duration pulses, but as pulse duration increases inlet tolerance is greater with the constant corrected airflow engine ($K_T = 0$). Results for the gust disturbance are shown in Fig. 8(b) and are about the same for the short duration pulses, as in the ambient temperature case. However, as pulse duration increases, the inlet with the constant corrected airflow engine becomes less tolerant to the disturbance, just the opposite of the temperature case. Obviously, the choice of K_T greatly affects the results and the relative importance of gust and ambient temperature disturbances. The steady-state value of K_T can range in value from -0.2 to -5.0 depending on the engine and its control and operating condition and it can also be a function of frequency.[6] The value of $K_T = -1$ was selected as a representative value and was made independent of frequency because no specific engine was selected for this study. Corrected airflow changes could also result from changes in inlet total pressure. However, it is felt that the temperature effect is more important and was therefore selected for illustration here. It is apparent that, given a specific engine, a correct representation of its airflow characteristics is important, especially for gust and ambient temperature disturbances.

Traces showing the transient response of normal shock position to triangular wave pulses in ambient temperature, relative velocity, and ambient pressure are shown in Fig. 9. The transients were obtained with the same nonlinear analysis as for the results of Fig. 7. The results show that the normal shock will initially travel upstream when ambient temperature increases and relative velocity and ambient pressure decrease. This was found to be generally true over the range of pulse widths tested. The shock is displaced upstream of the throat without unstart for rapid disturbances like these, as in the case of rapid engine disturbances. Note that the normal shock has a substantial overshoot in the downstream direction for both the relative velocity and ambient pressure disturbances. This was generally observed for pulse zero-to-peak times of 0.1 second or less and indicates that a disturbance of this wave shape but of the opposite sign could unstart the inlet, even though the shock would go downstream initially. The reason for the overshoot is that the gain of shock position to either the relative velocity disturbance for $K_T = -1$ (or the ambient pressure disturbance for any K_T), is nearly zero; therefore, after the disturbance stops decreasing, the shock tends to return rapidly to the operating point. The reversal of the disturbances causes shock position to overshoot in the opposite direction. The conclusion is that the disturbances that tend to cause unstart are increases in ambient temperature and decreases in relative velocity and ambient pressure. Figure 7 indicates that the rate of change of ambient pressure and relative velocity must be very rapid, although the relative velocity result depends on engine corrected airflow sensitivity to changes in air total temperature.

<u>With inlet controls active</u>. Results from the nonlinear analysis obtained with both the overboard bypass and centerbody control systems active, are presented in Fig. 10, along with the results without control from Fig. 7. Results were obtained for two different bypass corner frequencies ω_{bp}. Also shown are lines indicating the level of disturbance amplitudes that might be expected. In the temperature case (Fig. 10(a)) the expected disturbance level is based on flight data.[6] It represents the worst-case data and was extrapolated for zero-to-peak times less than 0.1 second. No probability of occurrence was associated with the data. Two points based on Concorde flight experience[3] are plotted as the solid symbols along with the calculated time between encounters. The data shows that with the controls active, the inlet should not unstart. However, the inlet does come close to unstart with the slow bypass control in the vicinity of $\Delta T = 0.1$ second. Unstarts would occur only when the inlet control is inactive for disturbance zero-to-peak times greater than 0.1 second.

Results for the longitudinal gust case are shown in Fig. 10(b). The disturbance amplitudes that might be expected are based on gust criteria used for the cancelled American SST, and were extrapolated for ΔT's below 0.03 second. A point based on unpublished YF-12 aircraft flight experience, obtained during the NASA flight research program, is plotted as the solid symbol. No probability of occurrence was associated with these data. The data show that no unstart is predicted to occur due to a gust. The faster bypass provides somewhat more tolerance than does the slow bypass or inlet without control. The latter two curves coincide.

Results for the ambient pressure case with inlet control using either bypass are not shown because they were the same as for the inlet without control (Fig. 7(c)). The disturbance criteria for the SST was for passing aircraft separated by 500 feet. The calculated maximum decrease in pressure that occurs is 14 percent in 0.013 second. The analysis predicts that such a disturbance would unstart the inlet.

It should be recalled that the absolute levels predicted by the analysis have not been verified by experiment. Data taken during the wind tunnel program of Ref. 9 indicated that the actual change in steady-state Mach number (that changed mass-flow rate but not total temperature and pressure) required to unstart that inlet was less than the value predicted by the analysis. One possible explanation is that the shock boundary-layer interaction caused the inlet to unstart earlier than the analysis predicts. The analysis was found to give much better agreement if constant coefficients, depending on the Mach number just upstream of the normal shock, were based on the average value rather than the initial value. When that technique was applied to the temperature case (Fig. 10(a)), no significant difference in the analysis steady-state value was found, indicating that the value shown should be nearly correct. However, there were no experimental steady-state data for unstarts due to temperature available to verify the analysis. The inlet with the slow bypass provides only marginal tolerance to unstart due to temperature in the vicinity of $\Delta T = 0.1$. The faster bypass system would appear to be adequate even if predicted analysis levels had to be shifted down by 10 to 20 percent, keeping in mind that the control system sensors were assumed to respond instantaneously. Ambient temperature disturbances appear to be more significant than longitudinal gusts; although that conclusion depends on engine airflow characteristics (e.g., the value of K_T). More data are needed to verify the levels predicted by the analysis and to increase knowledge of expected disturbance levels before the bypass requirements can be fully assessed. A gust probe has been installed on a NASA YF-12 aircraft in the hope of providing additional information in this area.[11] One inlet on the aircraft is highly instrumented so that inlet response can also be measured.

There are several alternatives to consider with respect to bypass requirements. It appears that bypass doors with a corner frequency on the order of 50 rad/sec would be required to provide high inlet performance. This could probably be achieved only by using several individual bypass valves with their own actuators, hydraulic lines, etc. Such a system would be necessarily complex, possibly with low reliability.

An alternate system that could provide the same inlet performance would be to augment a slow overboard bypass system with a throat-bypass stability system. A throat-bypass system could use relief-type mechanical valves or vortex valves to bleed airflow in the throat region when the normal shock moves upstream toward unstart. Such a system using mechanical valves was tested in a flight hardware inlet[9] and found to work very well for both internal and external disturbances. The valves are self-acting, which eliminates sensor lags, and are fast responding because they are small. The system bleeds little or no airflow when the shock is at the desired position and could be incorporated as part of the boundary-layer bleed system. Serious consideration should be given to incorporating a throat-bypass system during the initial design stages of an inlet.

Maximization of inlet performance accomplished by using special hardware may not be the best overall answer. Inlet tolerance to unstart can be increased by simply operating it more supercritically with corresponding lower performance. The alternatives must be examined by conducting mission, cost and reliability studies before the final choice can be made.

Throat Choking Unstarts

Unstarts initiated by throat choking were investigated by means of the linear analysis. The assumption was that unstart occurred when the throat Mach number decreased from the operating value of 1.24 to 1.0. Since normal-shock/boundary-layer interaction is not modeled, the shock was assumed to be too far supercritical to affect the results. Thus, only centerbody position, which affects throat Mach number, and its control are important. The results are shown in Fig. 11 with inlet controls active and inactive. Ambient temperature increases required to unstart the inlet, with or without control, are well above the expected disturbance levels that were shown in Fig. 10(a) and are more than twice the level predicted to initiate unstart due to a normal shock excursion. The same is true for the gust case (Fig. 11(b)) except for the uncontrolled inlet at ΔT's greater than 0.5 second. Results for ambient pressure disturbances are not shown because they do not affect throat Mach number significantly. A throat-bypass stability system can provide additional protection against external disturbances by relieving pressure rises in the throat region and giving the slower acting conventional control more time to respond.[9] In this application it also has the advantage that the stability system itself does not drive the normal shock upstream toward unstart, which can occur when the centerbody is extended.

The absolute levels predicted by the analysis are again in question. Some data were obtained for the experimental inlet[12] upon which the study inlet is based. Those data indicate that the inlet will actually unstart due to a 3.5 percent decrease in Mach number rather than the predicted decrease in velocity of 4.7 or increase in temperature of 9.1 percent. A possible reason for the difference is that boundary-layer separation occurs initiating unstart before the throat Mach number can decrease continuously to one. Even though the actual value causing unstart is less than that predicted, the throat-choking type unstart appears to be a less serious problem than that due to a normal shock

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excursion. This conclusion might not be the same if the shock operating point was more supercritical. Also, angle of attack effects and motions of the centerbody relative to the cowl induced by atmospheric disturbances may compound the throat choking problem. In actuality, the two types of unstart may be inseparable because of shock boundary layer interaction effects.

Conclusions

A primarily linear analysis was modified for a significant geometric nonlinearity to realistically simulate mixed-compression inlet dynamic behavior in the vicinity of unstart. The analysis was used to investigate inlet response to independent disturbances in ambient temperature and pressure and relative velocity (longitudinal gust), with and without inlet controls active.

The nonlinear analysis predicts greater inlet tolerance to fast pulse-type disturbances than does the linear analysis. The main reason is that the nonlinear analysis correctly allows the normal shock to make momentary excursions upstream of the throat in response to rapid disturbances; whereas the linear analysis results are based on the assumption that the inlet unstarts when the shock reaches the throat. Therefore the linear analysis would predict a greater frequency of unstart for a given atmospheric model, indicating a possible need to operate the inlet less efficiently than necessary.

Atmospheric-type disturbances represent a potentially greater inlet control problem than do engine disturbances. This is because they are usually not anticipated and because rapid disturbances are not attenuated in the inlet like engine disturbances. Ambient temperature disturbances were found to be potentially more hazardous than longitudinal gusts. However, inlet response to those disturbances is significantly affected by engine corrected airflow sensitivity to air total temperature, indicating that airflow characteristics for a specific engine should be properly accounted for. As engine airflow sensitivity to temperature increases, ambient temperature disturbances become more important relative to gusts. Ambient pressure disturbances are the least significant; although, a large rapid decrease could unstart an inlet. Of course combinations of disturbances are likely to occur, that could act to reinforce or cancel each other.

Longitudinal gusts are more likely to initiate unstart by throat choking. However, disturbance amplitudes required to cause throat choking were found to be greater than those required to initiate unstart by a normal shock excursion, indicating that the latter type unstarts are a more serious problem. This conclusion could change if shock/boundary-layer interaction effects were included in the analysis or if the normal shock operating point had been more supercritical.

It appears that an overboard bypass system with a corner frequency on the order of 50 rad/sec or a slow bypass system (12 rad/sec) augmented by a throat-bypass stability system will be required to provide high inlet performance with low unstart probability. Before inlet controls requirements can be fully assessed, more statistics on extreme atmospheric disturbances are needed, as well as some verification of absolute levels predicted by the analysis.

Symbol List

A	inlet duct flow area, cm^2
A_c	inlet capture area, cm^2
K_T	ratio of percent change in engine corrected airflow to percent change in air total temperature, $(\Delta W_{ec}/\overline{W}_{ec})/(\Delta T_t/\overline{T}_t)$
M	Mach number
P	total pressure, N/cm^2
PR	control pressure ratio (Fig. 6)
p	static pressure, N/cm^2
R_c	radius of inlet capture area, 79.2 cm
r	local centerbody or cowl radius, cm
s	Laplace variable, sec^{-1}
ΔT	zero-to-peak time of triangular wave pulse, sec
T_a	ambient temperature, K
T_t	air total temperature, K
u	longitudinal velocity of inlet relative to air at centerbody tip, m/sec
W	actual airflow, kg/sec
W_{bl}	boundary-layer bleed airflow, kg/sec
W_c	inlet capture airflow, kg/sec
W_{ec}	engine corrected airflow, $(W\sqrt{\theta}/\delta)_{eng}$, kg/sec
X_s	normal shock displacement from throat (positive in downstream direction), cm
x	inlet longitudinal coordinate, cm
Δ	perturbation quantity
δ	ratio of local total pressure to standard sea level pressure
θ	ratio of local total temperature to standard sea level temperature
ω_{bp}	overboard bypass corner frequency, rad/sec

Subscripts:

a	ambient
av	average
com	command value
d	inlet duct static
eng	engine
s	Pitot-static probe static
t	Pitot-static probe total

x local longitudinal value

0 centerbody-tip conditions

Superscript:

($\bar{\ }$) indicates operating point value of ( )

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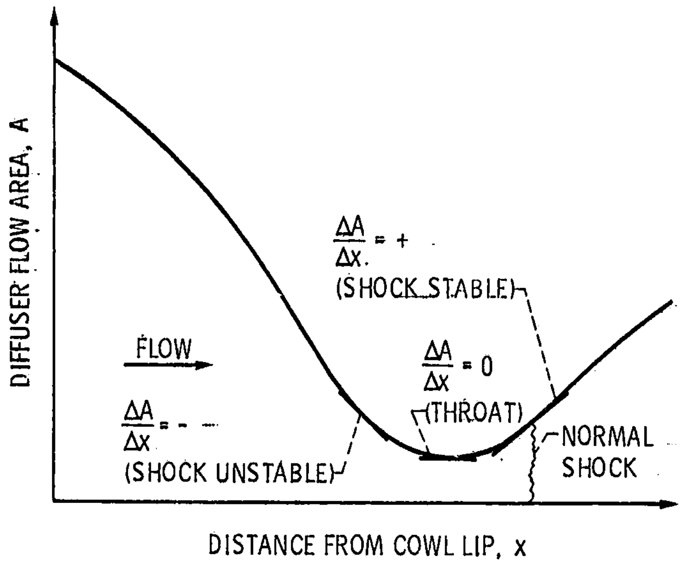

Figure 1. - Typical mixed-compression inlet diffuser flow-area variation.

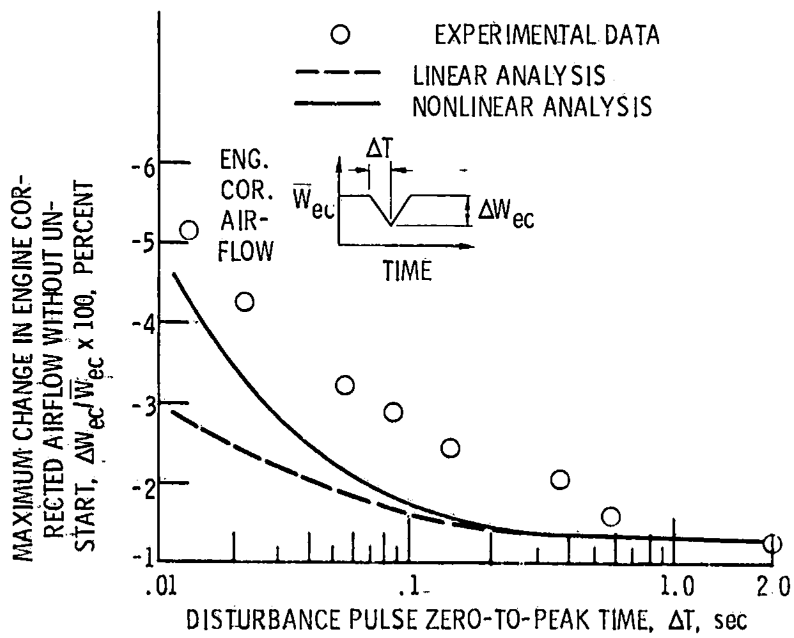

Figure 2. - Comparison of experimental and analysis results of YF-12 inlet response to engine corrected airflow disturbance.

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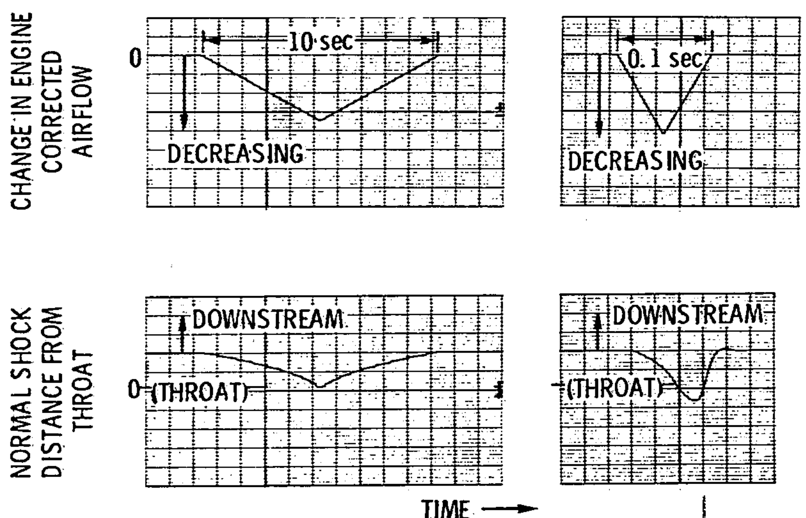
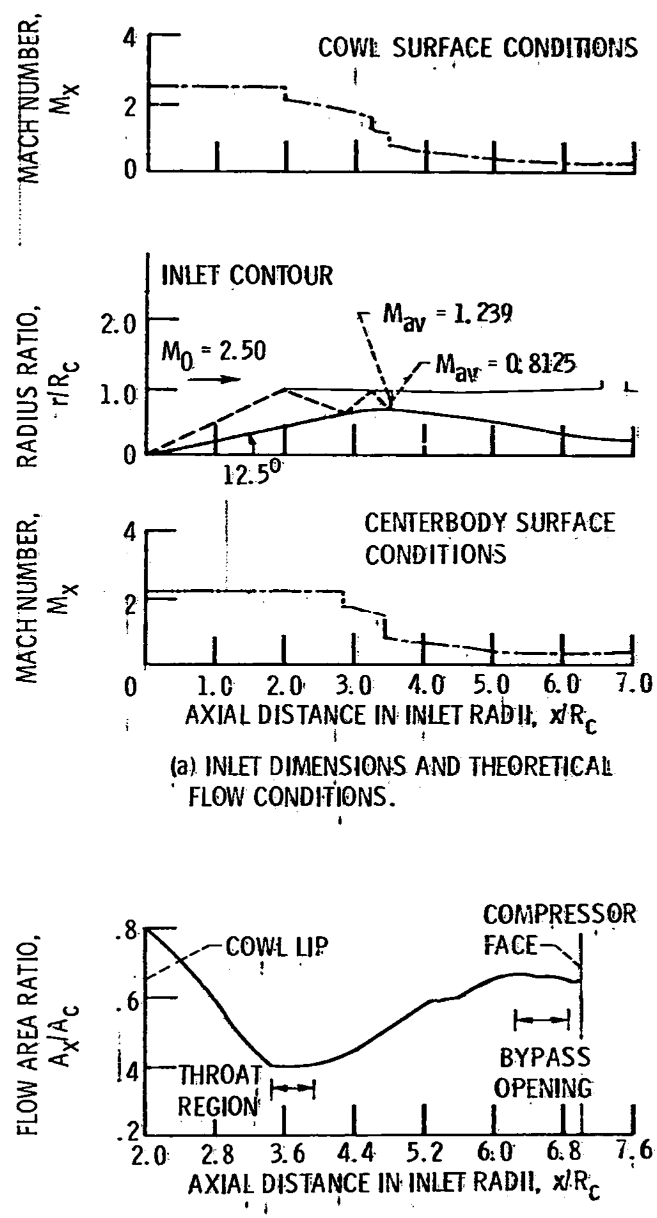


Figure 3. - Normal shock response to decrease in engine corrected airflow. Nonlinear analysis.



(a) INLET DIMENSIONS AND THEORETICAL FLOW CONDITIONS.

(b) DIFFUSER AREA VARIATION FOR CRUISE CENTERBODY POSITION.

Figure 4. - Inlet aerodynamic and geometric characteristics.

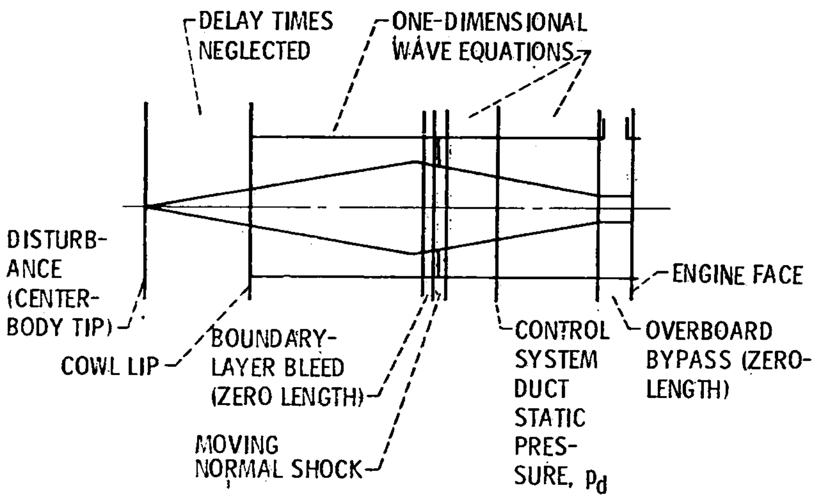


Figure 5. - Schematic of idealized inlet.

ELEMENT TRANSFER FUNCTION	FREQUENCY DEPENDENT TRANSFER FUNCTION
CENTERBODY POSITION TO POSITION COMMAND	$\frac{(37.7)^2}{s^2 + 2(0.707)(37.7)s + (37.7)^2}$
BYPASS POSITION TO POSITION COMMAND	$\frac{\omega_{bp}}{s + \omega_{bp}}$ ω_{bp} = 50.3 OR 12.6 rad/sec
BYPASS CONTROLLER	$\frac{s/100 + 1}{s}$

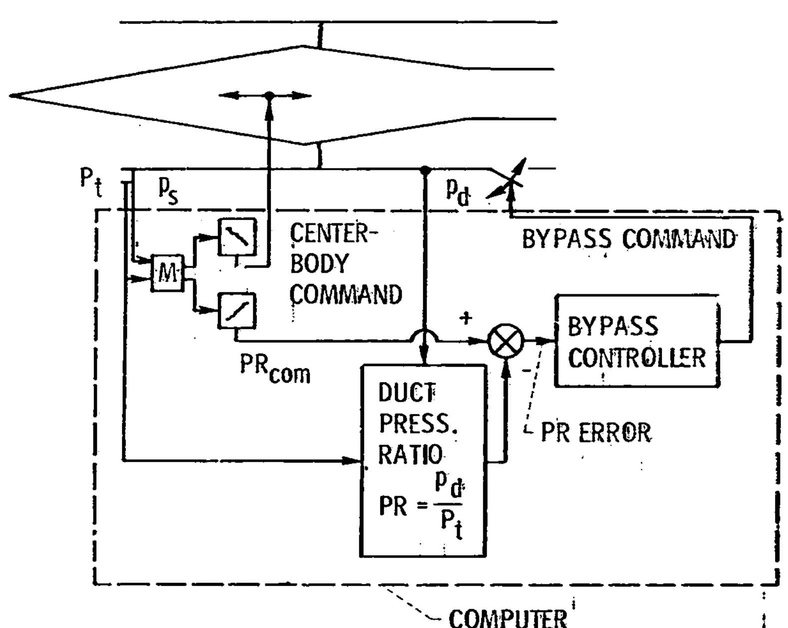
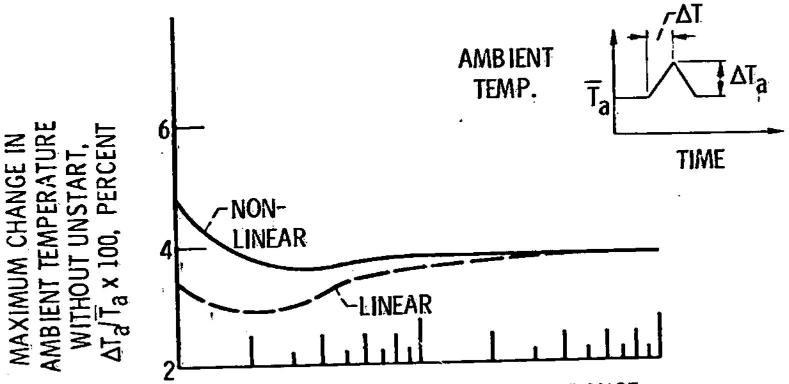
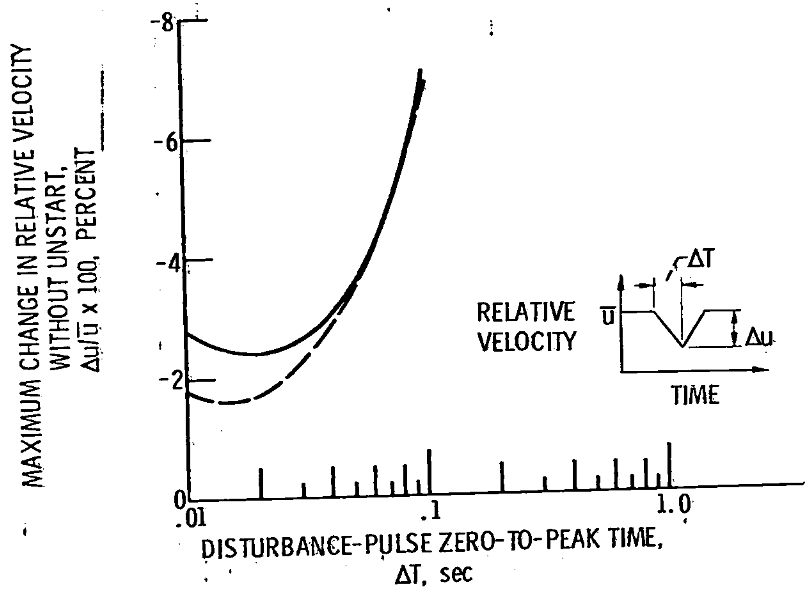


Figure 6. - Schematic of inlet control system.

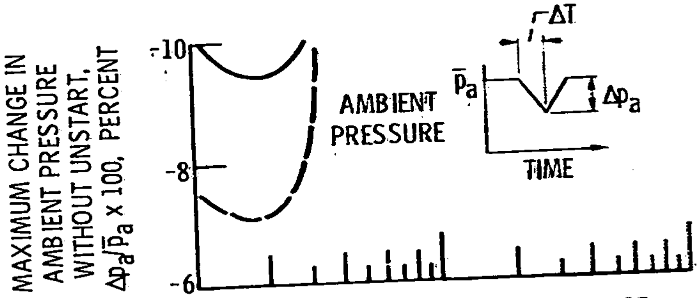


(a) AMBIENT TEMPERATURE DISTURBANCE

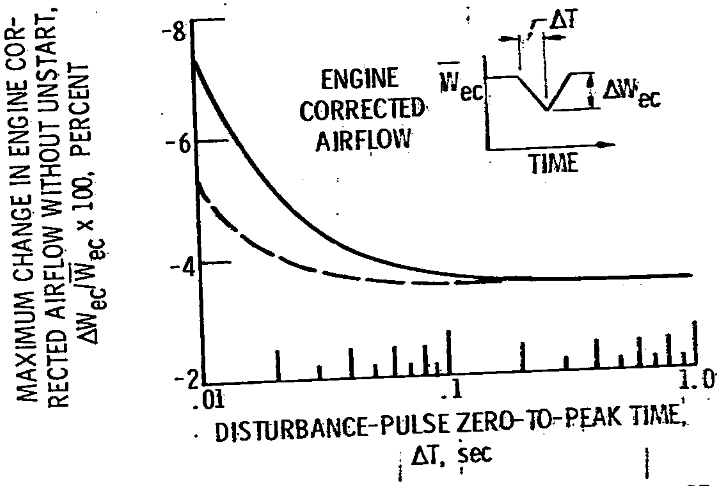


(b) RELATIVE VELOCITY DISTURBANCE.

Figure 7. - Maximum disturbance-pulse amplitude without unstart due to normal shock excursion upstream of throat for various atmospheric disturbances: comparison of linear to nonlinear analysis. Engine corrected airflow margin from unstart 3.5 percent; change in engine corrected airflow with air total temperature, $K_T = -1$.



(c) AMBIENT PRESSURE DISTURBANCE.



(d) ENGINE CORRECTED AIRFLOW DISTURBANCE.

Figure 7. - Concluded.

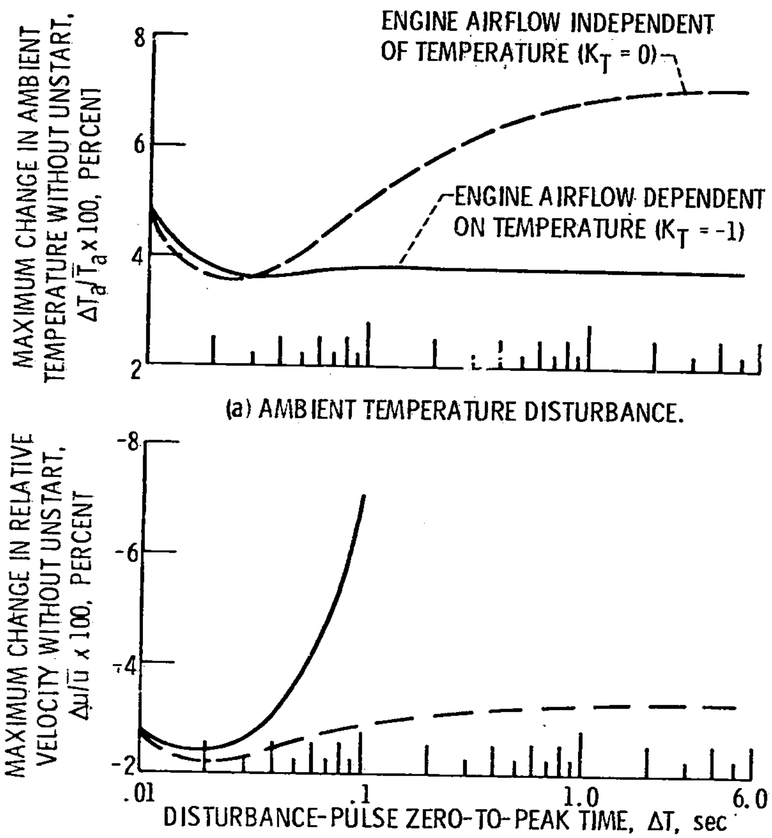


Figure 8. - Effect of engine corrected airflow sensitivity to air total temperature on nonlinear-analysis normal-shock unstart results. Engine corrected airflow margin from unstart, 3.5 percent.

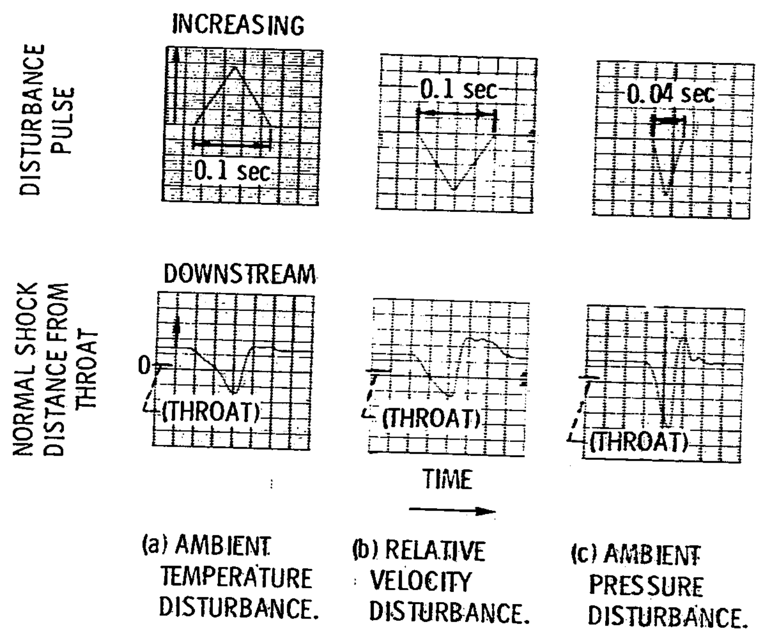
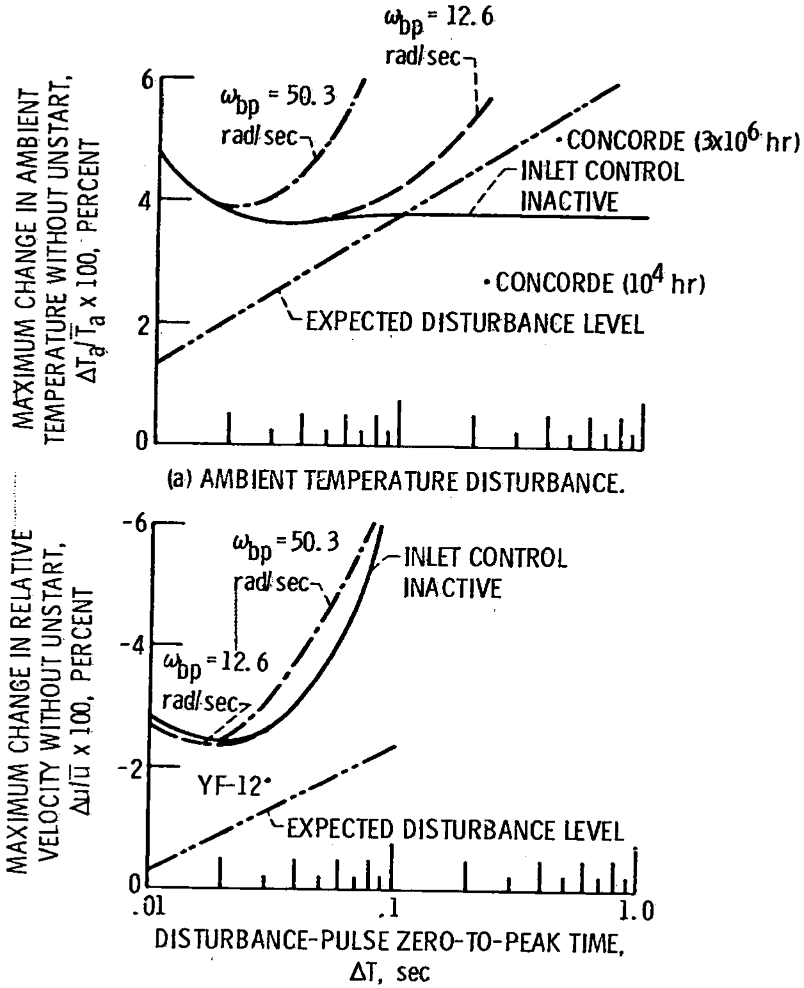
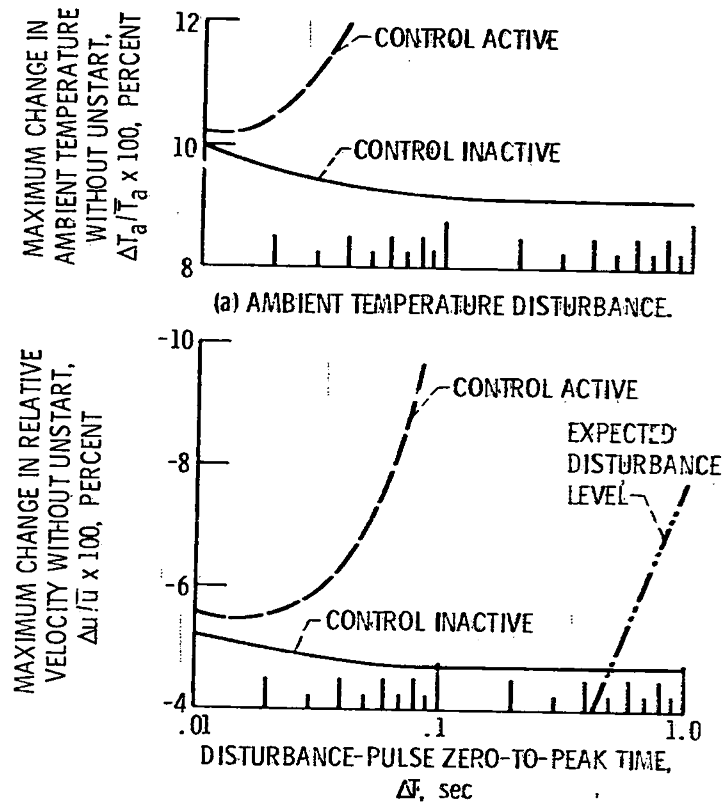


Figure 9. - Normal shock position transient response to various atmospheric disturbances. Nonlinear analysis. Change in engine corrected airflow with air total temperature, K_T = -1.



(b) RELATIVE VELOCITY DISTURBANCE.

Figure 10. - Effect of inlet control bypass response on nonlinear - analysis normal-shock unstart results. Engine corrected airflow margin from unstart, 3.5 percent; change in engine correct airflow with air total temperature, $K_T = -1$.



(b) RELATIVE VELOCITY DISTURBANCE.

Figure 11. - Maximum disturbance amplitude without unstart due to throat choking for various atmospheric disturbances: comparison with and without inlet control.