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NUMERICAL STUDY OF CONTROL OF DYNAMIC PROPERTIES OF A SUPERSONIC INLET USING BYPASS BLEED

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SUMMARY

Several problems of supersonic-inlet control are discussed and shown to indicate that the use of an on-off bypass-door control system linked to a flow property just ahead of the door would be beneficial for the control of the flow in a supersonic inlet. Results computed by using one-dimensional unsteady-flow characteristic methods are presented. These results show that the bypass-door control system will control the flow when the engine-face mass-flow requirement is reduced to 0.2 for various stall cycles or to 0.6 for a throttle-chop transient. The bypass-door results are compared with those from a perforated-wall system and with those from a combination of both systems.

INTRODUCTION

The necessity of establishing an efficient control system for a supersonic inlet has been demonstrated in a number of studies. (See, for example, refs. 1 to 7.) An analysis of the methods of control suggested in these references shows that only two means of changing the flow properties in a supersonic inlet are available for use. These methods are changing the area distribution or allowing the fluid to escape through the wall either through a bypass door or through perforations, as discussed in references 6 and 7. In order to maintain a control system, variable-opening doors, collapsing walls, movable spikes, or variable ramps are usually activated by some mechanism which is controlled from a signal based on the difference between an inlet flow parameter and a reference signal. The inlet flow parameter may be a Mach number, a static pressure, an average of pressures, some normal-shock-sensor method, and possibly others. The bypass door is usually used to control small engine-face transients so that the flow will be more or less optimum. At times, however, conditions such as engine flame out, stall, or reduction in power, may cause severe flow transients. The problem then is to determine if a bypass door controlled with sufficient speed will be capable of controlling the flow to prevent inlet unstart. One possible method of making a qualitative survey of this problem is to compute the flow through a supersonic inlet while a bypass door and appropriate control system are being used. These computations can be readily made using one-dimensional unsteady-flow characteristic methods, with the advantage that conditions can be investigated which may not be feasible experimentally because of mechanical limitations. It is the purpose of this investigation to make such a study on the effectiveness of the use of bypass doors to control fast, severe inlet transients and to demonstrate the use of one-dimensional unsteady-flow characteristics for the computation of such problems.

The data presented from calculations of the flow in an external-internal-compression inlet using the bypass-door system to control engine transients consisted of bypass-door-opening shock location, Mach number, static pressure, and mass flow at the engine face and at the location of the control input.

SYMBOLS

A_{ch}	area at downstream choked end of inlet
a	nondimensional sonic speed (nondimensionalized with respect to sonic speed at initial free-stream conditions)
B, C, D, E, F, G, H, I	various points (see sketch (a))
M	local Mach number
m/m_{cap}	ratio of local mass flow to capture mass flow
N	number of stall cycles
P	characteristic line of slope $u + a$
$p_s/p_{t,\infty}$	ratio of local static pressure to free-stream total pressure
Q	characteristic line of slope $u - a$
t	unit time based on ratio of inlet-entrance height to stream sonic speed, which is equivalent to 0.0033 second for an inlet with a 1-meter entrance height
u	nondimensional local velocity (nondimensionalized with respect to sonic speed at initial free-stream conditions)
x	nondimensional length or inlet station based on entrance height

δ intensity of transient

Ψ proportion of local open area to total area of walls at bypass opening

ω angular frequency of cosine transient

Subscripts:

f in front of shock

o initial value

r at rear of shock

ref value to which control input is referenced

BYPASS-DOOR CONTROL SYSTEMS

A bypass-door control system is essentially any method by which the mass flow can escape through the inlet wall. Such a control may be simulated by considering that the wall is perforated with variable-area holes which can be opened or closed according to the mass-flow-escape needs of the system. Proper operation of the bypass door requires that it open just enough to let the difference between the engine-face mass flow and the capture mass-flow escape. This operation requires a control unit which is capable of sensing the engine-face mass flow and then opening the bypass door just enough to compensate for any reduction of the mass flow or closing to compensate for an increase. This functional relationship between bypass-door opening and engine-face mass-flow reduction may not always be consistent and could vary so much between different types of transients that no reasonable mechanical system could be designed to keep the door opened the correct amount for all occasions.

However, one of the more important requirements of the control system is that it keep the shock downstream of the throat and near its inlet-design location. This requirement can be met by holding the flow properties downstream of the shock approximately constant. Thus, the flow just ahead of the bypass door must be constant, and just downstream of the door, the flow must meet the engine requirements. The requirement of constancy of the flow ahead of the bypass door suggests the use of a flow sensor at that point which would instantaneously open the bypass door when the sensed flow would cause the shock to move upstream and would similarly close the door when the sensed flow would cause the shock to move downstream. Such a system is typical of many nonlinear on-off or "bang-bang" control systems used. However, mechanisms do not operate instantly so that time must be allowed for the bypass doors to open or close. It is, therefore, necessary to introduce an opening rate into the system. This rate can also be expressed as the opening time or the time required for the system to open from fully closed to fully open. It is this type of control system which will be investigated herein.

Investigation of the bypass-door system with the on-off control showed that a hunting tendency had developed which produced a limit cycle in the on-off system. A dead band was then included so that the bypass opening would remain stationary whenever the control input signal was within a few percent, usually 2 to 5 percent of the reference signal.

DESCRIPTION OF INLET

In this analysis an external-internal-compression inlet with a ramp or spike external-compression surface operating on design at Mach 3 with full capture is considered. The actual area distribution considered is the two-dimensional external-internal inlet "C" presented in reference 8 with a nondimensional throat height of 0.275 located at $x = 4.0$. The area distribution of this inlet after reduction to nondimensional units and smoothing is presented in figure 1. Several features relevant to the computing should be pointed out. Even though the inlet considered is an external-internal-compression inlet, it is more readily treated by considering it as an internal-compression inlet with the wall ahead of the lip closed to supersonic flow and fully open to subsonic flow. This approximation of the inlet is convenient to make with one-dimensional methods.

The region between the lip and throat can be perforated; that is, considered closed to supersonic and partially open to subsonic flow. In the majority of computations presented in this analysis, a perforated inlet for control studies was not considered. The bypass-opening region, in terms of the proportion of local open area to total area of the walls at the bypass opening Ψ, is shown in figure 1 and is considered as variable between zero (fully closed) and 1 (fully open) for this study. In the last part of the inlet, a flow-control plug was used to control entrance of transients into the flow. The transient was produced by changing the area distribution between the engine face and the choking position. Essentially, this method varies the mass flow at the exit in a prescribed fashion.

Additional flow transients may be caused by the method of changing the flow-control area distribution. Mechanically, the method could be simulated by having a long curved plate hinged at the upstream end and free to follow the A_{ch} variation at the downstream end with the constraint that the plate follow a parabolic curve with zero slope at the final choking location. When this system is closed rapidly, it acts as a bellows air pump, which forces the air in both directions. However, as the downstream opening is choked, much of the air is forced upstream in a strong pressure surge. In fact, this effect can be so strong that it can reverse the velocity of the engine-face flow, the Mach number, and the mass flow as well. The bypass-door opening was considered to be controlled from either a pressure, Mach number, or mass-flow value at a station just ahead of the door ($x = 8.6$). The control system was considered to open or close at a uniform rate whenever the flow parameter indicated that it was necessary to open or close the door to prevent shock movement.

METHOD OF ANALYSIS

The results presented in this study were obtained by computing the one-dimensional unsteady flow through an external-internal-compression supersonic inlet. A description of the method used in handling the characteristic system and the control system is presented in the appendix. A dead band was used in some of the calculations described. Both systems were incorporated into the program as described in the appendix.

A single-cycle or multiple-cycle stall wave represented by $\left[1 + \frac{\delta}{2}(1 - \cos \omega t)\right]$ was used as an exciting transient on the choked area A_{ch} at the end of the inlet; that is,

$$A_{ch} = A_{ch,o}\left[1 + \frac{\delta}{2}(1 - \cos \omega t)\right] \qquad \left(0 < t < \frac{2\pi N}{\omega}\right)$$

$$A_{ch} = A_{ch,o} \qquad \left(t < 0; \quad t > \frac{2\pi N}{\omega}\right)$$

The changes in flow demand at the engine face caused by varying A_{ch} must, in order to control the shock position, be reasonably compensated for by allowing the inlet mass flow in excess of that required at the engine face to escape through the bypass exit. If this exit can be controlled correctly, then the shock position should remain fairly stable. Correct control of the system is judged on this basis.

PRESENTATION OF DATA

The results of a number of computations of the flow through the described inlet are presented in three groups. In the first group, figures 2 to 4, the applied impulse consists of a single-cycle simulated stall of 30 time units duration, in which the choking area A_{ch} is reduced to 0.2 of its original value with a resultant reduction in the engine-face mass flow. This group uses the on-off bypass-door control system with either the static pressure, Mach number, or the mass flow measured just in front of the bypass opening as the control input. The results of the use of the on-off system for each of the above inputs are presented for several bypass opening times.

The second group, figure 5, presents similar control conditions; however, for these the applied impulse consists of a ramp impulse, which simulates throttle reduction, occurring over a period of 15 time units in which A_{ch} is reduced linearly from its original value to 0.6 of that value. The third group, figure 6, consists of several multiple-cycle stalls with varying periods rather than the single cycle of the first group. These conditions permit a study of the control of multiple-cycle stalls and stalls of different time duration.

Two extra studies have been made in which the flow is controlled solely with the perforated-wall method of reference 7 and with a combination of the bypass-door and perforated-wall systems. The results of these studies are presented in figures 7 and 8, respectively. These are used as a basis for comparison of the two methods of inlet-flow control.

Each figure of the three groups presents the amount of bypass opening, the applied impulse, the shock location, and the Mach number, and the static-pressure ratio and mass-flow ratio in front of the bypass door (station 8.6) and at the engine face (station 9.6). All impulses were applied by varying the choking area A_{ch} of the inlet. (See fig. 1.)

ANALYSIS OF RESULTS

Simulated Stall Transients

The results of using an on-off control system with static pressure as the input to the system are shown in figures 2(a) to 2(d), where the time for bypass-door opening is varied from 4 time units for the system to change from closed to completely open to 100 time units for the same change. The applied impulse is a single-cycle stall which could approximately represent an engine flameout.

A comparison of the curves of figures 2(a) to 2(c) shows that the time variations of the static pressures, Mach numbers, and mass flows are on the average quite similar and that the shock is contained within the inlet (x greater than 3) even though the average engine-face mass flow is reduced to about 0.2 of its initial steady-state value. It is also observed that the perturbations in the flow reduce to a minimum for an opening time of 25 units. The indications are that an ideal opening time exists for each stall transient. This time probably depends on both the period and amplitude of the transient. Since the control is based on the static pressure immediately upstream of the bypass opening, this pressure is maintained reasonably constant throughout the duration of the transient. When the static-pressure system successfully controls the shock location, the Mach number and mass flow at the control station are held reasonably constant. Also, both Mach number and mass flow at the engine face follow reasonably well the changes indicated by the applied impulse, and the engine-face static pressure remains reasonably constant.

The system can be set to open too slowly (see fig. 2(d)); when the shock escapes, the flow to the engine deteriorates with a reduction in static pressure, and large changes occur in both Mach number and engine-face mass flow.

Although these figures indicate that an ideal opening time exists for a given transient, the use of this ideal opening rate for each transient is not practical since the transient duration and amplitude cannot be predicted. Hence, the choice of an opening time would depend on the most rapid transient expected. The use of too rapid an opening time involves a large degree of hunting, in which the amount of opening of the system varies greatly on either side of the correct values. Although the shock is not expelled, the flow to the engine face is rougher under these conditions. Although perturbation in the flow would exist for slower transients, this problem is less severe than is the problem of an unstart when the transient is too fast for the opening rate of the bypass control.

It is interesting to note that the bypass-opening curves of all the successfully controlled flows have about the same average values regardless of opening time. This similarity is to be expected since only so much mass has to escape through the bypass to keep best control of the flow. Regardless of the opening time of the system, the average opening curves should be about the same. If the average curves were not about the same, then transients would occur at the 8.6 station. These transients would either expel the shock if the bypass mass flow were too small or would draw the shock too far downstream if the bypass mass flow were too large. These results show that one-dimensional unsteady-flow characteristic methods can be used to calculate the effectiveness of a system for controlling the flow in a supersonic inlet where the change in the flow parameters is too great to consider with linearized methods. The bypass-door system based on static pressure cannot be used alone, since additional information concerning the actual shock position is required for successful inlet control. For example, a change in input Mach number would require changing the dead-band location if the shock were to be held stable. This input Mach number change would also require a change in the area distribution. A shock-position sensor is also required for accurate regulation of steady-state shock position as well as to help in the flow regulation during the transient. Thus, although the simple on-off control system can apparently handle the severe transient, additional equipment is needed for a practical control system. Also, this control system has instantaneous changes in direction which would cause severe accelerations and hence high mechanical stresses.

Other flow properties can also be used to control the flow. Mach number or mass flow are examples. Either of these would require an intermediate system to convert the necessary pressure or other measured data into the required flow property. However, even though the use of other flow properties as a control input may be experimentally difficult, their use may be readily investigated with the computer. The results of the use of Mach number and mass flow as control inputs are presented in figures 3 and 4, respectively.

Examination of figures 2, 3, and 4 shows nearly the same results. The shock is controlled at a bypass-door opening time of 25 units with the smoothed flow occurring then. The shock is expelled for all three control inputs at a 100-unit opening time. Figure 3(d) presents the results for an opening time of 50 units, which was not calculated for the others. This figure shows that the shock almost escapes. It is believed that this bypass-door opening time is about as slow as could be used to control this particular transient; however, the use of a faster opening time results in a smoother flow pattern.

It is believed that the drift of the flow properties, especially the shock location as seen in both the Mach number and mass-flow controlled systems, is due mostly to the finite-interval nature of the computing methods and to round-off effects in the computer. Some evidence for this belief is found in later computations using an x distribution every 0.5 unit rather than using the 0.2 unit of this study. For the x distribution of 0.5 unit, the shock-location drift for similar transients was more severe. It is interesting to note that this drift is less with the static-pressure-based control system.

The use of the dead band, shown in figure 4, had little effect on the drift. Comparing figures 2(b), 3(b), and 4(a) shows a slight smoothing effect due to the dead band. The hunting of the control system seen in the bypass-door-opening curves of figures 2(b) and 3(b) is greatly reduced by the dead band (fig. 4(a)). This reduction should result in improved flow quality.

Analysis of Control-Input Systems

Several points of interest may be observed from figures 2 to 4. First, any of the three flow parameters – static pressure, Mach number, or mass flow – may be used as an input to the on-off control system. The choice depends on the particular property most desired to be held constant. The rate of opening for the smoothest operation of the bypass system is dependent upon the transient duration: if the rate is somewhat too fast, no serious problems seem to occur, whereas if the rate is too slow, shock ejection and flow breakdown result. Generally, the time average properties of the flow, when successfully controlled, as well as the opening rates of the control system are relatively independent of the flow parameter used as a control input.

Simulated Throttle Chop or Ramp Impulse

Several computer runs were made to determine the capability of the on-off bypass system to control the flow properties when the choked mass flow is reduced by a given amount and then held at that value. This particular ramp impulse consisted of a reduction of the choking area A_{ch} from its original value to 0.6 of that value over a period of 15 time units; thus, a reduction in engine mass-flow demand was simulated. The results of several such calculations are shown in figure 5. For figure 5(a), the Mach number just upstream of the bypass opening was used as the control input, whereas in figures 5(b) and 5(c) static pressure at the same location was used for the control input.

The curves for control based on Mach number in figure 5(a) show many features similar to those presented previously. The shock is successfully contained and the engine-face mass flow follows the area change of the applied impulse closely. In addition, the overshoot due to the fast response of the control system causes minor perturbation in the flow. However, the amount of bypass opening is adjusted so that the average mass flow to the engine matches the engine requirement of about 0.6. Further, the flow is slightly overcontrolled in that the average shock position moves downstream slightly with a small reduction in static pressure.

The curves for control based on static pressure in figure 5(b) also show similar results except that the static pressure is not allowed to change and the average shock position also remains at about its initial value. With a bypass opening time of 10 units, flow at the engine is almost identical for both control inputs. Calculations were also made for a longer time of 25 units for the static-pressure-based control system, and curves from this calculation are shown in figure 5(c). The flow is shown to be exceptionally well controlled. This excellent control is partially due to better match of the control rate with the impulse rate and partially due to a more effective use of the dead band than occurred in the calculation presented by the curves in figure 5(b). The use of the dead band is more effective in the calculations of figure 5(c) than in those of figure 5(b) because the better match of the control system and the transient permits the control to remain within the dead band for longer times; thus, much smoother control motion results. In fact, the control motion in figure 5(b) is practically unaffected by the dead band as only the peaks and valleys are chopped off. As may be seen in the bypass-door-opening curve (fig. 5(c)), the control value remains constant for small changes in the flow properties; hence, the small perturbations in the flow due to overshoot in the control system are either eliminated or reduced.

Multiple-Cycle Stalls

It is reasonable to expect that if simulated stall cycles occur at such a low rate that the flow after one cycle becomes stable before the next cycle starts, then the control-system parameters which can control a single cycle should control any number of cycles. This result is shown in figure 6(a) which presents the flow calculations for two consecutive cycles with the same period and amplitude as the single cycle studies in figure 2. It is observed that the bypass opening, the Mach number, and the mass-flow distributions are similar for both cycles. Thus, the expectation is that a long series of these cycles would be controlled with an opening rate of 25 units.

It has previously been suggested that changes of period or amplitude would require different opening rates for successful control. The results for calculations of two-cycle 15-unit input transients and three-cycle 10-unit input transients are presented in figures 6(b) and 6(c) and (d), respectively. It was necessary to shorten the opening times for the 15-unit and 10-unit cycles to 4- and 1-unit cycles, respectively, to gain Mach number control. These opening times would not control the flow when static pressure was used as the input.

These shorter period transients are more difficult to control for several reasons. First, it is seen that the bellows effect of the area variation, which occurs between the engine face and the choked-flow location A_{ch} (fig. 1), forces a pressure wave upstream thereby reducing the mass flow at the engine face from 0.2 to large negative mass flows and reducing the Mach numbers due to a reverse motion of the fluid. Another factor is that the control system appears to have a limit cycle (constant-amplitude oscillation) with a period of about 3 units which becomes evident whenever the rate of opening exceeds the requirements of the inlet. (See figs. 2 to 5.) The period of this limit cycle seems to be practically independent of the opening rate. Since the limit-cycle period does not appreciably change with transient speed, it is reasonable to expect that larger fluctuations will develop for a fast transient than for a slow one; hence, the transient effects were more difficult to control. This increase in fluctuation is observed by comparing the various results of figures 6(b) and 6(c). Control is lost and the fluctuation becomes worse when the control input is changed from Mach number (fig. 6(c)) to static pressure (fig. 6(d)). Another element which may contribute to the difficulty of control of the faster transients is the possibility of interference of one cycle on the following cycle due to pressure waves traveling between the shock and the choked end of the inlet. Some evidence that such waves might exist has been shown in a frequency analysis of the shock response to the engine-face Mach number input. This response is generally smooth with little variation for periods greater than about 30 units. However, for periods less than 30 units, the frequency response becomes very irregular; thus, the resonance phenomena which could easily cause interference between waves are indicated. Such interference could then be expected to add to the difficulties of controlling the flow for faster transients.

PERFORATED-WALL CONTROL SYSTEM

Several computations were made using the perforated-wall control system in order to permit comparison with the bypass-door control system. In the perforated-wall system, the wall of the supersonic part of the inlet contains perforations which are closed to supersonic flow and are open to subsonic flow; thus, the flow can bleed through the wall whenever the shock moves ahead of the throat. These walls are studied in greater detail in reference 7. Computations were made for the one-, two-, and three-cycle stalls of figures 3(c), 6(b), and 6(c) and for the ramp impulse of figure 5. The results are presented in figures 7(a) to 7(d), respectively.

In figure 7(a), it is observed that the shock is immediately moved ahead of the throat as may be expected since the perforated wall which controls the flow assists only upstream of the throat. The shock, however, is returned after passage of the transient, thus the restart of potentialities of this control system based on a one-dimensional analysis is indicated. The Mach number and mass-flow distributions follow reasonably well the transient distribution, although some delay occurs in recovery along with a slight overshoot in both Mach number and mass flow before the flow settles out after the passage of the transient. This overshoot phenomenon was observed for similar transients studied in reference 7. The static-pressure distribution is strongly affected by the bellows phenomenon of the method used to apply the end boundary condition. The pressure rise is probably severely accented since there is no relief due to the opening of the bypass doors as occurs with the bypass system. Thus although the perforated wall can either prevent unstart or quickly restart the system after a transient has passed, the variations in all the flow parameters can become quite severe.

The results of the computations for the two- and three-cycle stall transients are shown in figures 7(b) and 7(c), respectively. Examination of these figures tends to verify the conclusions observed from the single-cycle computation. With the perforated-wall control system, the reduction in Mach number and mass flow becomes even larger than for the single cycle because of less control of the strong effects of the bellows action at the far downstream end of the inlet.

If the results shown in figures 7(a), 7(b), and 7(c) are compared directly with those of figures 3(c), 6(b), and 6(c), it is seen that the on-off system produces smoother flow only for the slower single-cycle transient. The rapid opening and closing of the on-off system required to control the faster transient results in higher frequency fluctuations than the perforated-wall system, but the magnitude of the flow variations at the engine face is more or less comparable. Thus, for fast transients the systems are somewhat comparable, but for slow transients the on-off bypass system produces a better flow.

The results of the calculation made by using the ramp impulse (throttle chop) are shown in figure 7(d). As may be expected, the shock is expelled and no restart can occur at this mass-flow condition. The shock must necessarily stay in the perforated region so that the excess mass flow may escape. Since the shock cannot return, it is seen that severe losses occur in static pressure and engine-face mass flow due to the nature of the unstarted flow. Thus, the perforated-wall system cannot properly control phenomena in which the inlet flow changes permanently. An augmenting system such as the bypass control is needed to compensate for necessary changes in the inlet flow due to changes in engine requirements. The use of both systems for control is suggested by these observations. The perforated wall could be used to control the faster transients so that only a low-speed system would then be required to handle mass-flow adjustments and/or low-speed transients.

The results of several computations using this combination are presented in figure 8. The results of the computation of a ramp-impulse reduction of $\delta = -0.4$ in A_{ch} are presented in figure 8(a). For this computation, the control opening rate was slowed to 250 time units. It is seen that the flow is controlled adequately and that the shock is prevented from escaping by the small amount of perforation which exists between the 4.2 station with no perforation and the 4.0 station which is perforated with an opened-to-closed ratio of 0.3. The variation of perforation is linear between the two stations. Some variation in the flow properties is seen, especially in the neighborhood of 24 to 36 time units where the perforated wall is assisting in the control. However, eventually the bypass control draws the shock back to nearly its original position with the flow settling to the final ramp values.

The results presented in figure 8(b) show that if too much dependence is placed in the perforated wall, the flow properties can become distorted severely. It is not evident from this figure whether the perforated wall and bypass control can work together to draw the shock back to its original position; however, it is believed that more time would be required for the flow to settle to values comparable with those presented in figure 8(a).

One of the more difficult transients to control was the three-stall cycle presented in figure 6(c). The calculation of this transient was repeated by using the same perforated wall but with an on-off bypass opening time of 10 units. These results are presented in figure 8(c). It is seen here that the flow is not controlled, as the shock is forced beyond the throat twice at the time of 14 units and 34.5 units. However, at both times the restart of the flow occurs within about 6 time units; thus, it is indicated that the perforated wall could add a safety factor to the inlet-control system. A comparison of the results presented in figure 7(c) for the perforated-wall control only and in figure 8(c) for the combination control system shows that the flow parameters are about the same, indicating that most of the control of the inlet is due to the perforated wall. The most prominent effect of the combination control is that the shock is drawn farther downstream in the inlet. A comparison of figures 8(c) and 6(c) shows that the combination system results in some reduction in both the Mach number and mass-flow variations of the on-off system. It is noted that the combination control system eliminates the short-period fluctuations caused by the limit-cycle characteristics found in the fast on-off control system. This elimination is caused by using a bypass-door control system with a larger opening time; that is, 10 units rather than 1 unit. (See figs. 6(c) and 8(c).) Thus, this combination control system, in which the perforated-wall system controls restarts and the bypass-door system controls the flow parameters, results in a smoother flow for high-speed transients than can be obtained with either the perforated-wall or the bypass-door control system alone. If the transients are lower speed, then the bypass-door control system causes less distortion of the flow parameters than can be obtained with the perforated-wall system alone. (Compare figs. 2(a) and 7(a).)

CONCLUSIONS

Analysis of the flow through an external-internal-compression inlet as computed with one-dimensional unsteady-flow characteristics has shown the following results:

1. An on-off control system linked to a flow property just upstream of the bypass door was found capable of controlling stall transients in which the engine mass-flow requirement was reduced to 0.2 of its original value.

2. A minimum bypass-door opening rate was found below which the shock was expelled; however, opening rates somewhat higher gave the smoothest flow pattern.

3. Too rapid bypass-door opening rates set up "hunting" oscillations which were not large enough to expel the shock. The engine-face location, however, did not experience as smooth a flow under these conditions.

4. The flow properties upstream of the bypass door were held reasonably constant when the shock location was held near its original position by the control system.

5. The system was found capable of adjusting the bypass door so that the effects of reduced mass-flow requirements from throttle chop were readily accounted for.

6. The system was found capable of handling multiple-cycle stalls provided the period of the disturbance was sufficiently long so that pressure waves from one cycle would not interfere strongly with those of the next cycle.

7. The bypass-door system causes less distortion of flow parameters than a perforated-wall system except for high-frequency transients, where a combined system of a perforated wall for restart control and a bypass-door system for flow control gave improved flow properties over those for a bypass-door control only.

Langley Research Center,
National Aeronautics and Space Administration,
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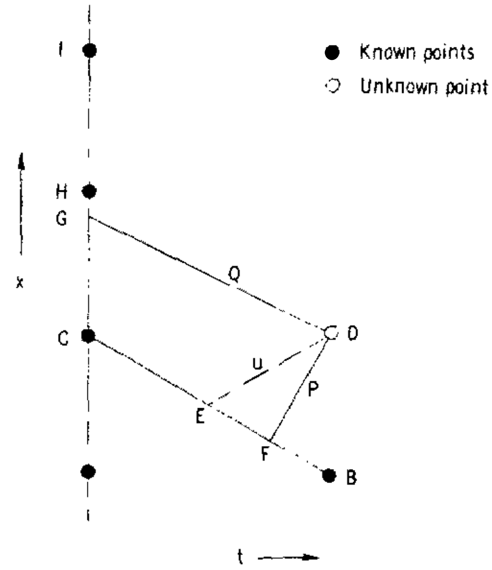
APPENDIX

SPECIFIED-TIME-INTERVAL CHARACTERISTIC METHOD

In most methods of computing one-dimensional unsteady-flow characteristics, the flow field along the axis is not computed for the same time for each x point of the inlet. In reference 7, for example, the flow-field point at the exit is calculated at a greater time value than the corresponding point at the entrance because the computational methods usually follow the characteristic lines in some fashion or another. This property of the usual methods is not very satisfactory for control-system calculations, as the information required to compute a given point may depend upon the information at some other point which has not yet been calculated. For example, if a control system were based on shock location and the calculations were following the characteristic line of slope $u + a$, the data required to compute all the remaining points along that line are unavailable, as these points occur at a greater time because of the positive slope of the characteristic line.

A method of flow-field-point determination is given in reference 9, where the time problem is eliminated. In this method, the entire flow field is calculated at the same specified time for each field point, then an advance is made to the next specified time and the entire flow field is recalculated for the next time value. This procedure is repeated until the desired time range is covered. Thus, it is assured that all the information needed to calculate any flow-field point will be available.

As for the actual computation of the specified-time-interval systems, the equations to integrate along the characteristic lines, the shock relations, and the relations expressing the effects of porosity on the inlet are expressed by the same equations as those used in references 7 and 10 and so need not be repeated here. In the specified-time-interval method, the characteristic equations are applied in the same manner as in reference 7; that is, the characteristic equations are integrated along the P characteristic lines of slope $u + a$ (see sketch (a)) and along the Q characteristic lines of slope $u - a$, and the entropy function is integrated along the streamline of slope u. The shock equations of reference 7 are applied to the shock herein in the same manner as in that reference. However, because the specified-time-interval method of reference 9 allows prelocation of all the field points in both space and time, it is necessary to determine the characteristic lines differently from those determined in reference 7. This necessity is because in reference 7 the characteristic lines proceeded directly from known field points to determine a new field point at their intersection. However, in the specified-time-interval method, the field location is preselected so that the characteristic lines must be followed backward from the new point to the previously calculated points. Since these lines will not intersect the calculated points, it becomes necessary to use interpolation methods to obtain the required field points.

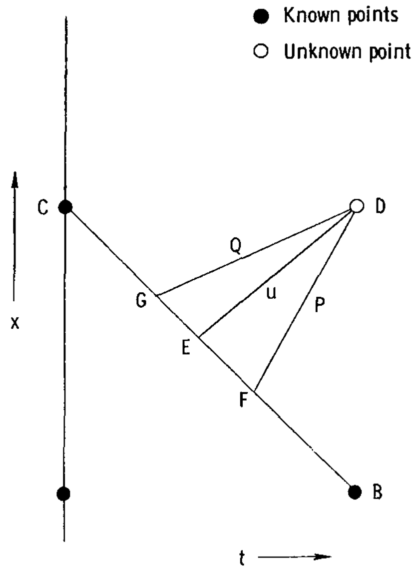


Sketch (a)

In sketch (a), which presents a subsonic flow field, the points B, C, and H have previously been calculated, and the point D is to be calculated. The Q line, whose slope is u - a, has a negative slope and, therefore, must originate at a point downstream of the point D. This line will not usually originate at the point H but will intersect the line HC at some point, say G. Since the flow values are already known at H and C, the values at G may be interpolated from the known values at H and C. Since the P line and the streamline have positive velocities or slopes, when traced backward from the point D, they will be found to intersect the line BC at the points E and F, respectively. As E and F can be readily determined from interpolation, their values can be used as a base point for integration along the streamline and the line P.

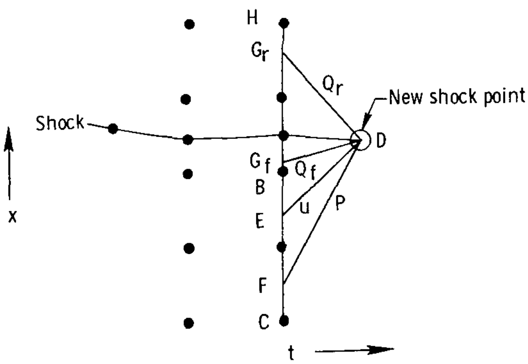
This extensive use of interpolation is valid so long as the flow field is continuous. Continuity of the flow field is assured provided the input transients are sufficiently weak so that characteristic line intersections will not occur to form weak shocks. The more rapidly changing stronger transients considered in this study may be expected to produce some weak shocks especially when the shock moves downstream because of low pressures behind it. Examples of such shock formation are seen in reference 7. Since the specified-time-interval method cannot easily recognize weak shock formations, their effects will be spread by the interpolation methods but should show as a smooth compression of the flow field.

For supersonic flow, the Q characteristic line originates upstream of the point D. (See sketch (b).) Since the points for the P characteristic line and the streamline were picked from the line BC, the intersection of the Q line with BC, namely point G, was used as the point from which to start integration. Once the points G, E, and F are known, the calculations proceed exactly as in reference 7.



Sketch (b)

The shock calculation was treated in a corresponding manner. It was convenient to calculate the shock first, as a knowledge of the shock location was necessary to avoid the possibility of crossing it with a characteristic line. However, because the shock was calculated first, the known point B of sketches (a) and (b) was unavailable. Hence, all characteristic lines had to proceed from the line HC, as shown in sketch (c). Since the normal shock of this study is due to intersection of Q characteristic lines, one of these must proceed from a point forward of and one from a point rearward of the shock, namely G_f and G_r. Again, though, as with the field points, once E, F, G_f, and G_r are determined then the shock computation proceeds exactly as for reference 7.



Sketch (c)

The interpolation method proceeded exactly as in reference 7. In characteristic computations, a second-order accuracy is attained if the slopes of the characteristic lines and streamlines are set equal to the average values of the slopes at the end points; for example, the slope of the Q line DG of sketch (a) is equal to the average of the value of $u - a$ at points D and G. The slopes of the other lines are computed in a corresponding manner. The interpolation equation must then take this average slope into account as well as a linear variation of the properties of any point G as it moves along the line HC. Once the equations are set up, then they may be solved so that the point G has the proper value for its location between H and C and the slope of the line DG is equal to the average of the slopes at points D and G. The interpolation must also include tests to determine whether G is between H and C and, if not, to instruct the main program to try the next set of points, H and I, for better interpolation values.

An examination of this method shows that the x,t field coverage is uniform and that all information is available to compute any point along the X axis with, at most, a time lag of the difference between any two time values. However, computation is slowed somewhat by more interpolation. Also because interpolation is required, there can be no discontinuities, such as shocks between the x points, unless a special program is entered to prevent the extension of a characteristic line across a shock. Such precautions were taken for the normal shock. As characteristic lines are not followed, their intersections cannot be determined and so the weak shocks, which may appear with the use of conventional methods, do not show with the use of the specified-time-interval method. It was observed though that the flow could suddenly change from supersonic to subsonic values between two x points. When this phenomenon was seen to occur, it was plotted as a secondary shock on the figures. (See fig. 8(c), for example.) This secondary shock usually occurs only when the shock moves rapidly downstream.

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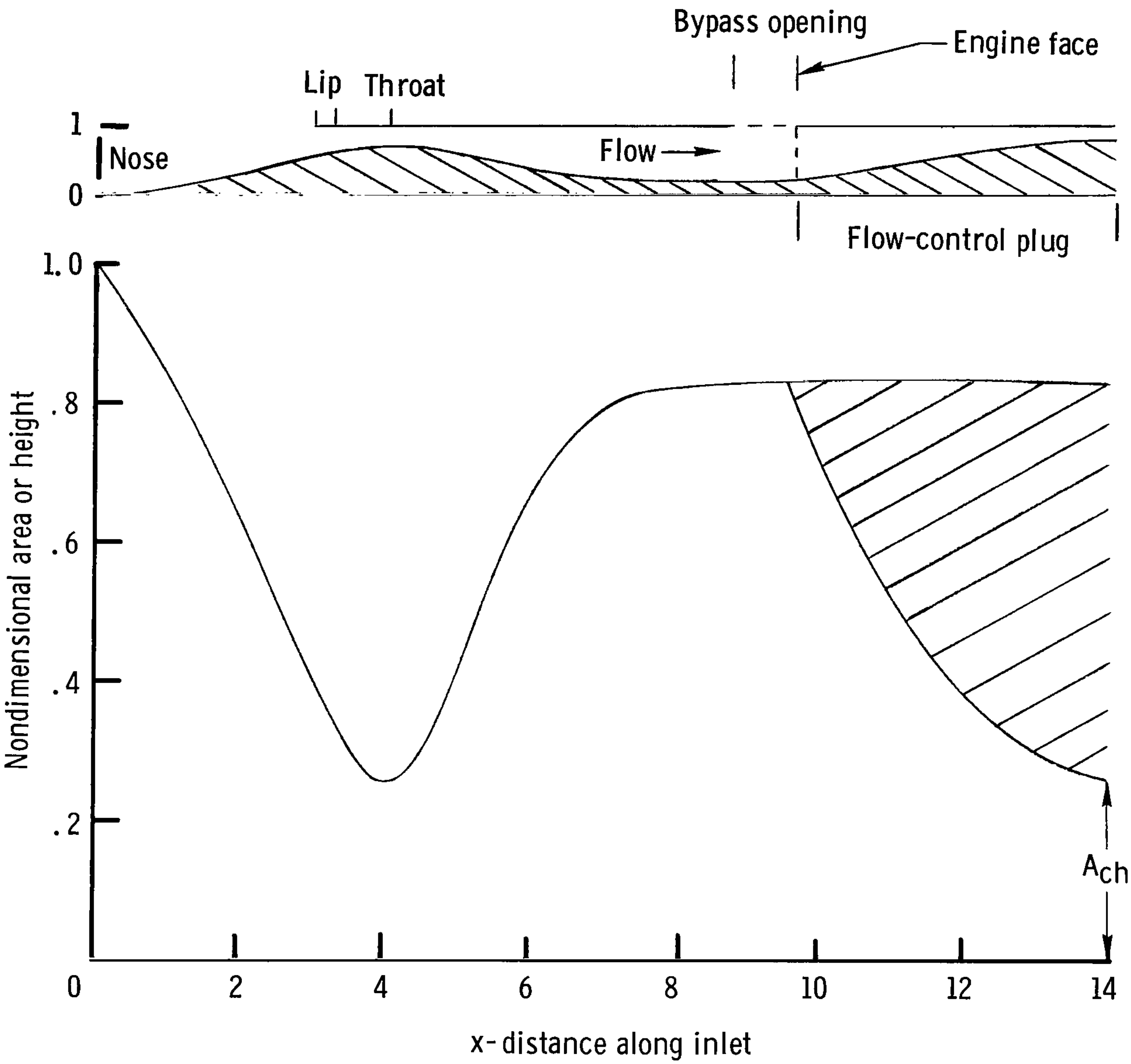
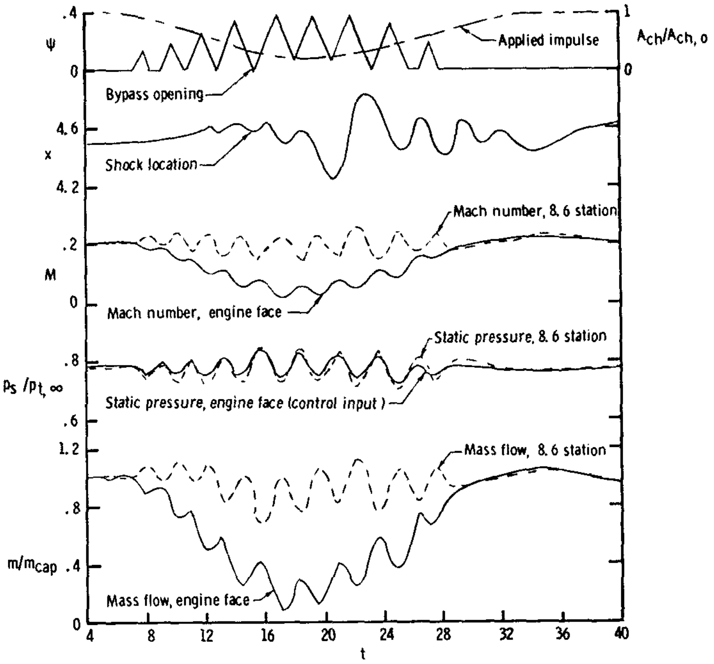
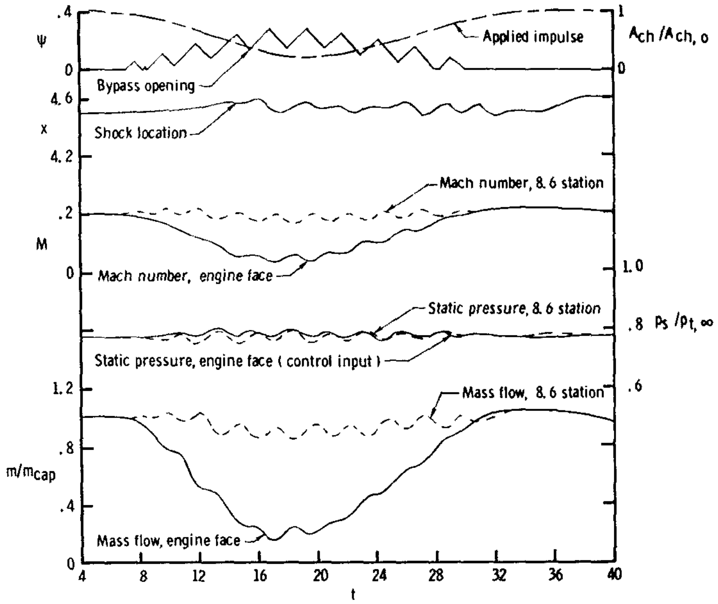


Figure 1.- Area of height distribution and schematic diagram of inlet.

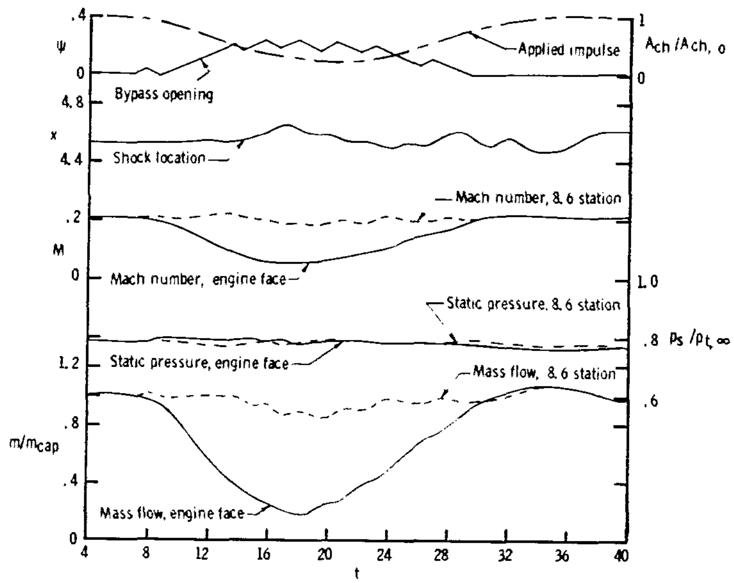


(a) Opening time, 4 units.

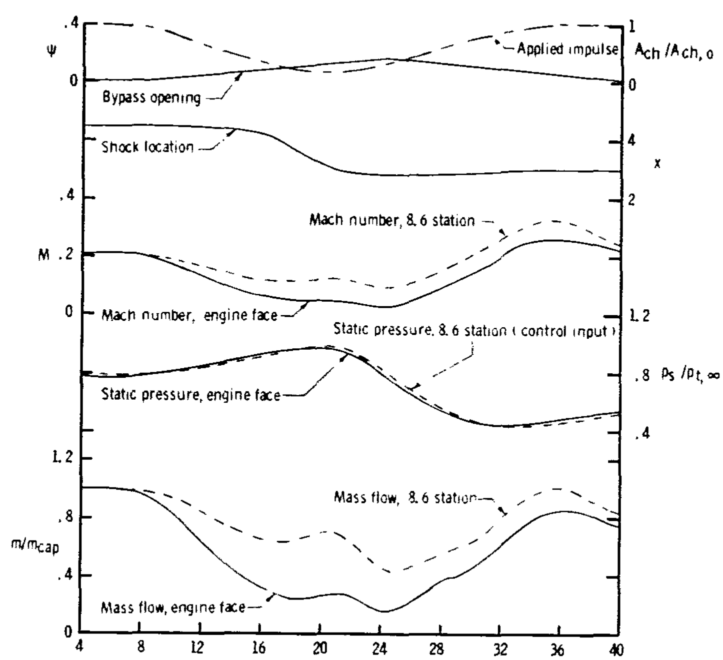


(b) Opening time, 10 units.

Figure 2.- Computed flow properties for a single-cycle, 30-time-unit stall with static-pressure-based on-off control. δ = -0.8; no dead band.

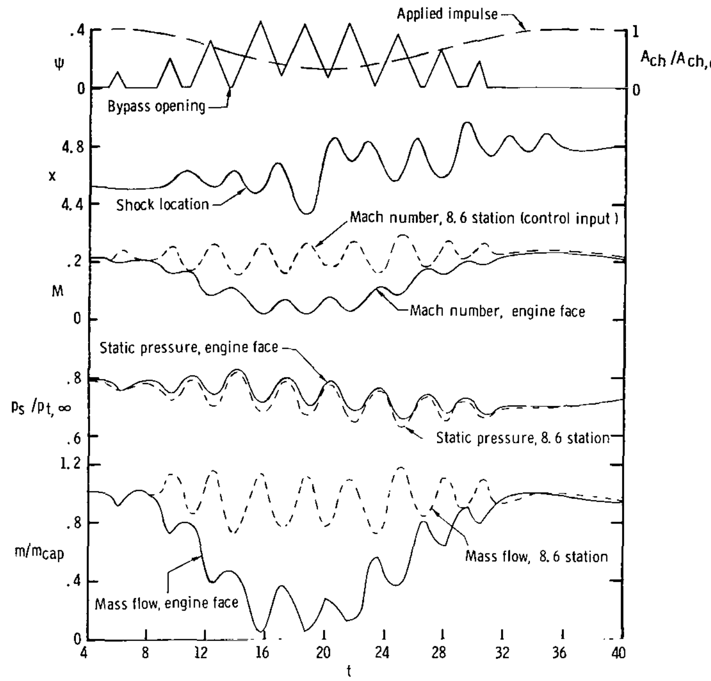


(c) Opening time, 25 units.

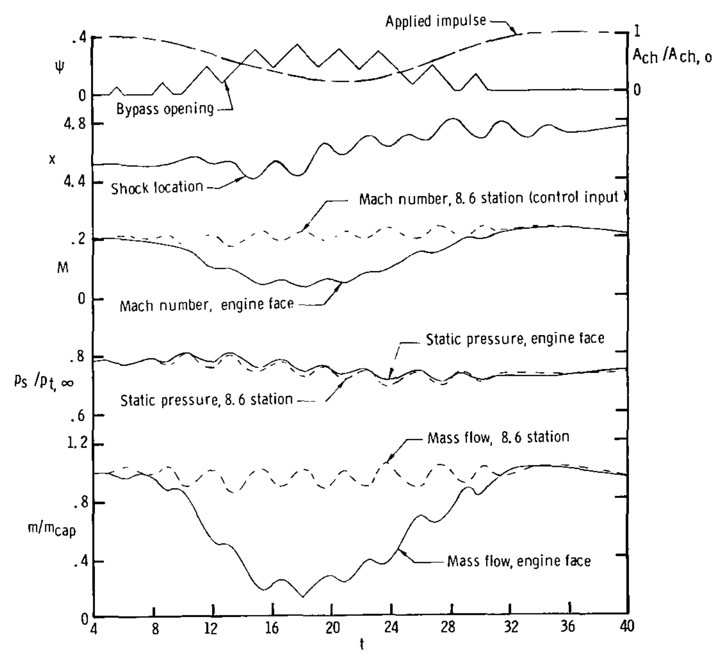


(d) Opening time, 100 units.

Figure 2.- Concluded.

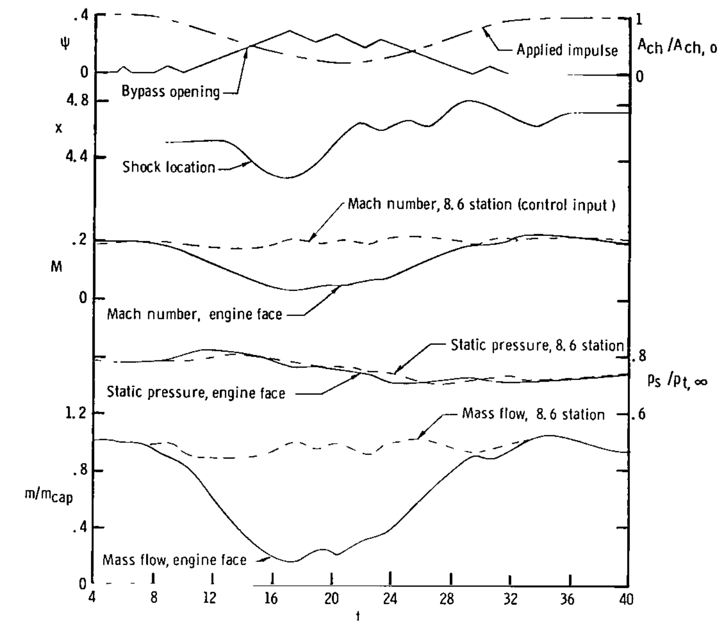


(a) Opening time, 4 units.

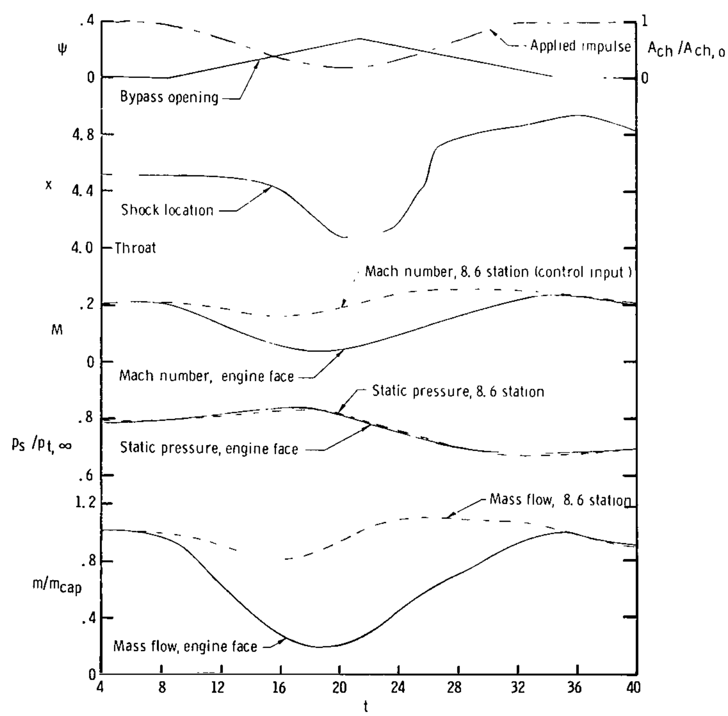


(b) Opening time, 10 units.

Figure 3.- Computed flow properties for a single-cycle, 30-time-unit stall with Mach number based on-off control. $\delta = -0.8$; no dead band.

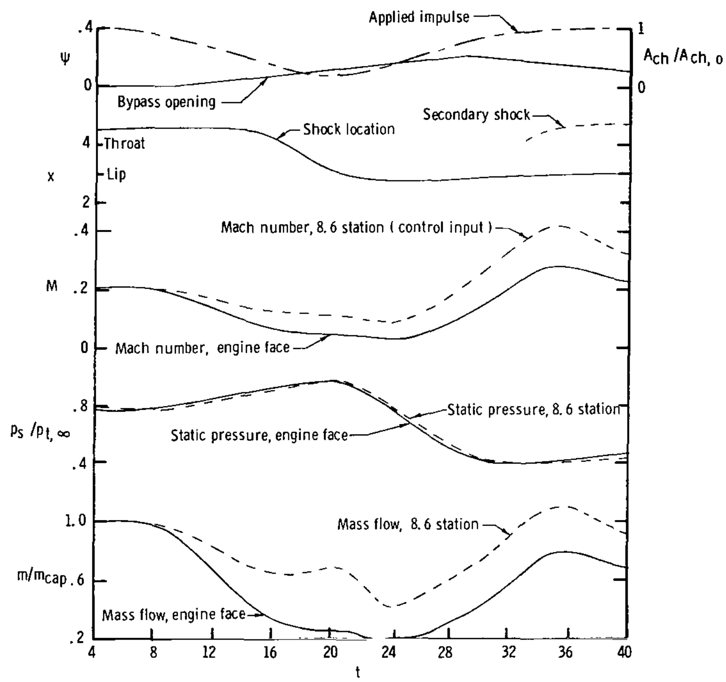


(c) Opening time, 25 units.



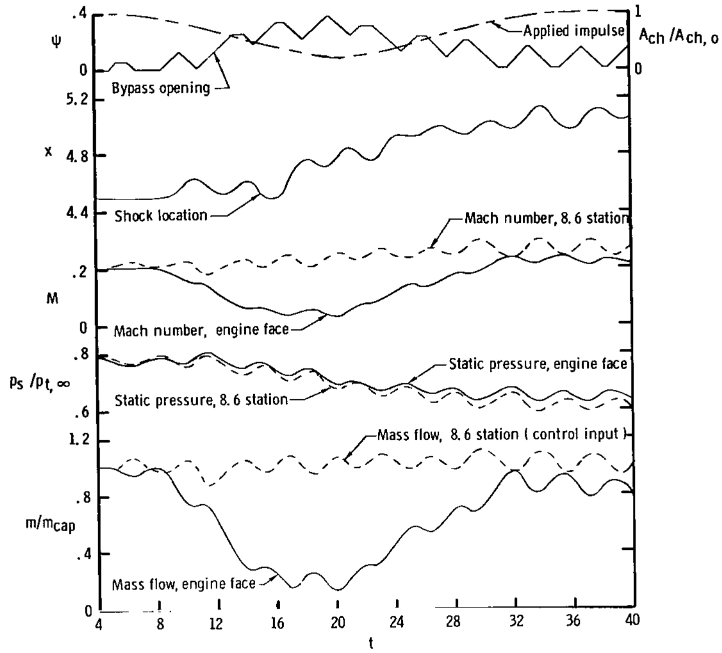
(d) Opening time, 50 units.

Figure 3. - Continued.

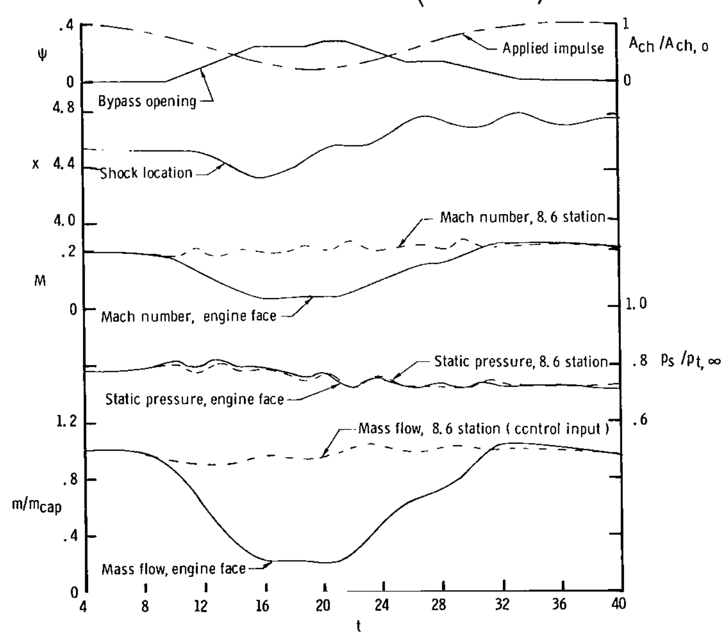


(e) Opening time, 100 units.

Figure 3.- Concluded.

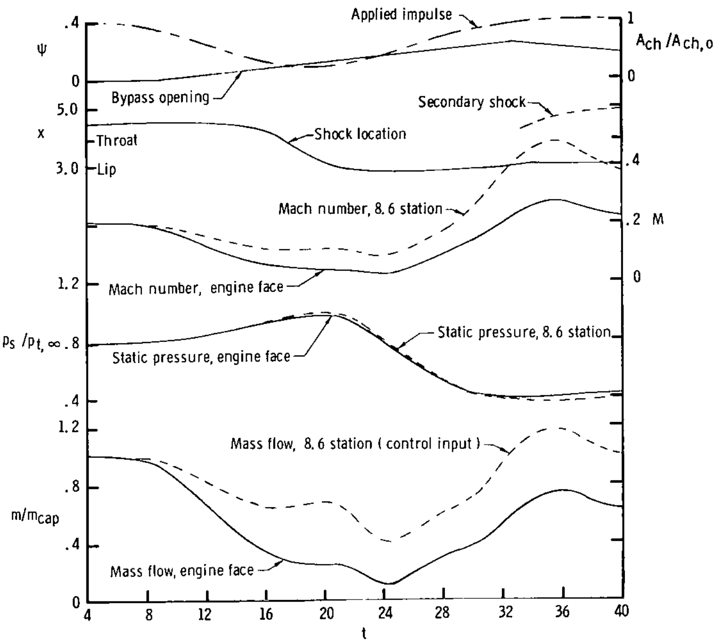


(a) Opening time, 10 units; opens if $m/m_{cap} < (m/m_{cap})_{ref}$; closes if $m/m_{cap} > 1.05(m/m_{cap})_{ref}$.



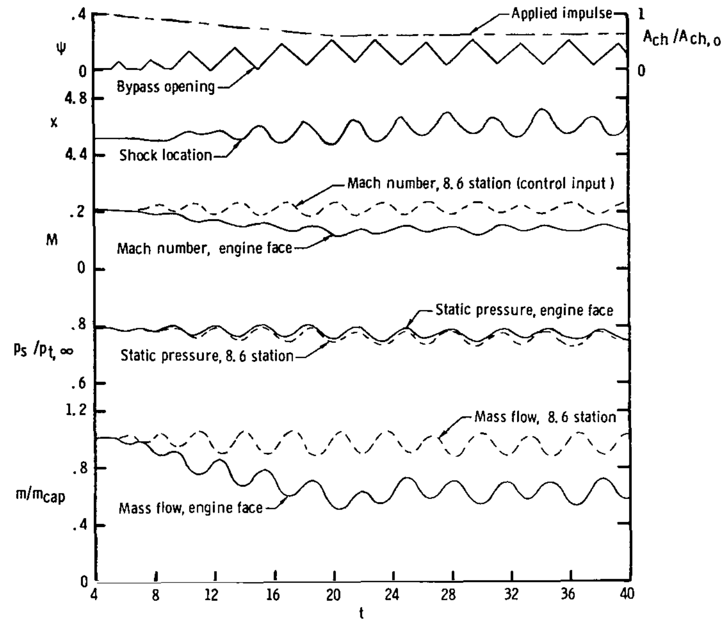
(b) Opening time, 25 units; opens if $m/m_{cap} < 0.99(m/m_{cap})_{ref}$; closes if $m/m_{cap} > 1.05(m/m_{cap})_{ref}$.

Figure 4.- Computed flow properties for a single-cycle, 30-time-unit stall with mass-flow-based on-off control. $\delta = -0.8$; no dead band.

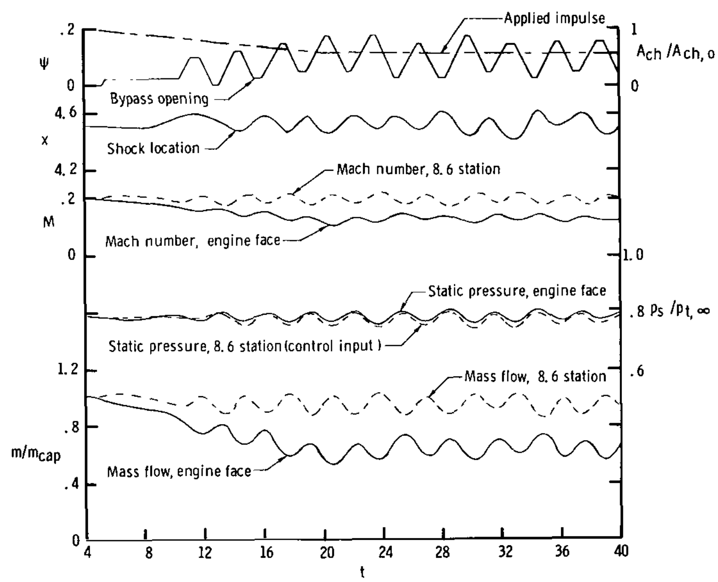


(c) Opening time, 100 units; opens if $m/m_{cap} < (m/m_{cap})_{ref}$; closes if $m/m_{cap} > 1.02(m/m_{cap})_{ref}$.

Figure 4. - Concluded.

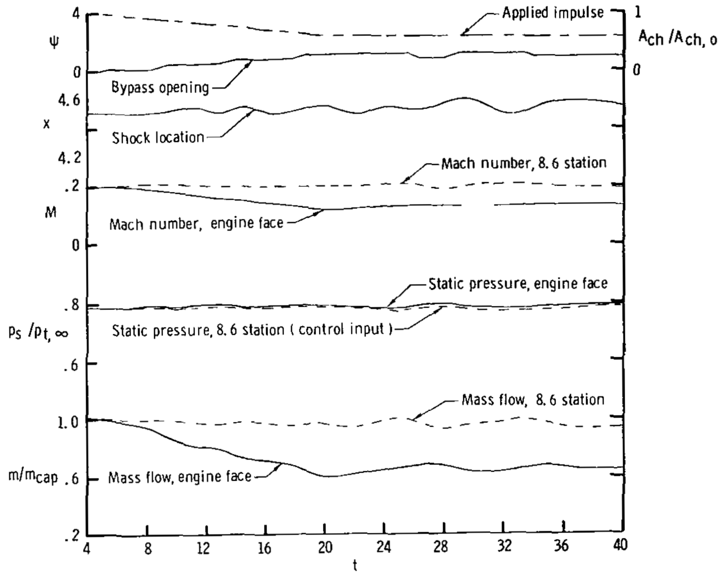


(a) Opening time, 10 units; Mach number based on-off control; no dead band.



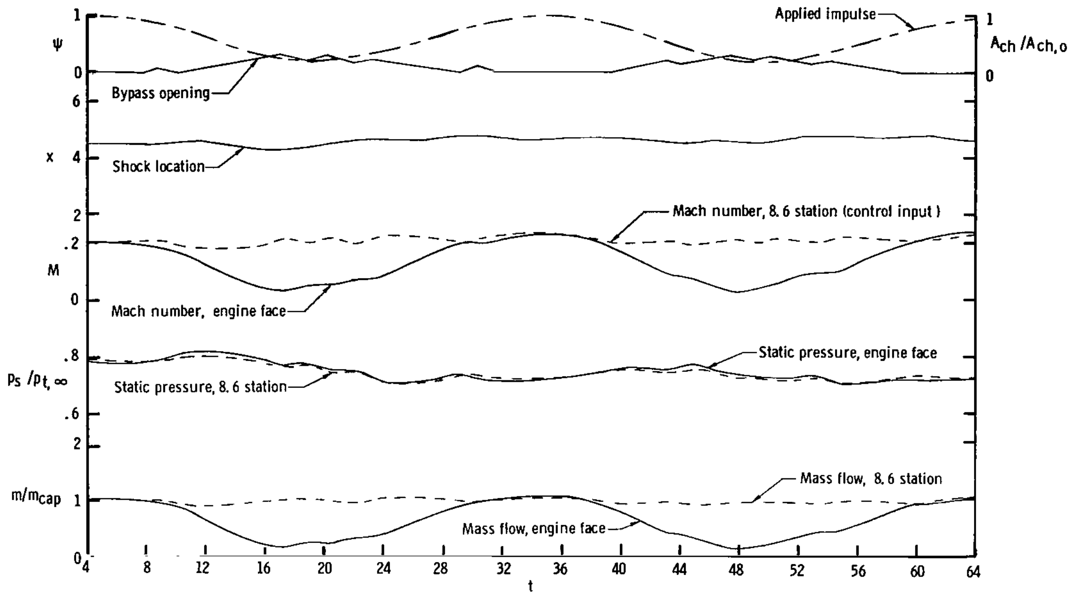
(b) Opening time, 10 units; static-pressure-based on-off control; opens if $p_s/p_{t,\infty} > 1.02(p_s/p_{t,\infty})_{ref}$; closes if $p_s/p_{t,\infty} < (p_s/p_{t,\infty})_{ref}$.

Figure 5.- Computed flow properties for a 15-time-unit ramp impulse. δ = -0.4.

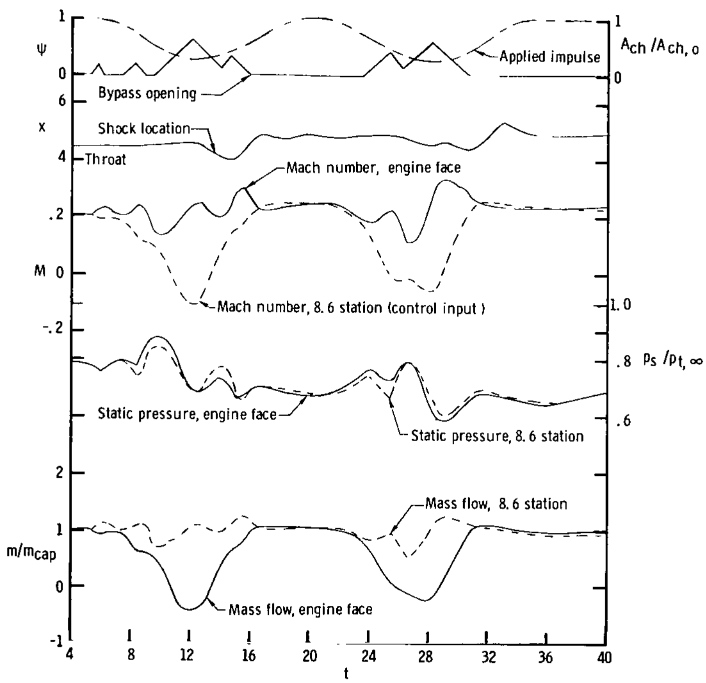


(c) Opening time, 25 units; static-pressure-based on-off control; opens if $p_s/p_{t,\infty} > 1.02(p_s/p_{t,\infty})_{ref}$; closes if $p_s/p_{t,\infty} < (p_s/p_{t,\infty})_{ref}$.

Figure 5.- Concluded.

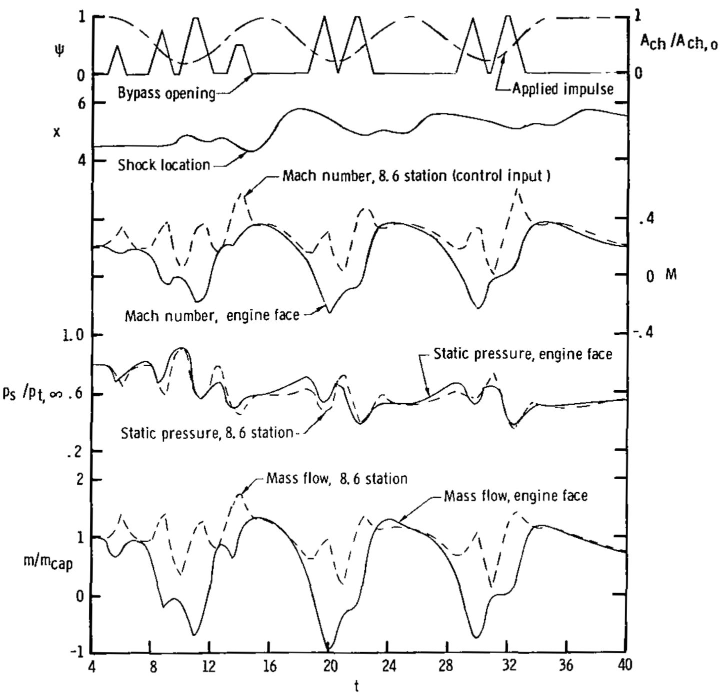


(a) Two-cycle, 30-time-unit stall; Mach number based on-off control; opening time, 25 units; no dead band.

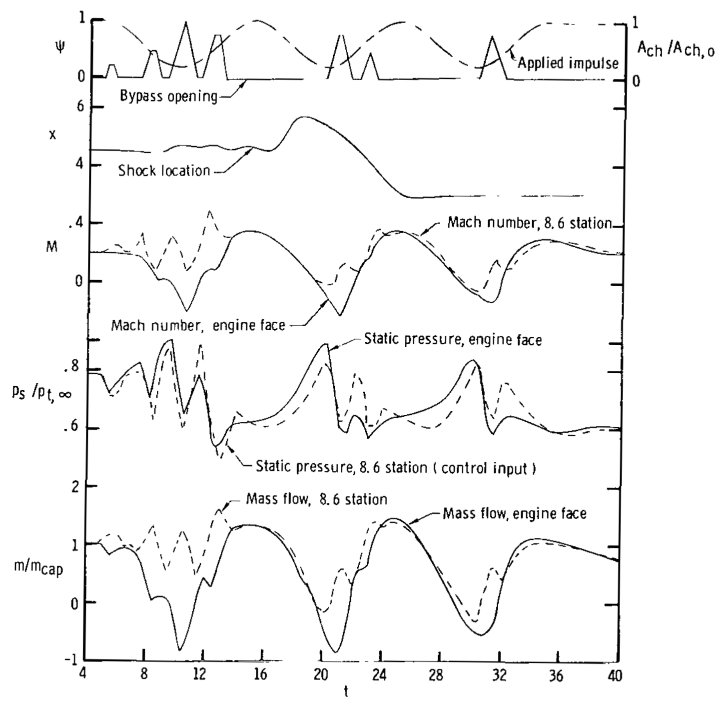


(b) Two-cycle, 15-time-unit stall; Mach number based on-off control; opening time, 4 units.

Figure 6.- Computed flow properties for multiple-cycle stall. $\delta = -0.8$.

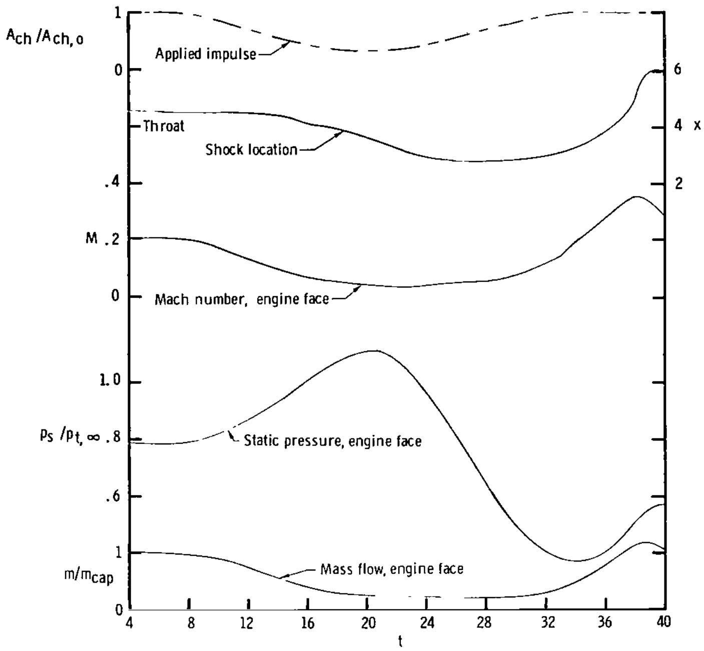


(c) Three-cycle, 10-time-unit stall; Mach number based on-off control; opening time, 1 unit; opens if $M < 0.98M_{ref}$; closes if $M > M_{ref}$.

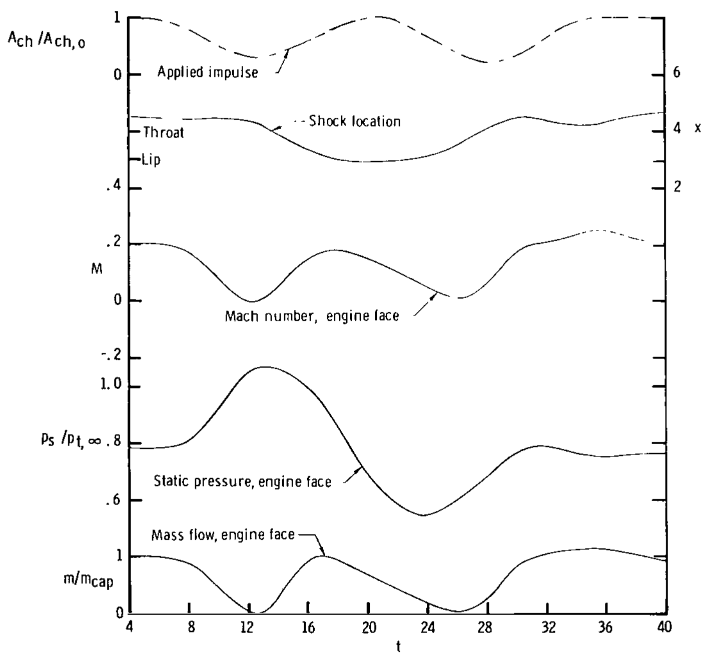


(d) Three-cycle, 10-time-unit stall; static-pressure-based on-off control; opening time, 1 unit; opens if $p_s/p_{t,\infty} > 1.02(p_s/p_{t,\infty})_{ref}$; closes if $p_s/p_{t,\infty} < (p_s/p_{t,\infty})_{ref}$.

Figure 6.- Concluded.

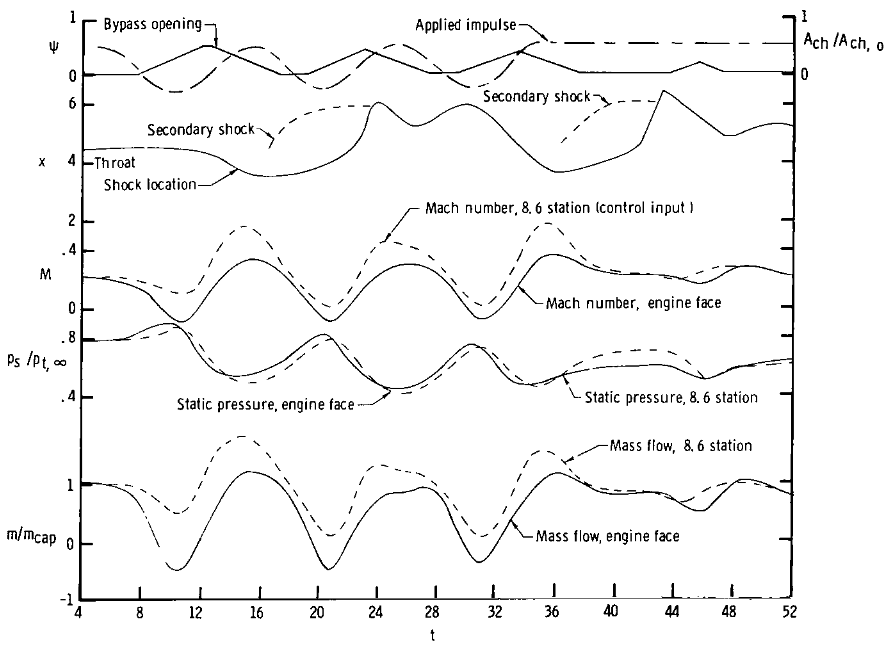


(a) Single-cycle, 30-time-unit stall.



(b) Two-cycle, 15-time-unit stall.

Figure 7.- Computed flow properties for inlet with perforated-wall control. Wall open ratio, 0.3.



(c) Multiple-impulse, 10-time-unit stall; $\delta = -0.8$; opening time, 10 units.

Figure 8.- Concluded.

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