ON THE INSTABILITY PHENOMENON OF SUPERSONIC INTAKE DIFFUSERS

by

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SUMMARY

The instability phenomenon of supersonic intake diffusers is critically reviewed and discussed. A few examples of similar unsteady aerodynamic systems in nature exhibiting the same characteristics of self-excited and sustained oscillations are discussed, in view of obtaining a better understanding of the basic mechanisms involved. Previous significant research works are critically analysed, and an effort is made to clarify the various contradictions. Methods of approach for further investigations of this problem are also given in detail.

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NOTATION

A	-	flow area
M	-	mach number
m	-	mass flow
P	-	stagnation pressure
p	-	static pressure
T	-	temperature
V	-	flow velocity
ρ	-	density
γ	-	ratio of the specific heats
R	-	gas constant
C_p	-	specific heat at constant pressure

Subscript

o	-	free stream conditions
*	-	sonic conditions
s	-	stagnation conditions
2	-	conditions at diffuser exit.

1. INTRODUCTION

1.1 General

Aerodynamic systems containing heat, mass and entropy sources are intrinisically unstable. A random stream disturbance on interacting with the source produces temperature, pressure and entropy perturbations in the steady flow. These perturbations traverse the system in the form of waves and on reflecting from the system boundaries interact with the source again. Under the proper conditions, the waves can be amplified after successive reflections and the system becomes unstable and oscillation results. Typical examples of such unstable aerodynamic systems are ram-jets, turbojets and rocket engines, a wing aileron combination, duct systems containing a centrifugal or axial-flow compressor, and supersonic inlet diffusers.

A number of previous investigations of supersonic inlet diffusers (Ref. 1-9) indicate that self-excited oscillations can exist under certain mass flow conditions. The stability limits are found to be a function of the free stream Mach number and the mass flow. That is, as the mass flow is reduced somewhat below the diffuser critical point, there is a transition from steady flow to self-excited pulsating flow. The mechanism which enables the diffuser to extract energy from the free stream is connected with the presence of the detached shock wave system and possibly through the shock wave boundary layer interaction, since these are the distinguishing features of a supersonic diffuser as contrasted to a subsonic diffuser.

1.2. Discussion of Steady State Operation

In order to obtain a clear physical picture of the instability phenomenon, it is necessary to understand the different aspects of steady operation. The essential features of the steady state operation of the supersonic diffuser can be shown quite effectively by the theory of one-dimensional gasdynamics. Although the theory is quite simple and well known (Ref. 11), it is reproduced briefly here for the insight, and intuitive feeling which the derivation affords. The following analysis follows closely to the works of Daily (Ref. 9) and Herman (Ref. 8).

1.3. Steady Flow Analysis

With reference to Fig. 1 showing a simple converging-diverging type of supersonic inlet, the steady flow characteristics of the diffuser given are based on the following assumptions:

(1) Constant total temperature throughout the diffuser, in other words all processes are adiabatic.

(2) Constant mass flow along the duct, that is, no inbleed or outbleed of mass flow occurs.

The mass flow through any section is given by:

$$\rho VA = m = \rho AM\sqrt{\gamma RT} = pAM\sqrt{\frac{\gamma}{RT}} = \frac{Apf(M)}{\sqrt{C_p}} \qquad \ldots(1)$$

Mass conservation across the diffuser is therefore expressed as follows:

$$\frac{p_o A_o M_o}{\sqrt{T_o}} = \frac{p_2 A_2 M_2}{\sqrt{T_2}} = p_o \; A_o \; f(M_o) = p_2 \; A_2 \; f(M_2) \qquad \ldots(2)$$

In terms of the stagnation condition, equation (2) can be written as:

$$\frac{p_o A_o M_o}{\sqrt{T_{s_o}}} \; \frac{\sqrt{\frac{T_{s_o}}{T_o}}}{\frac{P_o}{p_o}} = \frac{P_2 A_2 M_2}{T_{s_2}} \frac{\sqrt{\frac{T_{s_2}}{T_2}}}{\frac{P_2}{p_2}} = P_o \; A_o \; F(M_o) = P_2 \; A_2 \; F(M_2) \qquad \ldots(3)$$

Solving for the stagnation pressure ratio yields:

$$\frac{P_2}{P_o} = \frac{A_o}{A_2} \; \frac{M_o}{M_2} \; \frac{\sqrt{\frac{T_{s_o}}{T_o}}}{\sqrt{\frac{T_{s_2}}{T_2}}} \; \frac{\frac{P_2}{p_2}}{\frac{P_o}{p_o}} \; \frac{A_o}{A_2} \; \frac{F(M_o)}{F(M_2)} \qquad \ldots(4)$$

Since equation (4) can be applied between upstream and downstream sonic points (see Ref. 8, pp. 35-37), it follows that when $M_o = M = 1$

$$\frac{P_2}{P_o} = \frac{A^*_o}{A^*_2} = \frac{A_o}{A_2} \; \frac{\frac{A^*_o}{A_o}}{\frac{A^*_2}{A_2}} \qquad \ldots(5)$$

The area ratio $\frac{A_o}{A_2}$ is a dimensionless quantity representing the mass flow entering the diffuser. In practice it is convenient to use the maximum mass flow, (i.e. the critical or supercritical value) as a reference. Thus writing the area ratio in terms of the capture area yields:

$$\frac{A_o}{A_2} = \frac{A_o}{A_{o_c}} \left(\frac{A_{o_c}}{A_2}\right) \qquad \ldots(6)$$

The relative mass flow is now a measure of how close the diffuser is to its critical point. The remaining factor for a given engine is a design constant, which is specified by such requirements as the fuel-air ratio, the combustion velocity, etc.

The mass conservation condition for a diffuser therefore results in the following relations:

$$\frac{P_2}{P_o} = \left(\frac{A_o}{A_{o_c}}\right)\left(\frac{A_{o_c}}{A_2}\right)\left(\frac{\frac{A_o^*}{A_o}}{\frac{A_2^*}{A_2}}\right) \qquad \ldots(7)$$

A qualitative picture of the diffuser performance as a function of the relative flow can be obtained from equation (7) based on the shock configurations shown in Fig.2.

During supercritical operation where the shock is swallowed, (Fig. 2) the stagnation pressure ratio is determined by the plenum chamber Mach number. The stagnation pressure ratio increases as M_2 decreases by reducing the exit area. The reduction of the exit area forces the shock to move out to the inlet of the diffuser until at critical conditions the shock is just at the cowling lip. During the supercritical and critical regimes, the mass flow through the diffuser remains constant.

If the exit area is further reduced, the shock moves out of the inlet; the mass flow through the diffuser is reduced by spillage in the subsonic region between the detached shock and the inlet (Fig. 2). The shock system efficiency is about the same as that of the critical regime, but the overall efficiency is slightly increased due to lower mass flows and reduced losses in the internal passage.

Hence, based on these qualitative considerations, the diffuser performance for steady operation over a range of mass flow must be as shown in Fig. 3.

1.4. Description of the Unsteady Phenomenon

The instability phenomenon of supersonic diffusers is extremely complicated and is observed in all the different types of supersonic inlet diffusers operating at subcritical and near critical regimes. The characteristics of the unsteady processes reported for diffusers of different geometrical configuration are different, indicating that the phenomenon is a function of numerous factors, each of which can initiate the instability or alter the characteristics of the non-stationary flow processes.

The important features of the unsteady flow processes were first described by Oswatitsch (Ref. 1) in 1944 in an experimental investigation of a supersonic spike intake diffuser. He observed a large scattering of the pressure measurements and deviations from the expected analytical behaviour during the subcritical regime. Pitot tubes in the plenum chamber indicated reversed flow direction and spark schlieren photographs revealed a non-stationary and unsymmetrical configuration of the expelled shock system.

From the high speed schlieren movies of the phenomenon in a spike diffuser, (Ref. 2), the general picture of the non-stationary flow process is as follows: The normal shock is suddenly expelled from the cowling lip, moving upstream and causing spillage. The shock comes to rest at a certain position on the spike but this is an unstable one. It then moves back downstream to the cowl lip, usually with a much slower motion than during expelling. Finally, when it reaches the cowl lip, the shock is swallowed through the throat into the diverging portion of the diffuser, as indicated by the oscillograph records of the pressure transducers installed in the duct. The swallowed shock being unstable in this supercritical position with respect to the free stream conditions, moves upstream and the cycle begins again. The shock is observed to be random and only average in frequency and in amplitude of travel. During the shock oscillations, strong pressure fluctuations are recorded in the combustion chamber.

The most violent oscillations occurs at low mass flow in the subcritical regime. However, non-stability shock oscillations are also found to occur in the low supercritical and near critical regimes at high mass flow rate. The frequencies and amplitudes for both subcritical and near critical buzz depend greatly on the type of the diffuser and the engine size, and in general one cannot draw any conclusion except that the frequency and amplitude are different for the same model for the two unstable regimes.

1.5 Examples of Self-sustained Oscillations Occurring in Aerodynamic and Aero-thermodynamic Systems

To gain a better understanding of the physical mechanisms involved in the instability phenomenon of supersonic inlet diffusers, it is interesting to describe a few related aerodynamic systems exhibiting similar unstable characteristics.

1.5a. Hartmann Sound Generator

This apparatus was first discovered in 1931 by J. Hartmann and is reported in Ref. 12. Its physical and performance characteristics are summarized in Fig. 4. In essence, an organ pipe with the open end pointing upstream is inserted into a supersonic stream issuing from a choked orifice. The jet chamber pressure is substantially higher than that required to produce $M = 1$ at the orifice so that further expansion exists in the jet stream. The characteristic wavy underexpanded supersonic jet is shown in Fig.5, and is explained in detail by Prandtl (Ref. 13). The pitot stagnation pressure along the jet axis as measured by Hartmann in Ref. 12, is reproduced in Fig. 4. As the organ pipe is inserted into the jet near the orifice where $M = 1$, no instability is observed, but as it is moved downstream where M 1, instability occurs and the frequency emitted, as measured by Hartmann with a Kundt's tube, corresponds to the natural frequency of the organ pipe. Similar results are obtained by using a Hemholtz resonator.

With this organ pipe resonator, it is possible to attain frequencies of the order 200,000 cycles per second to one or two cycles per second by simply changing the resonator length. The energy radiated from the tube is of the order of 10 - 20% of the energy in the jet stream. This indicates that a significant amount of energy can be extracted from the free stream to maintain the pulsating motion.

It should be noted that the Hartman sound generator is geometrically very similar to a normal shock diffuser. Stoolman's (Ref. 10) experimental investigation on normal shock supersonic diffusers in the subcritical unstable regime produced similar qualitative results. This suggests that the unstable mechanism could be the same, but due to the simplicity of the Hartman sound generator, a more detailed theoretical treatment can be obtained.

1.5b Liquid Rocket Motors.

The liquid rocket motor is an aero-thermodynamic system in which liquid fuel and oxidizer are injected at the front end of a chamber. The fuel combines chemically with the oxidizer forming a high pressure and high temperature gaseous mixture, which expands through a nozzle at the aft end of the chamber, producing thrust. As the fuel flow is increased above a certain critical value, high frequency self-excited oscillations are observed of the order of the natural acoustic frequency of the chamber.

In Crocco's analysis of rocket motor instability (Ref. 14), it is shown that a pressure sensitive fuel feeding system is not a necessary mechanism for inducing the self-sustained oscillations. He explained that the oscillations are initiated by the interaction of a random flow disturbance with the flame zone (a source of heat, mass and entropy), producing corresponding perturbations in the pressure, temperature and entropy from their steady values. These perturbation quantities traverse the system in the form of waves, and on reflecting from the nozzle exit, propagate upstream to interact with the source again. Successive reflections lead to amplification, and the proposed mechanism for the wave amplification is linked with the time lag involved in the production of combustion gases from the liquid fuel and oxidizer, and the time required for the disturbance waves to traverse the system and back. Under the proper conditions, the two time constants are matched, and the oscillations are in phase, increasing in amplitude until the limit where viscous damping becomes predominant. Other works on the instability in aerodynamic systems containing a heat and mass source are reported in Ref. 15 and 16.

Although a supersonic diffuser is a pure aerodynamic system with no heat addition, the mechanism of wave amplification by successive reflections from the ends of the system (as in a rocket engine), could be a mechanism for initiating and sustaining the non-stationary flow.

There are numerous other aerodynamic systems which are unstable and capable of self excited oscillations. The phenomenon of airplane flutter is another typical example analogous to the instability of supersonic intakes where energy is extracted from the free stream to sustain the oscillations. Hence a careful study of the characteristics of other related systems can be extremely helpful in analysing the present problem of supersonic intakes.

1.6 Effects of Pulsating Flows in Supersonic Diffusers

Instability in supersonic diffusers occurs mostly in the subcritical and the near critical regimes, and only the subcritical 'buzz' is found to be the most detrimental due to its large pressure amplitudes. These unstable regimes, however, cannot be avoided in practice, say, in the manoeuvering of the aircraft. The pressure oscillations can result in serious structural, as well as combustion, instability problems of the engine. Even in the less severe cases where the pressure amplitudes are small, great losses in the overall performance of the engine results. Inspite of the considerable research in the past on this problem, the basic mechanisms are not fully understood and explored. The author feels that further investigations are needed and future work should be directed more towards the analysis of simple related systems to eliminate as many variables as possible so that the more basic mechanisms can be singled out. Such approach will be more fruitful towards the main goal of understanding this important phenomenon.

2. REVIEW OF PREVIOUS SIGNIFICANT INVESTIGATIONS

A number of investigations, both theoretical and experimental, have been carried out during the past two decades, increasing both the knowledge of the unsteady phenomenon and also the confusions and contradictions among theories proposed by different investigators. This is due to the large number of variables involved, such as the geometry of the diffuser and combustion chamber. It would therefore be unrealistic to expect that one general theory can predict the phenomenon in all the different types of diffusers. The conclusions of a few significant investigations will be critically reviewed and discussed below.

2.1. The Vortex Sheet Theory

Ferri and Nucci in 1951 (Ref. 2) proposed that the starting of the instability is related to the existence in the flow field of a velocity discontinuity or a vortex sheet which originates at the shock intersection. The theory of oblique shocks indicates that such a vortex sheet must exist behind any "triple point" of shocks, the point where two oblique shocks meet to form a third one of strong intensity. The streamline passing through the triple point divides the flow field downstream of the shock system into two regions. One region where the stream-lines have passed through two oblique shocks, and one region where the streamlines only passed through one shock. Immediately adjacent to the separating streamlines the resulting streamline deflections through the shock are equal, hence the entropy increase across the shocks must be different in the two regions. Consequently, the entropy and the total pressure are different in the two regions, but the static pressure must be equal on both sides of the streamline hence a velocity discontinuity results. The dividing streamline is a vortex sheet, or often termed a "velocity discontinuity" or "entropy discontinuity" layer.

Ferri and Nucci postulated that instability starts when the vortex sheet just enters the cowling lip, causing separation on the inner wall of the cowling and chokes the diffuser. When separation of the boundary layer occurs on the cone of the spike inlet, a strong lambda shock is formed resulting in the formation of a vortex sheet entering the inlet. The geometrical configuration of the shock system and the generation of the vortex sheet as discussed above are shown in Fig. 6. It should be noted that Ferri and Nucci's experimental investigation is only limited to spike inlets.

Later C.L. Daily (Ref. 9) further investigated the oscillatory motion in inlet diffusers with particular emphasis on the frequencies involved. Again, his investigations are limited to spike diffusers. His experimental models all have large length; between 18 and 26 times the plenum chamber diameter. He observed that the instability processes are a mixture of two different phenomena. One is a high frequency oscillation

(500 to 900 cps) occurring mostly at very low and zero mass flow. The other is a longer period motion appearing at higher mass flows. The high frequency oscillation can be correlated to the 8th and 9th modes of a closed end organ pipe. The oscillation being so remote from the fundamental mode suggests that the frequency is determined by some forcing mechanism such as the vortex shedding from the sharp cowling lip. Daily's explanation of the initiation of the low frequency buzz is due to a strong interaction between the subcritical shock and the boundary layer on the cone surface which blocks the inlet. Further explanation of the oscillation is based on the concept of periodic unbalance of mass flow between the two throats as explained later in section 2.5.

2.2. Hemholtz Resonator Theory

Sterbentz and Evvard (Ref. 3) gave a theoretical acoustical approach to the buzz problem by treating the diffuser and combustion chamber as a Hemholtz resonator. With this simplified analysis, they concluded that if the curve of the diffuser pressure recovery as a function of mass flow has a positive slope of sufficient magnitude, the diffuser system will resonate. The critical slope can be calculated, and depends on the diffuser and combustion chamber geometry and also the Mach number in the combustion chamber entrance. When operating at mass flows where the slope of the curve is less than the critical value, the combustion chamber will not resonate. Their experimental investigation on two spike ram jet models of 8 inch and 16 inch diameter, in the Mach number range of 1.5 to 2.0, shows good agreement with their theoretical predictions.

Later Sterbentz and Davids (Ref. 4) presented a refinement of the diffuser resonator theory (Ref. 3). In order to obtain the variables which govern the pulsation amplitudes, finite amplitude disturbances were assumed, which require a point to point calculation throughout the cycle of oscillation. Theory and experiments show that the buzz amplitude increase with decreasing mass flow. The theoretical trends for change in amplitude, frequency and mean pressure recovery with a change in plenum chamber volume were also experimentally verified. A stability hysterisis loop was predicted on the pressure recovery mass flow curve for convergent-divergent perforated diffusers This hysterisis has been observed experimentally. They conclude by linking the phenomenon with the surging in duct systems containing a centrifugal or axial compressor.

2.3 Quasi One-dimensional Unsteady Flow Theory

Later Trimpi (Ref. 5, 6) investigated the buzz problem again experimentally by pressure transducers installed in the diffuser and proposed that the buzz phenomenon can be explained by quasi-one-dimensional unsteady flow theory. He criticizes Sterbentz and Evvard's (Ref. 3) theory by arguing that the proportions of the internal flow passages suggest a quasi one-dimensional theory with slight variation of the moving waves from the plane form, rather than a Hemholtz resonator type theory based on spherical waves caused by large abrupt area changes. His experimental models were of large lengths, 20 to 250 duct diameter hence introducing severe viscous effects. He found that it was necessary for him to use some experimental data at the start of the cycle as a basis to compute the remaining pressure points of cycle by the one-dimensional non-stationary method of characteristics. Good correlations were obtained from his experiments.

Later Trimpi (Ref. 6) presented an approximate theory for predicting the amplitudes of small pressure pulsations, which was derived on a linearized one-dimensional acoustical basis. He concluded that stability of the inlet flow is dependent on the instantaneous values of mass flow and total pressure recovery of both the supersonic diffuser and the immediate neighbouring subsonic diffuser, and that blocking or choking of the inlet is not a necessary factor in initiating the instability phenomenon. This is quite contradictory to Daily's (Ref. 9) results.

2.4 Acoustic Impedence Theory

By considering successive reflections and amplifications of a weak pressure pulse from the inlet and the nozzle exit, a stability criterion was proposed by Stoolman (Ref. 10), and later by Mirels (Ref. 17). This analysis was based on the acoustic impedence of the inlet. Stoolman's theoretical and experimental investigations were limited only to the open nose or normal shock diffuser where severe viscous effects and boundary layer separation can be avoided. He concluded that self-excited oscillation can occur without considering viscous dissipation in the flow other than that across a normal shock. A lower limit for the free stream Mach number was observed in which no instability could be detected. The frequencies of the self-excited oscillations were approximately equal to the natural frequency of the internal duct acting as an organ pipe resonator (i.e. on quarter wave length). One important observation, which contradicts Ferri's (Ref. 2) and Daily's (Ref. 9) work, is that the flow within the diffuser just before the onset of instability, as well as that in the neighbourhood of the inlet lip showed no significant viscous dissipation effects.

From his theoretical analysis, Stoolman concluded that a necessary condition for the existence of instability is that the ratio of the amplitudes of the reflected and impinging waves at the diffuser inlet be greater than one. In terms of the boundary conditions at the inlet, this implies that the transfer function (ratio of pressure to velocity perturbations, Ref. 18) is positive there. Increasing the mass flow through the diffuser has a double effect in eliminating the instability since it reduces the amount of diffusion in the inlet regime and also decreases the amount of wave motion energy reflected at the end.

Mirels (Ref. 17) followed the same basic treatment as Stoolman and extended it to the case where heat addition exists in the combustion chamber. He pointed out that the stability criterion still holds if the inlet is replaced by a compressor and thus demonstrated the similarity to the surging phenomenon in duct systems with a compressor. It should be noted that Pearce (Ref. 19) also pointed out this similarity. Mirels' conclusions are basically similar to those of Stoolman's.

Later Chang and Hsu (Ref. 7), following the same treatment as Stoolman's solved the basic equations for the external flow regime analytically as compared to Stoolman's numerical solution, and concluded that self-excited shock oscillation is not possible in the absence of viscous dissipation. Flow instability is found to be due to further entropy generated by viscous dissipation in addition to that due to shock oscillations. This contradicts Stoolman's conclusion. However, the neutral stability boundaries as obtained in terms of the ratio of perturbation entropy to the corresponding shock velocity are in agreement with Stoolman's experimental results. Chang's analysis confirms Trimpi's theory (Ref. 5) of instability and also justifies the Sterbentz-Evvard theory (Ref. 3) in the range of steady subcritical operation.

2.5 Periodic Unbalance of Mass Flow Theory

This explanation of the buzz phenomenon is given by Hermann and Hsu (Ref. 20) from their experimental investigation on spike inlet diffusers. They termed the diffuser with internal contraction a "two throat system". The first throat is the diffuser throat, the second, the exit nozzle throat. The origin of instability then is related to the possibility of shock swallowing and mass choking. The important regimes as functions of the two throats and the various conditions for instability are described in detail in Ref. 20. The essential mechanism is simply a sudden offset from the stable mass flow condition, caused by, say, a pressure disturbance interacting with the shock system causing an increase in spillage. This initiates a periodic unbalance of mass flow between the two throats resulting in oscillations. No theoretical work on this theory was presented.

3. ANALYSIS OF THE PHENOMENON FROM PREVIOUS INVESTIGATIONS

From the brief review given in section 2, one can observe that quite a number of theories have been proposed concerning both the origin and the characteristics of this instability phenomenon. Together with the vast amount of experimental data resulting from these investigations, a general confusion of the basic mechanism of the unsteady flow processes is created. The main reason for this, in the author's opinion, is that this phenomenon is extremely complicated and is a function of numerous variables. Therefore, formulating one general basic theory, based on the experimental observations of one particular model of diffuser, and in a certain Mach number range, can only at its best, result in a unique theory in explaining the "buzz" phenomenon for that particular model, the particular size tested and for only within that Mach number range. An example of this is the vortex sheet theory proposed by Ferri and Nucci (Ref. 2), which states that buzz is initiated when the vortex sheet generated at the shock triple point enters the cowling lip into the inlet causing separation and choking of the inlet flow. This theory is formulated from their experimental investigations on spike inlet which exhibit the shock configuration generating this vortex sheet at subcritical flow conditions (see Fig. 6). However, in another type of diffuser, such as a normal shock diffuser, the geometrical configuration cannot produce a vortex sheet at subcritical flow conditions, hence this vortex sheet theory cannot be applied to other types of diffusers other than the spike or central body type of supersonic inlet. One may again argue that in the supercritical flow regime in a normal shock diffuser where the shock is swallowed, a strong shock boundary layer interaction is capable of generating such a vortex sheet at the triple point of the lambda shock. However, the strength of the vortex sheet formed in this manner is weak, and even if it is strong enough to cause separation and initiate the instability phenomenon, the resultant unsteady flow processes will be qualitatively, quite different from subcritical buzz. Besides, supersonic diffusers are found to be stable in the supercritical regime, and from Stoolman's (Ref. 10) experimental investigations on normal shock diffusers, no significant effects of viscous separation in the flow within the diffuser, during the supercritical regime are observed.

From the above example, one can conclude that there is more than one mechanism that can initiate the non-stationary flow in a supersonic diffuser. Depending on the geometrical configuration of the diffuser and the Mach number range, one mechanism might be more dominant than the other. The remaining part of this section will be devoted to correlating the various theories of previous investigations, paying particular attention to the different types of diffusers and their geometrical configurations. An attempt is made to classify these possible machanisms according to the physical processes that can be involved.

3.1 Origin due to Viscous Effects

From the results of all the previous investigations, the origin of "buzz" in a supersonic diffuser can be generalized into the main types: one due to viscous dissipation effects and the other due to the interaction of pressure disturbances with the shock system. As pointed out before, these two types of mechanism can be present at the same time, but the classification given here is based on the geometrical configuration of the diffuser, whereby one is more dominant than the other, or one is completely absent. It should also be noted that the two mechanisms can be related to each other as will be discussed in a later section.

In spike or centre body diffusers, viscous effects are relatively more important than in normal shock diffusers. The boundary-layer on the cone surface due to separation increases the central body wake in the diverging portion of the diffuser (see Fig. 7). Hence the core flow velocity in the annular subsonic diffuser will increase, reducing the pressure in the plenum chamber. If this flow were to mix completely before reaching the exit nozzle, a decrease in both the local stagnation pressure and the static pressure and hence a corresponding decrease in exit mass flow rate results. The resultant mass accumulation in the plenum chamber sends an upstream compression wave towards the inlet, forcing the shock outwards, causing spillage, and relaxing the accumulated mass. The expelled shock, being unstable once the mass is relieved, travels downstream again and the cycle repeats. In the more severe cases, the separation of the boundary layer on the central body surface can choke the inlet causing an upstream movement of the shock and the flow can momentarily by-pass the inlet altogether.

A strong shock wave boundary layer interaction can also cause separation and choke the inlet. The vortex sheet generated at the shock triple point when entering the cowl lip can also initiate separation. This mechanism agrees with the investigations of C.L. Daily (Ref. 9) and Ferri and Nucci (Ref. 2). Sterbentz and Evvards' (Ref. 3) theory of the Hemholtz resonator and their stability criterion based on the diffuser pressure recovery and mass flow curve having a positive slope of sufficient magnitude also falls into this category. This is because a large positive slope on this curve means a high adverse pressure gradient imposed on the boundary layer resulting in separation.

3.2. Origin due to Pressure Disturbances Interacting with the Shock System

Normal shocks in ducts are found to be unstable and capable of self-excited oscillations (Ref. 21). If the duct is terminated by a choked nozzle at the exit, the shock motion introduces a mass unbalance, generating pressure waves which interact with the shock again on reflecting from the nozzle exit, increasing its amplitude. The mechanism for initiating the self-excited oscillation of the normal shock is as follows: Consider a random stream disturbance in the form of a pressure wave or a temperature wave impinging on the downstream side of the shock. The flow properties are offset from their equilibrium values as determined from the Rankine-Hugoniot relationships. To achieve equilibrium, the shock strength must increase or decrease depending on whether the disturbance is in the form of a compression or a rarefaction wave. This can only be possible through a motion of the shock itself so that the relative velocity of the flow with respect to the shock is changed.

In a duct system such as a diffuser, during subcritical operation, the normal shock is stabilized downstream of the throat in the diverging section. A pressure disturbance, such as a compression wave, originating from the downstream side of the shock, on interacting with the shock, forces upstream. However, a further upstream shock position in a diverging duct results in the shock occurring in a lower Mach number region hence a weaker shock, and the shock will therefore be forced back to its original position. This supercritical shock position is stable unless the pressure disturbance is of such magnitude that it can force the shock past the throat whereby it is expelled. The resulting shock oscillations, will therefore be damped out and the flow is stable until the next disturbance that can force the shock out. This explains the relaxation type of oscillations observed at high mass flows where bursts of shock oscillations occur at random intervals. At subcritical flow, the normal shock is detached from the diffuser. Hence pressure disturbances interacting with the shock cause a change in the spillage of mass flow due to the shock motion. This change in mass flow generates pressure waves which traverse the diffuser duct system and under the proper conditions can be amplified and initiate the unstable flow processes. This type of mechanism is proposed by Stoolman (ref.10) and agrees qualitatively to his experimental investigations on normal shock diffusers.

Before closing this discussion on the mechanisms of supersonic diffusers instability, the relationships between the generation of pressure waves and viscous effects in duct flows must be mentioned. Pressure waves are generated whenever the local flow properties such as pressure, density or temperature are changed. Hence, it is obvious that the boundary layer build up in a constant area duct flow reduces the effective flow area, and changes in the flow properties then result. Changes in fluid properties are accomplished by a transient phenomenon in the form of waves, propagating at the local speed of sound throughout the rest of the fluid. Therefore, the boundary layer build up causes a continuous change in the effective flow area, hence fluid properties, and waves are generated. In the case of supersonic flows, the waves generated are swept downstream while the upstream conditions are uneffected and for the subsonic region waves can propagate in both upstream and downstream directions. It should be noted that waves generated by the boundary layer build up are very weak unless separation occurs where the flow area is substantially and abruptly reduced.

The above discussion is for straight ducts. For nozzles and diffusers where the duct area continuously changes the local fluid properties also change and waves are generated continuously as a result. The Mach lines or the expansion waves system in a supersonic nozzle can be easily observed from a schlieren photograph and these waves are generated as a result of changes in flow area.

Hence, it can be summarized that the whole problem of supersonic diffusers instability can be traced to two main mechanisms: the generation of transient waves and the subsequent effects of these waves on the system.

4. METHODS OF APPROACH FOR FURTHER STUDIES

From the extensive literature survey of previous investigations, of which the significant ones are reviewed in section 2, one can observe that much progress has been achieved in the study of the origin of the instability phenomenon of supersonic inlet flows for various different types of diffusers. However, in order to use this knowledge so acquired in the design of supersonic diffusers and the suppression of this undesirable phenomenon, it is necessary to study the basic mechanisms of the unsteady shock oscillation processes in a converging-diverging duct. It has been observed that during "buzz" the shock is alternately swallowed and expelled irrespective of the flow regimes in which the buzz is first initiated. Hence an investigation of the shock expelling and swallowing processes, and the conditions when this can occur, is necessary to further an understanding of the phenomenon during the unsteady flow processes. The method of damping out the shock motion will also be investigated in detail.

In Ref. 21, Kantrowitz investigated the stability of normal shock to stream disturbances in a converging-diverging duct and concluded that the shock is stable in the diverging section but not in the converging section. However, he did not study the expelling and the re-swallowing processes and the resultant mass flow perturbation on the self-sustained oscillations. This, the author believes is the most important process in buzz phenomenon and further investigations must be carried out both theoretically and experimentally.

Later Neice (Ref. 22) investigated the stability of shocks in a converging-diverging duct and proposed that mass removal by means of a surge tank could damp out transient shock motion caused by pressure disturbances originating downstream of the shock. With the same method of approach the author will further investigate the effectiveness of this method of damping the shock motion in the ducts during the unsteady shock oscillation and also the effect of mass removal on the performance of the diffuser. The work in reference 22 will be further extended to the case where the pressure wave originates from upstream in the supersonic region where it impinges on the upstream side of the shock.

Due to the complexity of this problem, the proposed investigations will be sub-divided into several phases such that the results obtained from each of these separate phases will supplement one another. Finally the results can be correlated together. Both theoretical and experimental work will be performed for each of the different phases of this investigation. The division of this programme into separate parts will be as follows:

4.1 Detailed Study of the Self-sustained Oscillation of the Swallowing Processes in a Converging-Diverging Duct

The model chosen for this phase of the investigation will be a simple converging-diverging supersonic diffuser followed by a short plenum chamber and an exit nozzle. The analysis will be based on the supercritical or high mass flow operating regime of the diffuser where the shock is swallowed and stabilized at the diverging section of the diffuser downstream of the first throat. In this supercritical operating regime, the shock is expected to be stable, and the investigation will be carried out on the interaction of a finite amplitude pressure pulse with the shock causing it to be expelled from the diffuser Being unstable in the expelled position, the shock will be swallowed again and will perform a series of relaxation cycles of oscillation before its motion will be finally damped out. The interaction of a strong pressure pulse with the shock and its subsequent motion, the expelling process once the shock is forced past the throat to the converging section, the re-swallowing process of the shock and the oscillations before the shock motion can be damped out will be investigated in detail both theoretically and experimentally.

Part II of this phase will investigate the self-sustained oscillation of the shock when the flow conditions are adjusted so that the shock is stabilized at a position very near the throat and is unstable to very small amplitudes of pressure disturbances. The mechanism for the extraction of energy from the flow by the shock to maintain the oscillation will also be investigated.

The experimental model of this phase of the investigation will be a simple, constant area converging-diverging supersonic diffuser with suction applied at the throat to control the shock location. A two dimensional model will be used and the non-stationary processes will be studied by means of high speed schlieren movies and pressure transducers.

4.2 Shock Damping by Mass Removal

The second phase of this investigation will be concerned with the damping of shocks by means of mass removal. When a normal shock propagating in a constant area channel reaches a sudden opening to a large volume at a lower pressure, the difference in pressure between the region behind the shock and the surge tank causes a mass outflow to the tank. Hence, the pressure behind the shock is reduced and the generated rarefaction waves catch up with the shock and weaken it. The shock attenuation due to mass removal in a two-dimensional duct will be investigated in detail by the method of characteristics of one-dimensional unsteady flow.

The experimental model for this part of the investigation will be a constant area two-dimensional channel. The shock is generated by a conventional shock tube. Shock attenuation will be measured by means of pressure transducers and schlieren streak photographs will be used to study the wave interactions.

4.3 The Damping of Shock Oscillations in a Diffuser by Means of Mass Removal

The final phase of the investigation will make use of the results of the two studies described above. The effectiveness of shock damping by mass removal in an actual diffuser will be critically examined. Its feasibility in actual practical application will be discussed with quantitative results in mind. The effectiveness of mass removal at only one section of the diffuser or at several locations will also be analysed. With the completion of this investigation it is hoped that a further understanding of the instability phenomenon of supersonic diffusers can be obtained.

5. CONCLUSION

A discussion of the instability phenomenon in supersonic diffusers has been presented and a few examples of self-sustained oscillations in related aerodynamic systems have been given to show the similarities of the unstable phenomenon. A review of significant previous investigations is given in Section 2. The origin of instability are critically analysed in Section 3 with special emphasis on the geometrical configuration of the diffuser. It is then classified into two basic mechanisms, one due to viscous effects and one due to the interaction of pressure disturbances with the shock system. The relationships between the two are pointed out and the conditions when one is more dominant than the other is linked with the geometry of the diffuser.

Methods of approach for further investigations are presented in detail in Section 4. The importance of the self-sustained oscillation of the shock expelling and swallowing processes is pointed out. The study of the damping of shock oscillations in a diffuser by means of mass removal is emphasized in the proposed programme.

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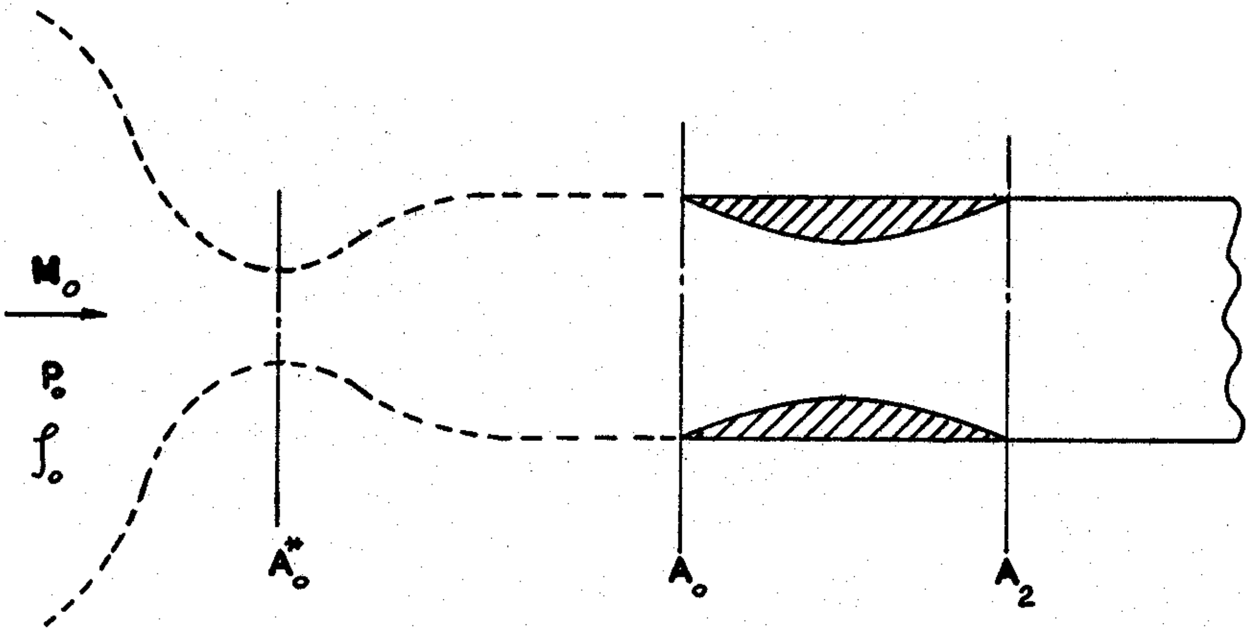

FIG. I SCHEMATIC SKETCH OF A CONVERGING – DIVERGING SUPERSONIC DIFFUSER

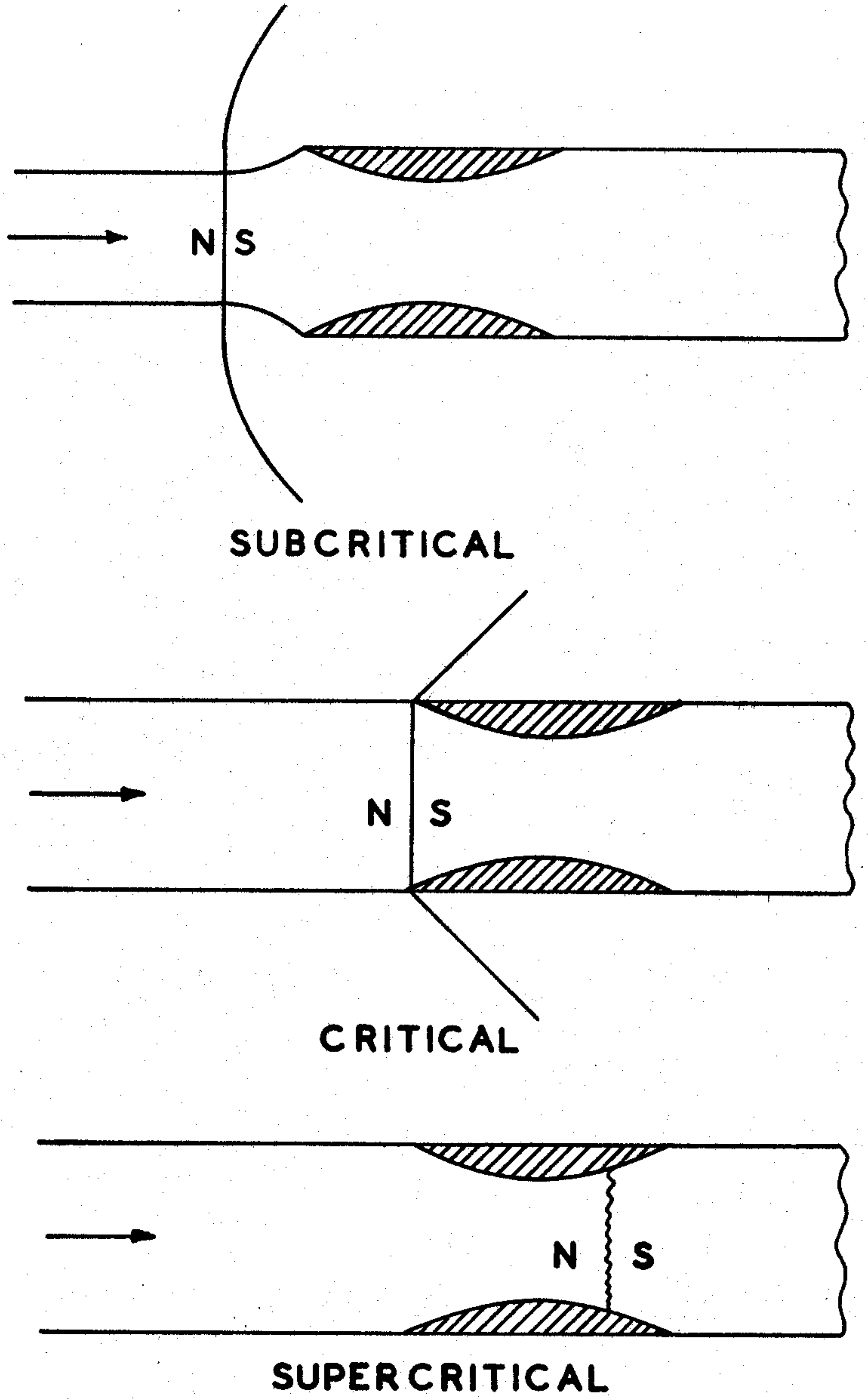

FIG. 2 OPERATING REGIMES OF A SUPERSONIC DIFFUSER

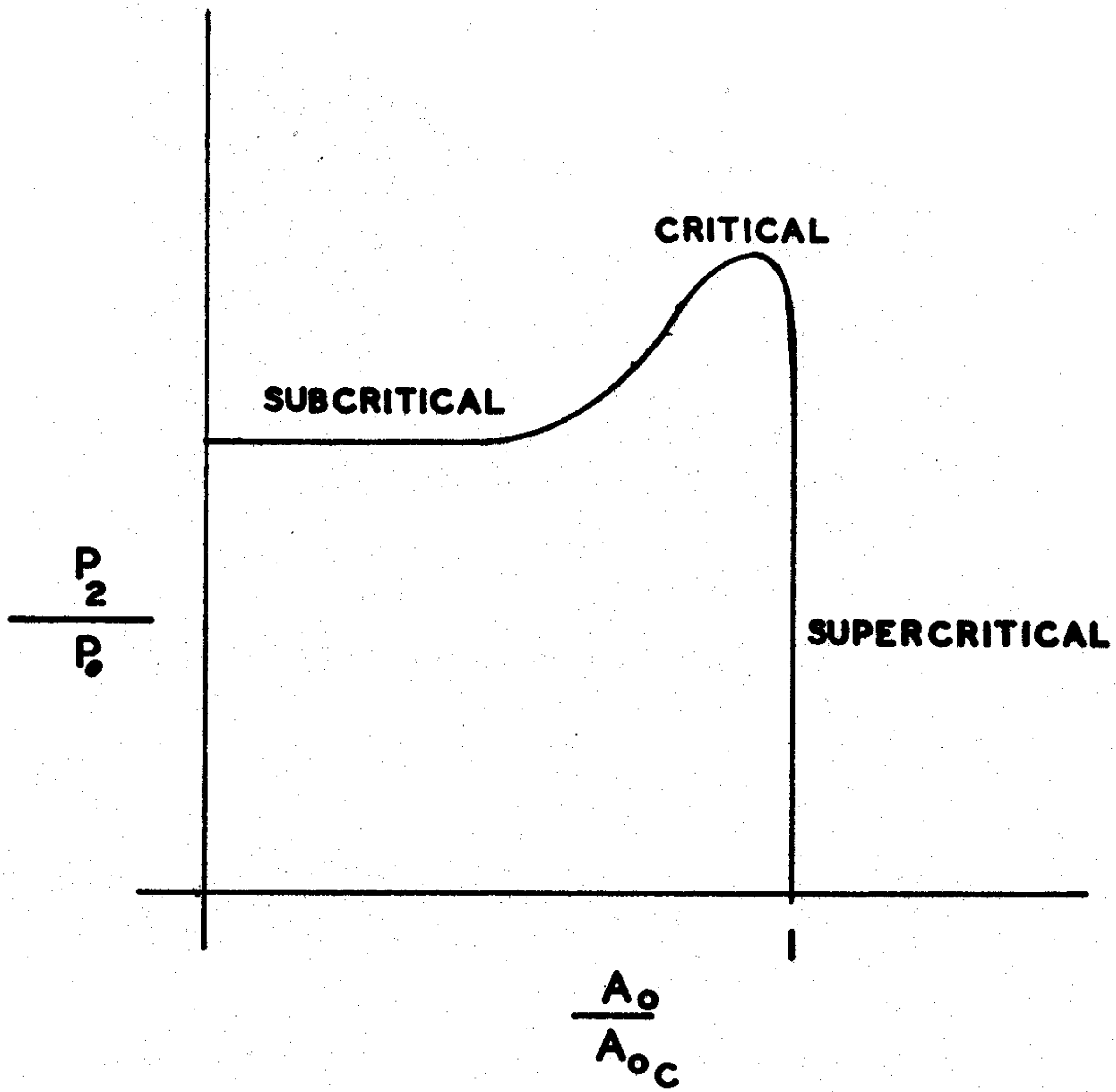

FIG.3 TYPICAL DIFFUSER PERFORMANCE CURVE

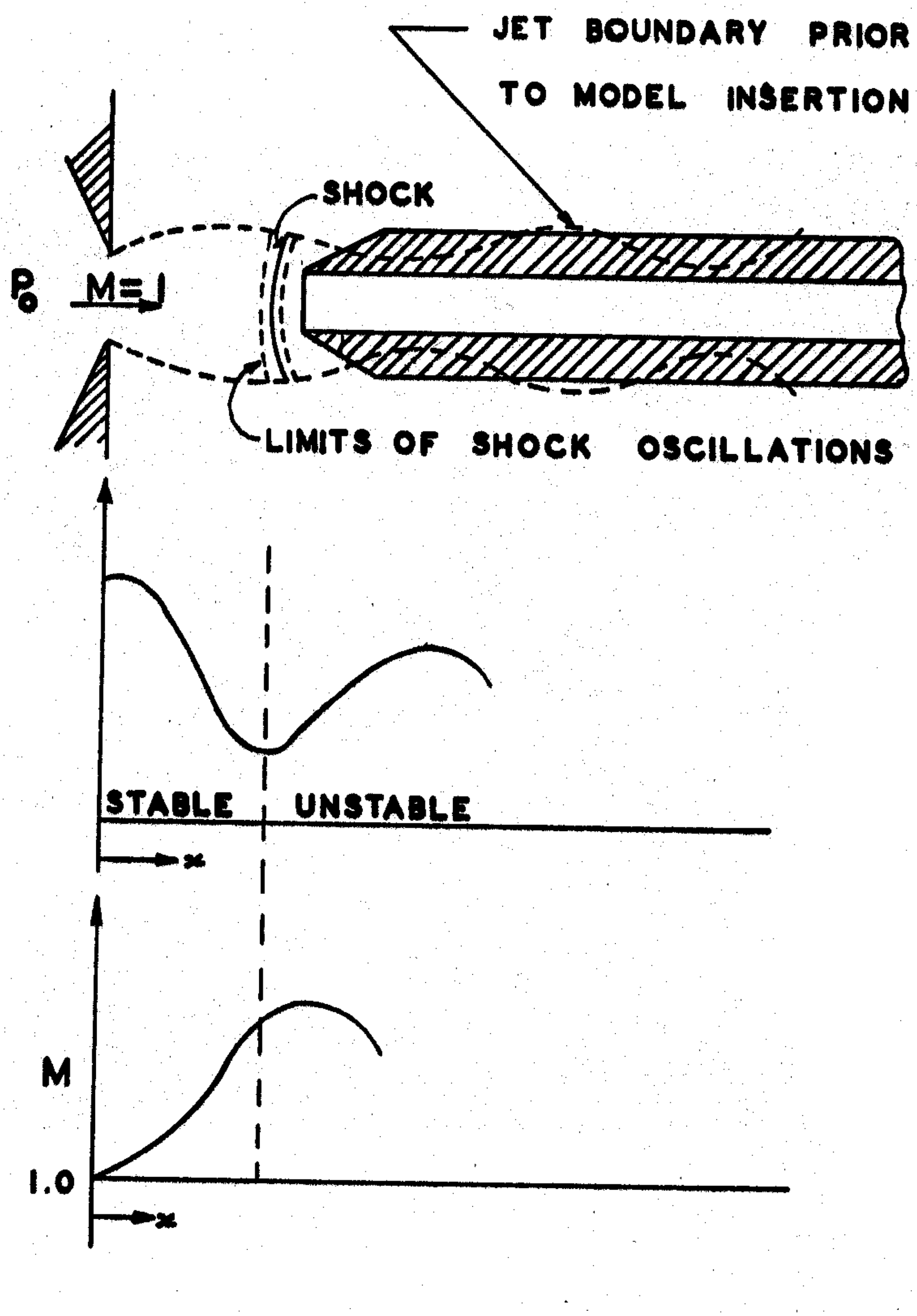

FIG. 4 CHARACTERISTICS OF THE HARTMANN SOUND GENERATOR

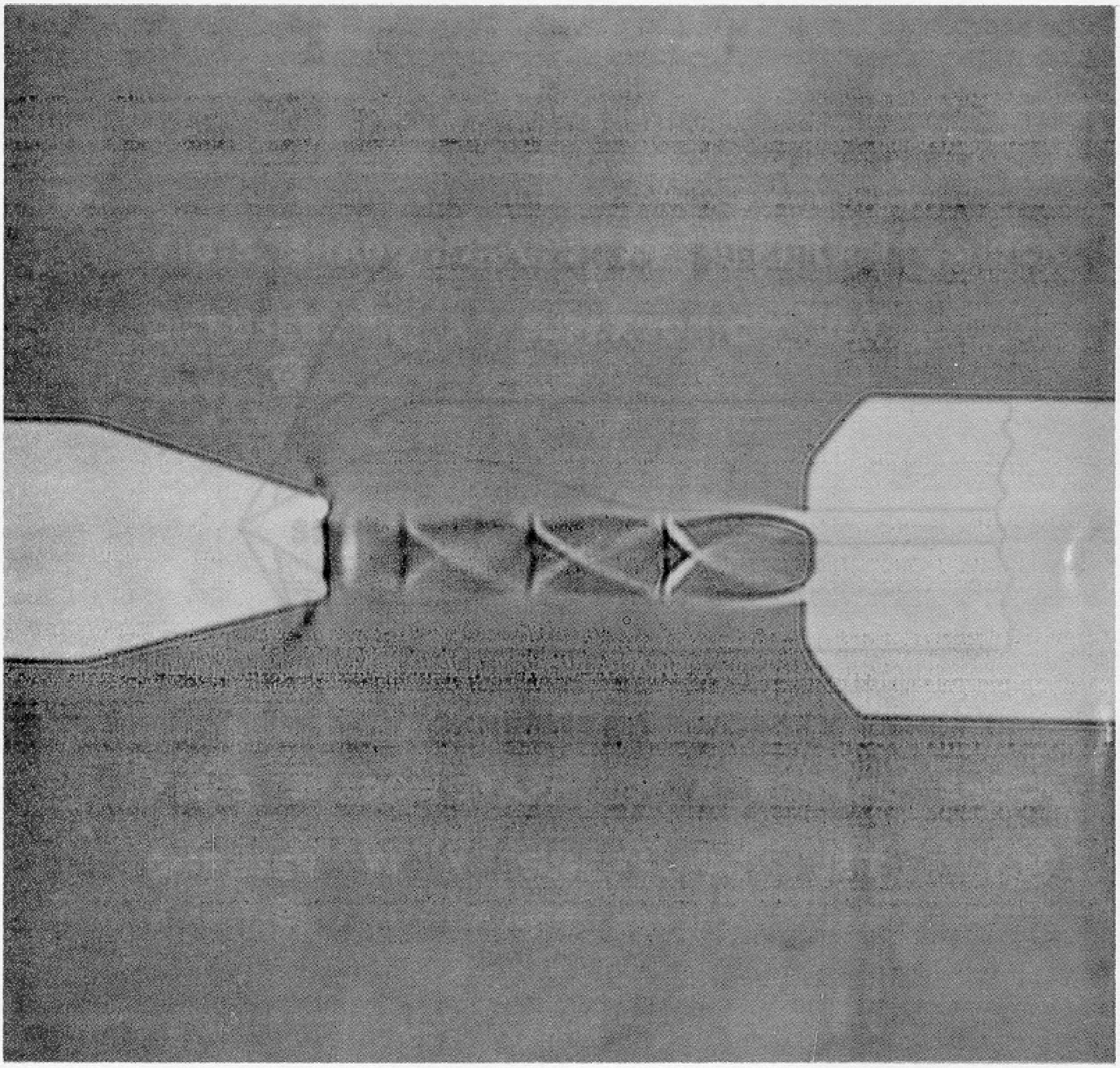

FIG. 5 SHADOWGRAPH OF A NORMAL SHOCK DIFFUSER IN A SUPERSONIC JET.

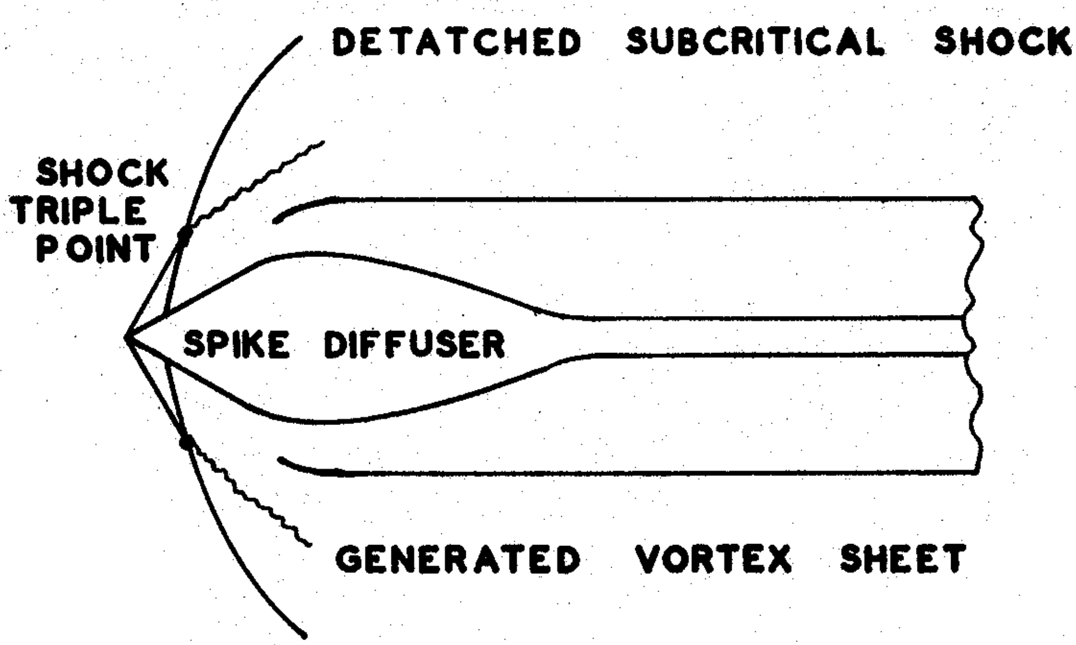

FIG. 6 SHOCK CONFIGURATION AT SUBCRITICAL OPERATION FOR A SPIKE DIFFUSER

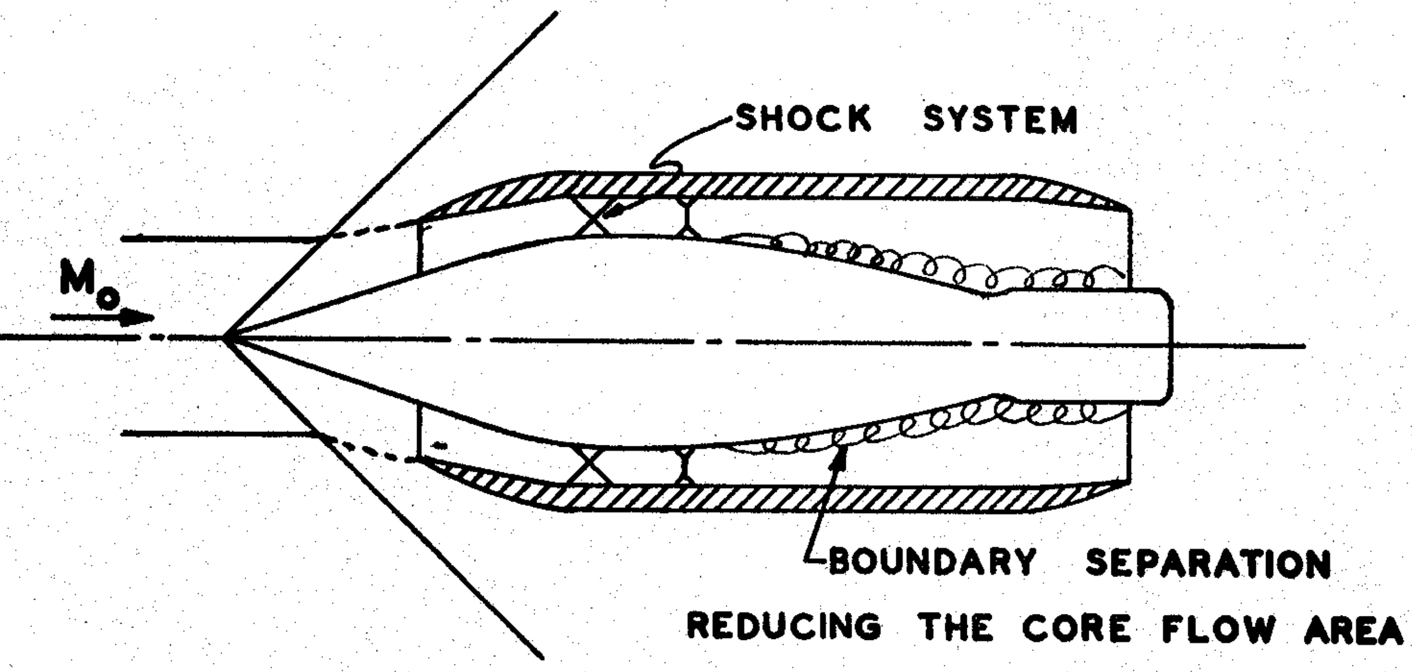

FIG. 7 DIFFUSER AT SUPERCRITICAL OPERATION
SHOWING BOUNDARY LAYER SEPARATION