On the Comparison of the Long Penetration Mode (LPM) Supersonic Counterflowing Jet to the Supersonic Screech Jet

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The authors provide a brief overview of the classic tonal screech noise problem created by underexpanded supersonic jets, briefly describing the fluid dynamic-acoustics feedback mechanism that has been long established as the basis for this well-known aeroacoustics problem. This is followed by a description of the Long Penetration Mode (LPM) supersonic underexpanded counterflowing jet phenomenon which has been demonstrated in several wind tunnel tests and modeled in several computational fluid dynamics (CFD) simulations. The authors provide evidence from test and CFD analysis of LPM that indicates that acoustics feedback and fluid interaction seen in LPM are analogous to the aeroacoustics interactions seen in screech jets. Finally, the authors propose applying certain methodologies to LPM which have been developed and successfully demonstrated in the study of screech jets and mechanically induced excitation in fluid oscillators for decades. The authors conclude that the large body of work done on jet screech, other aeroacoustic phenomena, and fluid oscillators can have direct application to the study and applications of LPM counterflowing supersonic cold flow jets.

Nomenclature

A_b	=	area of annular reflective surface surrounding the nozzle
A_n	=	nozzle exit surface area
F	=	a force
$m\text{-}dot$	=	mass flow rate
M	=	Mach number
$M\infty$	=	freestream Mach number
p_0	=	freestream pressure
p_j	=	jet exit pressure
Re	=	Reynolds number
W	=	work
x	=	a displacement
ω	=	angular velocity

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I. Introduction

PREVIOUS work by Daso et al.[1] and Chang et al.[2-4] describes the effects observed in test and modeled computationally when a supersonic underexpanded jet of unheated air is inserted into a supersonic freestream, in a direction of flow counter to the freestream. This work describes the existence of two jet shock structure modes reported by several earlier NASA researchers,[5-7] characterized as either short penetration mode (SPM) or long penetration mode (LPM).[8,9] While the SPM of counterflowing supersonic retropropulsion jets is well documented, this paper focuses on the lesser known and not-so-well-understood LPM due to its unusual interaction with the supersonic freestream boundary interface observed in wind tunnel tests.

Under certain jet flow conditions,[1,2] LPM can extend well forward of the nozzle into the supersonic freestream, where it modifies the nature of the supersonic compression shock boundary. As observed in wind tunnel testing,[1] LPM is inherently unsteady but maintains itself indefinitely under a fairly broad range of conditions and is not a transient phenomenon.

Full 3-D, time-accurate,[*] and axisymmetric computational fluid dynamics (CFD) studies of LPM[2-4] have shown the underexpanded LPM jet creates a subsonic volume of air in the vicinity of the jet, which is surrounded and encapsulated by the supersonic freestream. Animations of 3-D CFD results[10] show oscillations and complex flow patterns in the subsonic shear layer and associated acoustic waves in the subsonic region surrounding the LPM jet.

In this paper, we examine the aeroacoustic characteristics of LPM and compare it to the aeroacoustic supersonic jet screech noise mechanism. We then describe previous work in the area of movement-induced excitation (MIE) in a fluid oscillator (resonator), including jet screech noise, that may be applied to LPM and aid in its understanding and practical applications.

II. Overview of the Classic Jet Screech Aeroacoustic Noise Problem

Supersonic jet screech noise is a long-studied and well-understood aeroacoustics problem. It can occur spontaneously when underexpanded jets emanating from supersonic nozzles in air impinge on a wall or other physical interface to produce an acoustic feedback loop, resulting in undesirable high-amplitude tonal screech noise similar in volume and frequency to feedback in an electronic microphone system. In worst case situations, jet screech noise can adversely affect hardware in the vicinity of the jet, and many studies over the years have been dedicated to understanding and mitigating this troublesome noise phenomenon. Numerous sources on jet screech are referenced herein at the end of this paper.

The jet screech physical amplification mechanism is based in an acoustic feedback loop.[11] The underexpanded nature of the jet flow allows the shear layer of the jet to become unsteady. At some point downstream from the nozzle, usually in the third or fourth Mach cell, sound waves are emitted at some characteristic frequency. These sound waves travel back at the local speed of sound towards the nozzle lip where they can resonate and interact with the jet emanating from the nozzle to modulate the oscillations in the shear layer, and an acoustic resonance amplification feedback loop is established.

Rockwell and Naudascher[12] describe the supersonic jet impingement and noise generation as follows:

"In this case, the $M > 1$ expansion region of the jet terminates in a shockwave structure indicated (below in Fig. 1) by the bold black line upstream of a solid cylindrical obstacle containing no cavity. One can imagine that the perturbations of the shockwave could give rise to upstream and downstream travelling waves within the subsonic $M < 1$ region of the shock-obstacle domain, and potentially set up the equivalent of a closed-closed organ type resonance… L. Powell (1988) postulates a mechanism of oscillation in which the unstable shockwave responds to reflected pressure waves from the downstream boundary. The shock is viewed as the 'transducer' of the energy flow in the jet to force the oscillation. In other words, the mechanism that forces the oscillation involves a feedback to the region of unstable shockwave, but the feedback region is limited to the domain within the stand-off region. Powell's (1987) configurations include the more general consideration of round underexpanded jets impinging on normal plates of relatively small and large diameter. Many types of instabilities can occur depending upon the jet pressure ratio, the plate size, and its distance from the nozzle." (Ref. 12, page 7.47)
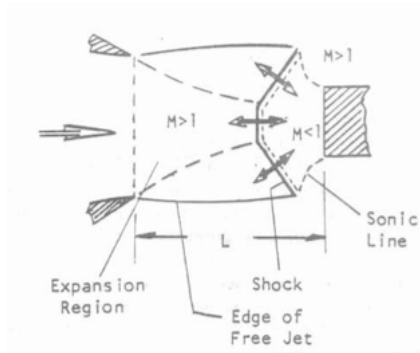

Figure 1. Rockwell and Naudascher[12] (Fig. 7.33) after Mørch.[13] Oscillations of a shockwave due to supersonic jet impingement upon a blunt obstacle. "It should be noted that resonant-type oscillations can occur even in absence of any apparent resonator geometry, as illustrated…" (This figure is used with permission of D. Rockwell from his notes and is unpublished elsewhere.)

Supersonic jet screech noise, being an aeroacoustics problem, can be mitigated by putting a physical notch in the nozzle lip, inserting physical dampers near the source of the unsteadiness, and other methods that disrupt the acoustic feedback loop. Likewise, studies have shown that reflectors of proper placement and design can amplify screech noise as shown in Fig. 2a below. Figure 2b shows the acoustic field of a large eddy simulation of a screech jet.

a)   b)
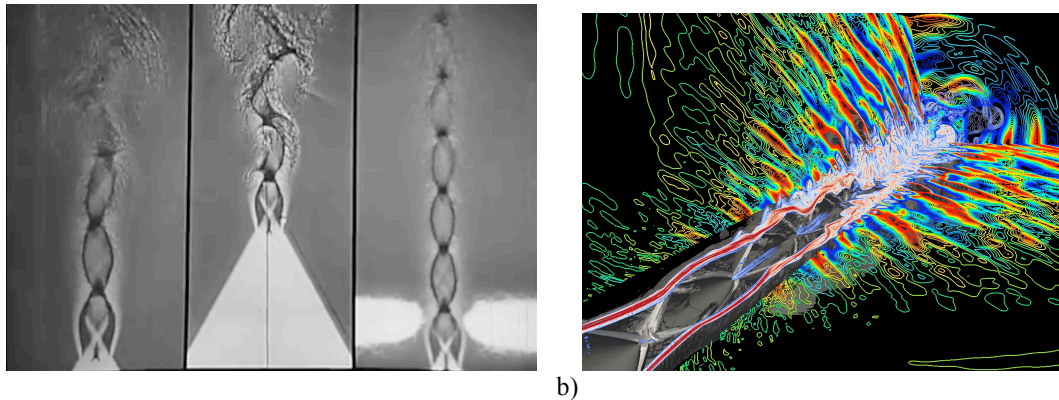
Figure 2. Shadowgraph comparison of a) (L-R) normal, reflector-amplified, and damped unsteady jet screech jets[14] and b) large eddy simulation of an overexpanded supersonic screech jet. (Fig. 2a: density gradient;[14] Fig. 2b: vorticity in the jet and fluctuating pressure outside the jet.[15])

For more information on the classic jet screech noise problem, the authors refer the reader to numerous papers reporting results of jet screech investigations listed following the References section. Rockwell and Naudascher[12] provide an in-depth discussion of unsteady shear layers and jet impingement (Ref. 12, Chapter 4).

III.   The Long Penetration Mode Supersonic Underexpanded Jet

A number of NASA studies[1-7] have examined supersonic cold flow counterflowing jets in an oncoming supersonic freestream. Finley[8] provides a thorough description of the flowfield characteristics of counterflowing jets ejected from a central nozzle configuration into a supersonic freestream. Some features observed include a bow shock, a jet terminal shock, free stagnation point, and recirculation regions in a highly complex and unsteady flowfield.

The complex jet-shock interaction and structure details of the internal LPM flowfield are dependent on the location of the free stagnation point[16] where the velocities of both freestream and jet decelerate to zero. The location of this free stagnation point varies depending on the freestream Mach number, jet nozzle design, and the jet mass flow rate (*m-dot*). Specifically, its location is a function of the ratio of the jet exit pressure (p_j) to that of the oncoming freestream (p_0).

Based on the p_j/p_0 ratio, the features and stability of this flowfield vary, and in practice, two distinct modes are observed. At values of p_j/p_0 above 1, a stable flowfield characterized by a compression bow shock that remains close but offset from the blunt body is formed and the jet does not penetrate the bow shock. However, at lower ratios of p_j/p_0, the jet flow is underexpanded and the jet becomes unsteady. In this mode, the unsteady jet forms a series of Mach diamonds and it penetrates the bow shock, thereby modifying it to a diffused shock.[2-4]

Jarvinen and Adams[9] have characterized these two distinct flow regimes as long penetration mode (LPM) and short penetration mode (SPM). Figure 3 illustrates typical schlieren images of baseline (no jet), LPM, and SPM as observed in a wind tunnel test in freestream Mach number of 3.48.[1]

a)   b)   c)

Figure 3. Wind tunnel schlieren images of a) baseline (no jet), b) LPM (underexpanded jet), and c) SPM (fully expanded jet). The nominal tunnel conditions for the Mach 3.48 and 4.0 freestreams were total pressures of 45 and 55 psi, respectively, total temperature of 580°R (140°F), with corresponding unit Reynolds numbers of 4.88 x 10^6/ft and 4.67 x 10^6/ft.[1] Counterflowing jet air was unheated.

These two modes are illustrated analytically in Fig. 4 below in terms of the p_j/p_0 ratio based on wind tunnel experiments[16] and in terms of the jet centerline pressure based on conservation element-spatial element (CESE) CFD.[2-4] These two comparisons illustrate the flowfield differences between steady SPM and unsteady LPM and provide a graphical representation of the conditions which create steady SPM flowfields and unsteady LPM flowfields.

a)   b)
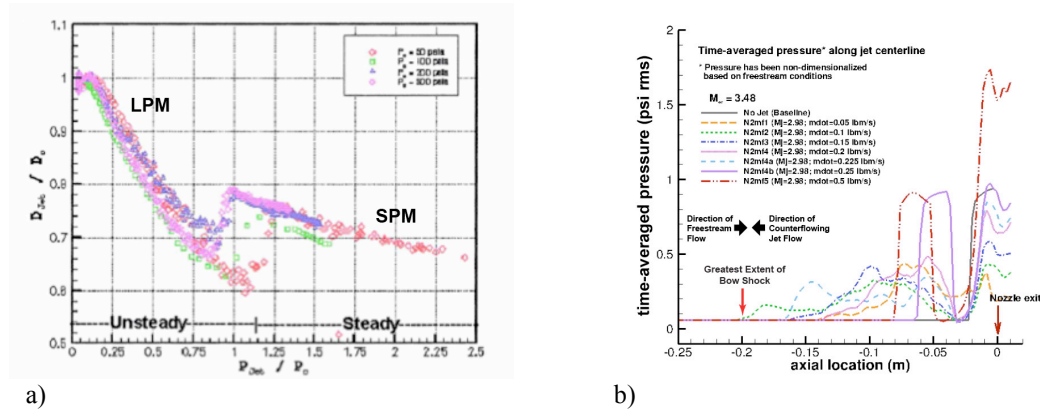
Figure 4. a) Ratio of p_j/p_0 for counterflowing cold flow jet in a freestream Mach number 5.85, showing regime of unsteady cases (LPM) and steady cases (SPM),[10,16] where measured drag force (D_{jet}/D_0) is normalized with respect to the no-injection case at different jet and wind tunnel stagnation conditions (small Reynolds number effect is indicated); and b) computed pressure data along the cold flow jet centerline for five LPM cases and one SPM case.[†]

Venkatachari et al.[2-4] describe the differences between LPM and SPM and the transition from LPM to SPM as follows:

> "…the shock displacement [in LPM] is significantly higher than that found in a stable flowfield…[SPM and with no jet]. In this [LPM] scenario, the jet flow is unable to remain contained within the shock layer. Instead it begins to interact strongly with the bow shock resulting in a large shock standoff distance, creating an unstable flowfield with a very dispersed shock. As the jet flow rate increases further, for reasons not yet clearly understood, the shock standoff distance

begins to decrease again and the flow eventually reverts back to a more stable [SPM] condition, where the flowfield structure is characterized by a jet terminal shock..."

Figure 5 provides qualitative representations of the differences between the LPM and SPM flowfield internal structures, based on CFD analyses reported by Venkatachari et al.[2-4]


a)   b)
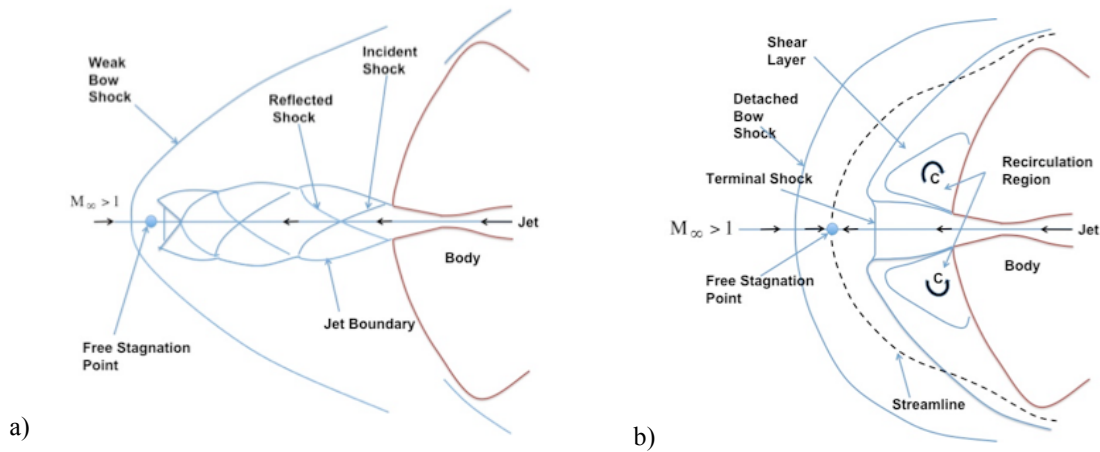
Figure 5. Schematic comparison of a) LPM and b) SPM flowfield features.[2-4]

While SPM is by far the more-studied counterflowing jet condition, anomalous LPM is not very well described. We note that certain characteristics of LPM discussed below indicate it is closely related to supersonic jet screech noise. This becomes evident with examination of the finer details of the internal fluid dynamics of LPM as revealed in full 3-D, Navier-Stokes, time-accurate LOCI-CHEM CFD analysis. An illustration of one frame from a density gradient animation showing many more complex details about the LPM jet flowfield is illustrated below in Fig. 6.
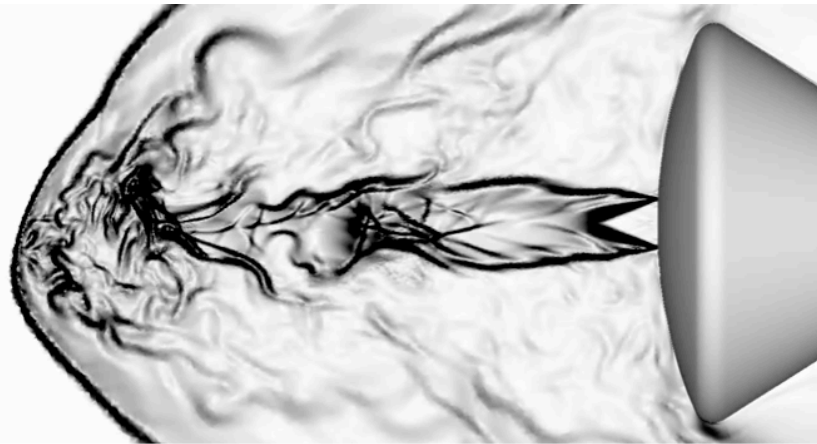
Figure 6. A close-up view of a single frame of density gradient LOCI-CHEM full 3-D CFD animation data at freestream Mach number 3.48, showing highly turbulent and unsteady flow associated with LPM (see footnote *).

Data from both CESE 2-D and LOCI-CHEM 3-D CFD studies show a volume of subsonic flow exists in the LPM cases, surrounding the supersonic jet and bounded by the supersonic freestream. This subsonic region extends from the surface of the blunt body to the stagnation point at the jet-freestream interface, as shown in Fig. 7.

LPM (N1mf2)
Mach Contour

Time Averaged Speed of Sound

a)   b)
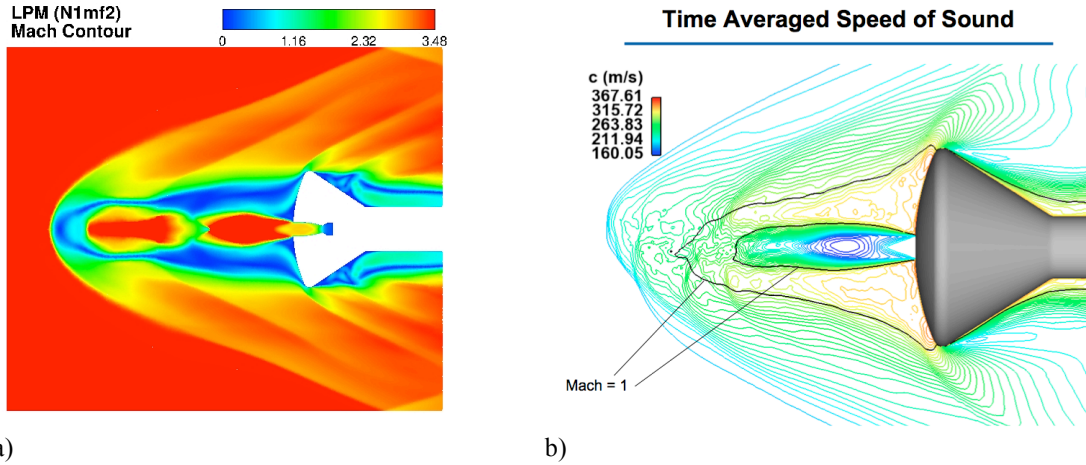
Figure 7. a) Mach number contours for CESE solution of N1mf2 LPM case (see footnote †); b) LOCI-CHEM time-averaged speed of sound contours for LPM N2mf2 case (see footnote *).

Furthermore, frame-by-frame analysis of the LOCI-CHEM 3-D CFD density gradient animation (see footnote *) shows both flow perturbation features advecting downstream in the unsteady jet shear layer, as well as acoustic features emanating from the region of the stagnation point and traveling through the subsonic volume in the opposite direction back towards the blunt body, where they are reflected and then interact with the jet shear layer at the nozzle lip to perturb it in a periodic manner, thereby inducing a system resonance.

In addition, NASA CESE CFD parametrics analysis of LPM cases (see footnote †) shows that a certain minimal amount of reflective surface surrounding the nozzle lip is required in order to create the LPM effect. Data from over 100 CFD cases show that a ratio of nozzle exit surface area to body reflective surface area of approximately 1:15 is required for the LPM effect to exist in a supersonic freestream of air at the conditions studied. In other words, as shown below in Fig. 8, A_b must be at least 15 times the area of A_n, where A_b is the area of the annular reflective surface surrounding the nozzle, and A_n is the nozzle exit surface area.
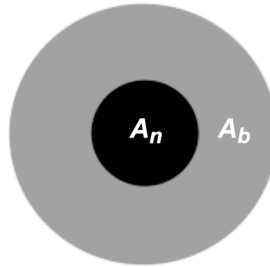

Figure 8. Schematic representation of LPM nozzle of exit area, A_n, and surrounding reflective surface area of the body, A_b.

The combination of a subsonic volume encased within a supersonic flow, unsteady shear layer perturbations in the jet, minimum necessary reflective surface area, and traveling acoustic waves in the subsonic bubble is a clear indication of the existence of an aeroacoustics phenomenon in LPM. These characteristics are also all found in the jet screech noise problem.

We propose to characterize LPM as a special case of jet screech, where the supersonic freestream provides the acoustically reflective boundary necessary for resonance, rather than a solid surface, which causes the highly unsteady condition of 'screech' to occur and amplify in LPM.

Acoustically, a supersonic-sonic boundary condition reflects all sound waves, just as a solid surface does, and acoustic waves are unable to cross the boundary in either case. While the physical mechanism of LPM and freestream interaction that causes the modification of the supersonic shock is not known at this time, it is clear from our data that an aeroacoustic interaction is involved in LPM. Further study and data analysis of LPM jets is needed to substantiate and quantify this interaction.

The acoustic feedback loop observed in LPM unsteady counterflowing jets has been previously described by Josyula et al.[10] referencing Shang et al.,[16] who are quoted as follows and illustrated in Fig. 9:
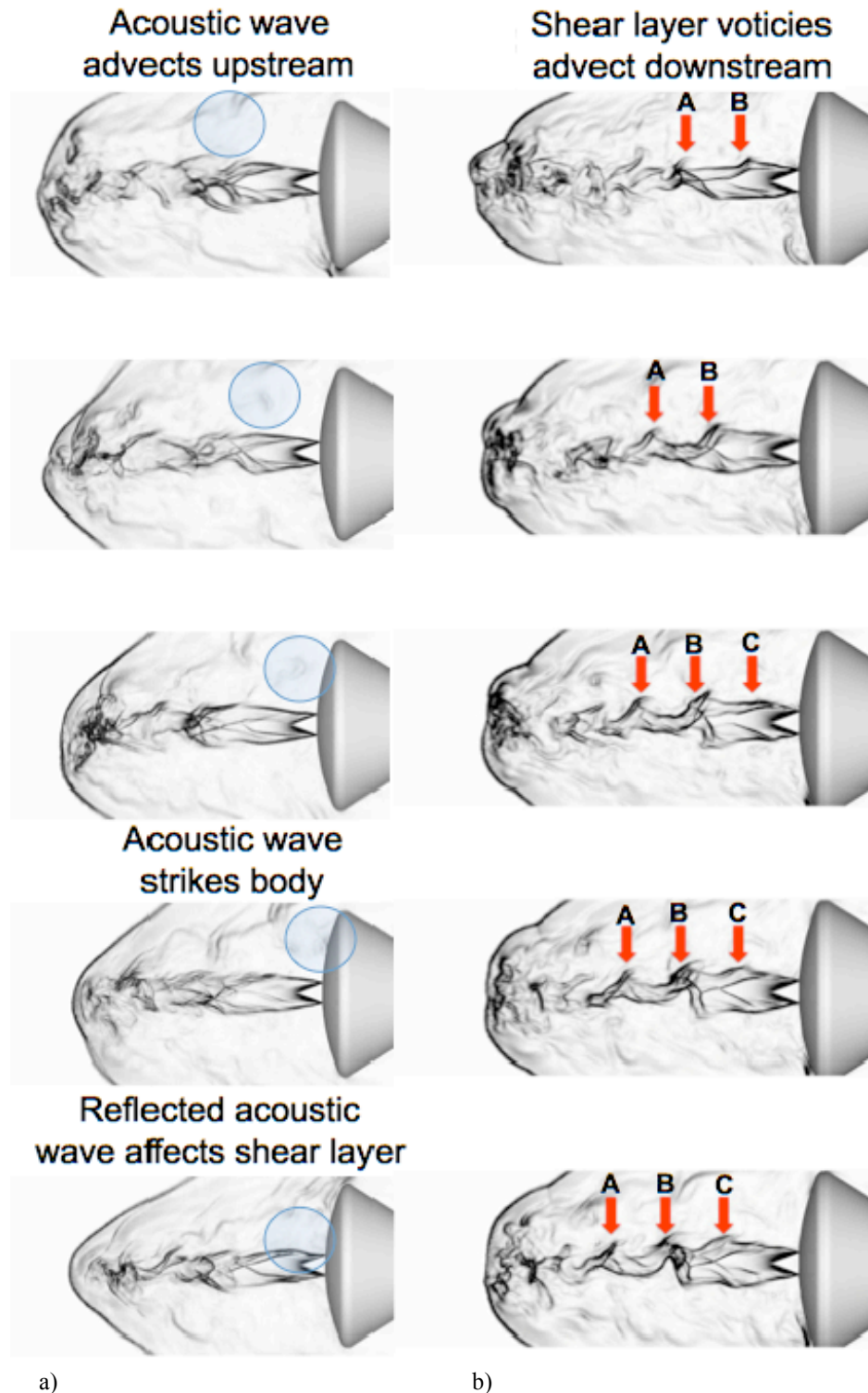
Figure 9. a) Acoustic wave propagation towards the blunt body; b) shear layer perturbations propagating towards the free stagnation point (N2mf2 case, 2012; see footnote *).

"At lower injection pressures, a self-sustained oscillatory motion is maintained by a feedback loop between the free shear layer over the recirculating zone surrounding the jet spike and the Mach disk. When the counter flow jet is generated by a sufficiently high stagnation pressure, a supersonic stream separates the embedded subsonic domain to break down the feedback loop, resonance ceases, and returns to a steady motion."

Comparison by the authors of CESE shock displacement results for several LPM cases and two SPM cases at different mass flow rates (see Fig. 10) shows the LPM jet extends farther and farther forward with increasing mass flow rate (*m-dot*), reaches a maximum, then retracts a bit before converting to SPM. This is an indication of a resonance phenomenon within the shock-subsonic flow-jet/body system as will be discussed later. It should be noted the behavior in the LPM regime is highly unsteady and the LPM data points are based on single frames taken from animations. Actual displacements will vary with time but should be in the same general range shown.
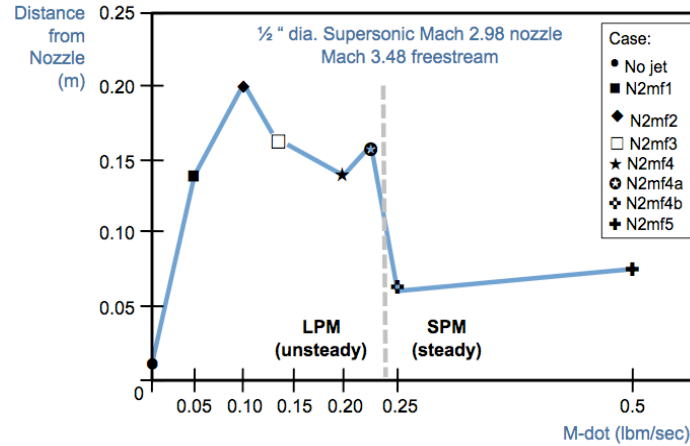
Figure 10.   Shock displacement data as a function of jet mass flow rate (*m-dot*) in a Mach 3.48 freestream (based on data derived from Fig. 3b).

A comparison of CESE Mach number results for several LPM cases and one SPM case at different nozzle mass flow rates shows the variability of the subsonic volume in LPM and the difference between LPM and SPM. In wind tunnel tests, the transition from LPM to SPM is extremely rapid and was observed to take less than 1/30 of a second based on schlieren videos. Examination of these CFD data plots verify this increasing 'pinching off' of the subsonic region of the LPM jet with increasing mass flow rates, as shown in Fig. 11.
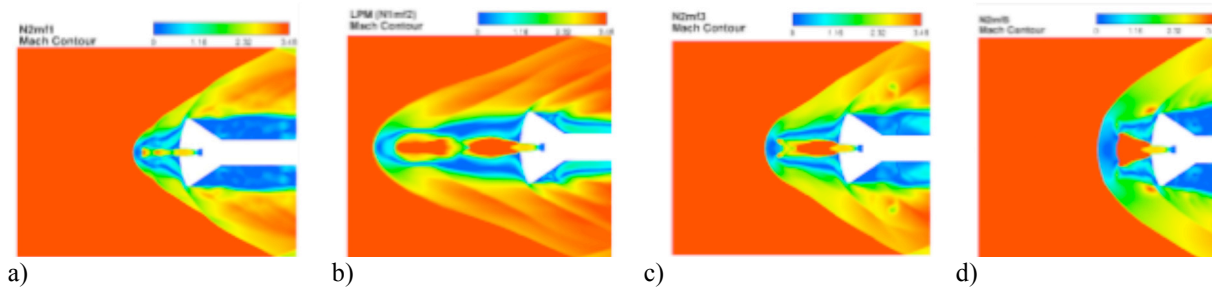

Figure 11.   CESE CFD 2-D axisymmetric results for Mach number: a) LPM case N2mf1, *m-dot* = 0.05 lbm/sec; b) LPM case N2mf2, *m-dot* = 0.1 lbm/sec; c) LPM case N2mf3, *m-dot* = 0.15 lbm/sec; and d) SPM case N2mf5, *m-dot* = 0.5 lbm/sec (see footnote †).

Based on these observations, it is reasonable to conclude that the collapse of the aeroacoustic feedback loop is the physical trigger that creates the rapid (<1/30 of a second), physical transition from LPM to SPM observed in wind tunnel tests.

IV.   Further Application of Screech Jet Behavior to Long Penetration Mode

In the case of a supersonic underexpanded screech jet, large-scale vortex formation is seen to result from the difference between the higher velocity along the centerline of the jet and the zero velocity in the surrounding fluid,

which can induce rapid amplification of the initial small disturbances at resonance (Ref. 12, page 2.5). Figure 12 shows high vorticity in the CESE CFD LPM case N2mf2 along the shear layer and the supersonic freestream boundary, consistent with this thinking.
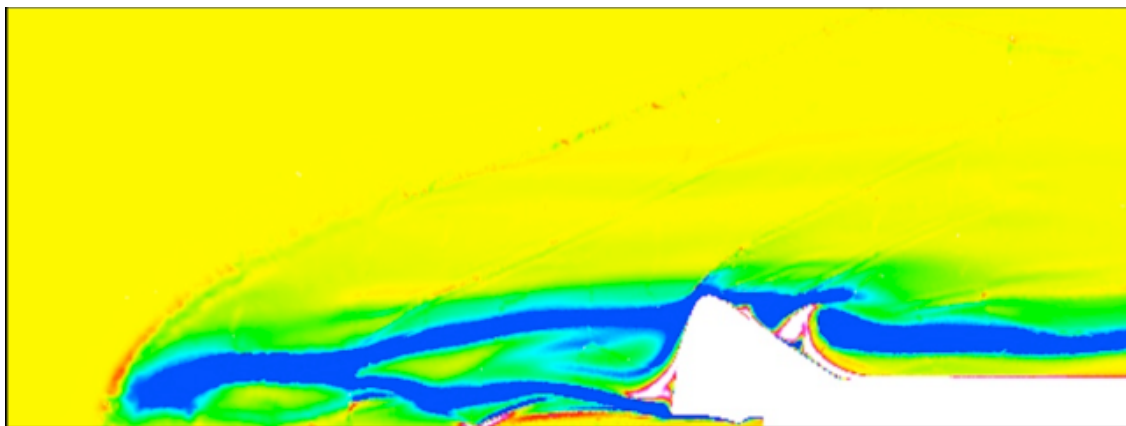
Figure 12.   CESE CFD solutions show high vorticity (dark blue) in the jet shear layer and in the sonic-supersonic interface later for LPM case N2mf2 (see footnote *).

Rockwell and Naudascher[12] describe how self-excited jet oscillations involve the entire jet of fluid, not just the shear layer, as follows:

"For the axisymmetric jet, one must account for the possibility of not only the thin shear layer instability, but also a column-type instability; the former scales on the shear layer thickness as described in the foregoing, and the latter on the jet diameter. Since its length scale is the jet diameter D rather than the shear layer thickness, it physically means that the jet column as a whole goes unstable. (We may liken this column instability to the column buckling of a solid rod of diameter D subjected to compressive loading - it too involves consideration of the entire cross-section of the rod.) If the jet has thin laminar shear layers at separation, the growth of the disturbance in the streamwise direction involves development of a single vortex, followed by pairing of these adjacent single vortices, and in turn, merging of paired vortices with each other... The result of this successive pairing is to produce a set of subharmonics of the original unstable frequency of the vortex formation fv until very large scale vorticies form. This large scale instability of the jet has a dimensionless frequency of 0.3 LT=to fD/U LT=to 0.5." (Ref. 12, page 4.4)

Furthermore, they continue by describing higher order frequency modes that form in the jet instability, such as helical instabilities:

"Finally, it should be noted that configurations such as the axisymmetric jet have more than one shear-layer instability mode. The axisymmetric mode discussed in the foregoing represents the zeroth mode while helical instabilities correspond to the higher order modes." (Ref. 12, page 4.4)

Recent work (see footnote † and Ref. 17) confirms this helical mode, shown modeled in Fig. 13, exists in supersonic jet screech and is a contributor to both noise frequency and location of noise origin. Based on results of full 3-D modeling, helical modes are also suspected in the LPM phenomenon, and this implies full 3-D modeling is necessary to capture the full behavior and aeroacoustic interactions of LPM.
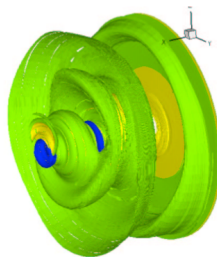
Figure 13.   Helical pressure iso-surfaces of jet screech at time step 130,000.[18]

V.   Movement-Induced Excitation (MIE) of Fluid Oscillators

In a broader sense, both supersonic jet screech and the LPM jet phenomena may be considered part of a larger group of phenomena known as fluid resonators, as described in great detail by Rockwell and Naudascher.[12] This class of self-induced instability phenomena in fluids includes jets, whistles, and Helmholz resonators. The onset of instability in fluid resonators is a function of Reynolds number, swirl- or cavitation-number (Ref. 12, page 4.1).

Fluid oscillators are sometimes found to be coupled mechanically with resonant structures which provide an additional source of MIE, also known as flutter. Flutter results from fluid feedback interactions with mass-spring systems, and thus can be induced by both resonant mechanical structures as well as by hydrodynamic shock structures. Rockwell and Naudascher[12] (page 2.3) add:

> "…MIE (movement-induced excitation) mechanisms such as shockwave oscillations may be enhanced in a similar fashion by presence of a fluid oscillator." And furthermore: "The analogous MIE excitation of the fluid resonator (oscillator) is indicated in…[Fig. 14]. In this case, the shockwave undergoes unsteady motion outside the resonator. There is no unstable vortex formation, or extraneous forcing of the shockwave displacement. Due to the movement of the shockwave, there are corresponding oscillations of the fluid within the resonator…"
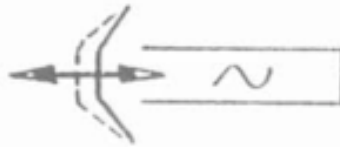
Figure 14.   Sketch of shockwave MIE in a fluid oscillator (resonator) (Ref. 12, Fig. 2.1). (Figure used with permission of D. Rockwell from his notes and is unpublished elsewhere.)

In the case of LPM, the subsonic bubble or 'compressive degree of freedom' created by the action of the supersonic jet in the supersonic freestream, can be viewed as an acoustic cavity. The oscillating supersonic shock at the stagnation point then excites the fluid (air) mechanically in this cavity, thereby exciting a system resonance condition. Thus, LPM can be considered an example of an MIE in a fluid oscillator resonator.

VI.   A Proposed Mechanism by Which LPM Modifies the Supersonic Shock

We postulate that by virtue of an acoustic feedback mechanism, LPM creates an out-of-phase aeroacoustic interaction with the supersonic compression shock that acts to diffuse it. Being rooted in aeroacoustics and a type of jet screech phenomenon, LPM should adhere to all related acoustical behavior, such as amplification, damping, and phase relationships. It is quite possible that a form of 'anti-noise' is created in the LPM interaction that disallows the supersonic shock to crest as a distinct discontinuity wave.

Rockwell and Naudascher[12] write:

> "…both the magnitude and sign of the out-of-phase component F, are important in determining whether or not the oscillation will be amplified; in essence, the sign of F, depends on whether the phase angle between F, and the displacement of the structure x, … is +r/2 (lead) or –r/2 (lag). Since both F_1 and x_1 rotate in the same direction with angular velocity ω and the phase angle between them is constant for all values of time… a positive force F_1 always leads the body displacement x_1; this phase lead between the out-of-phase force F_1 and displacement z , is … the criterion for positive work to be done by the fluid on the body, corresponding to energy transfer to the body, and amplification of the body oscillations. This criterion is a conservative one for single-mode vibrations; effects of structural damping will tend to lower the magnitude of an out-of-phase force that leads the displacement. If it is large enough, it will produce a phase lag of the resultant out-of-phase force (F_1- $B\omega x_0$), and the oscillation will be damped." (Ref. 12, page 5.5)

VII.   Long Penetration Mode in Terms of Work

The simplest definition of work (W) per cycle of oscillation is a function of force times displacement:

$$W = \int F dx \tag{1}$$

where the fluid force (F) creates displacement (x) in a body, to do positive work on the body. This positive work represents energy transfer from the fluid to the body. The changes in $F(t)$ with respect to $x(t)$ during a complete cycle must show a hysteresis loop with the area of the hysteresis loop corresponding to the amount of

thermodynamic work expended in the cycle. Positive work always indicates negative fluid-damping, and negative work indicates positive fluid damping. The phase angle between the total force and the body displacement determines the magnitude and sign of the work done by the fluid on the body (Ref. 12, page 5.7).

Long penetration mode obviously modifies the supersonic shock in an artificial way that must require some expenditure of energy. The LPM jet must be doing work on the shock in order to modify it. Rockwell and Naudascher[12] wrote, "We may liken this [jet] column instability to the column buckling of a solid rod…subjected to compressive loading…" (Ref. 12, page 4.7). This reference to an axisymmetric jet column buckling mode or spring constant has structural analogs and may be considered as another mechanism by which this work is being done.

Accordingly, we expect future investigations of LPM phenomenon during the full cycle of transition from LPM to SPM and back to LPM will show hysteresis and evidence that LPM is indeed doing work on the supersonic compression shock to modify it. Such hysteresis would also be a quantification of the amount of work being expended to induce this anomalous environment and should be within expected conservation of total energy limits minus thermodynamic losses.

VIII.   Conclusions

In a supersonic freestream, the internal structure of a supersonic counterflowing jet flowfield is dependent on the location of the free stagnation point, which varies depending on the freestream Mach number, jet nozzle design, and the underexpanded jet mass flow rate (*m-dot*). Specifically, the location of the free stagnation point is a function of the ratio of the jet pressure (p_j) to that of the oncoming freestream (p_0). Based on the p_j/p_0 ratio, the features and stability of this flowfield vary and two distinct modes are observed.

At values of p_j/p_0 above 1, a stable flowfield termed short penetration mode (SPM) and characterized by a compression bow shock that remains close but offset from the blunt body is formed and the jet does not penetrate the bow shock. However, at lower ratios of p_j/p_0, the jet flow is underexpanded and the jet becomes unstable. In this long penetration mode (LPM), the unsteady jet forms a series of Mach diamonds, penetrates the bow shock, and modifies it significantly to an expansion shock.

Computational fluid dynamics solutions of LPM show a region of subsonic flow surrounding the unsteady supersonic jet and bounded by the supersonic freestream. This subsonic acoustic cavity extends from the acoustically-reflective surface of the blunt body to the free stagnation point at the jet-freestream interface. Three-dimensional CFD density gradient animation shows flow perturbation features advecting downstream in the unsteady jet shear layer, as well as acoustic features emanating from the region of the stagnation point and traveling in the opposite direction back towards the blunt body, where they interact with the jet shear layer at the nozzle lip to perturb it in a periodic manner to create an aeroacoustics feedback loop very similar to jet screech.

Based on results of full 3-D CFD modeling, helical modes typical of jet screech are also suspected in the LPM phenomenon, and this implies full 3-D modeling is necessary to capture the full behavior and aeroacoustic interactions of LPM.

In addition, parametrics analysis of LPM cases show that a certain minimal amount of reflective surface surrounding the nozzle lip is required in order to create the LPM effect. Data from over 100 CFD cases show that a ratio of nozzle exit surface area to body reflective surface area of approximately 1:15 is required for the LPM effect to exist in a supersonic freestream of air at the conditions examined. In other words, in order to achieve the LPM condition, the reflective annular surface area of the body surrounding the nozzle lip must be at least 15 times that of the exit area of the nozzle at the freestream and nozzle flow conditions studied.

A subsonic acoustic cavity encased within a supersonic flow, unsteady shear layer perturbations in the jet, minimum necessary reflective surface area, and traveling acoustic waves in the subsonic bubble are clear indications of the existence of an aeroacoustics phenomenon in LPM. These characteristics are also all found in the jet screech noise problem. We therefore postulate that LPM is a special case of jet screech, where the supersonic freestream provides the reflective boundary necessary for resonance, rather than a solid surface characteristic of traditional screech in a stationary or subsonic fluid. This implies that the large body of knowledge gained over the years about jet screech may be applied to LPM.

Both supersonic jet screech and the LPM jet phenomena may be considered part of a larger group of phenomena known as fluid resonators. In the case of LPM, a subsonic bubble or 'compressive degree of freedom' forms an acoustic cavity which is created by the action of the supersonic jet in the supersonic freestream. The oscillating supersonic shock at the free stagnation point excites the fluid (air) mechanically in this cavity. Thus, LPM can be viewed as an example of movement-induced excitation (MIE) in a fluid oscillator resonator.

While the physical mechanism of LPM-to-freestream interaction that causes the modification of the supersonic compression shock is not known at this time, it is clear from our data that an aeroacoustic interaction is involved in

LPM. We postulate that in LPM, an out-of-phase aeroacoustic interaction feedback forms with the supersonic compressions shock and acts to diffuse and modify it.

In wind tunnel tests, the transition from LPM to SPM was observed to occur in less than 1/30 of a second. Examination of CFD data results verify increasing 'pinching off' of the subsonic region of the LPM jet with increasing nozzle mass flow rates. Based on these observations, it is reasonable to conclude that the collapse of the subsonic region, with increasing jet mass flow rate resulting in interruption of the aeroacoustic feedback loop, is the physical trigger that creates the observed rapid flowfield collapse and mode transition from unsteady LPM to steady SPM.

Interest in studying LPM and SPM continues around the world.[19,20] We expect future investigations of the transition from LPM to SPM and back to LPM will show hysteresis and provide additional evidence that LPM is indeed doing work on the supersonic compression shock to diffuse it. Such hysteresis would be a quantification of the amount of work being expended to induce this anomalous LPM environment and should be within expected conservation of total energy limits minus thermodynamic losses. We also expect analysis of the acoustic signals from future time-accurate CFD LPM studies will show acoustic signal-phase relationships in LPM at the nozzle lip and free stagnation point to be similar to those observed in the screech jet phenomenon.

Acknowledgments

This work is based on technology protected by "Method and System for Control of Upstream Flowfields of Vehicle in Supersonic or Hypersonic Atmospheric Flight" (U.S. Patent 8,251,312 (2012)) and "Method and System for Weakening Shockwave Strength at Leading Edge Surfaces of Vehicle in Supersonic Atmospheric Flight" (U.S. Patent [TBD], (2015)).

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