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Jet Noise Reduction: A Fresh Start

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Attempts to reduce jet noise began some 70 years ago. In the literature, there have been many publications written on this topic. By now, it is common knowledge that jet noise consists of a number of components. They possess different spectral and radiation characteristics and are generated by different mechanisms. It appears then that one may aim at the suppression of the noise of a single component instead of trying to reduce jet noise overall. The objective of the present project is to reduce large turbulence structures noise. It is the most dominant noise component radiating in the downstream direction. A rational way to start is to determine the location of the source of this component. To supplement the information provided by past experiments, a fairly comprehensive study of the noise source location, the characteristic features of the sound pulses, the size and structure of its turbulence source is carried out. The results are reported here. In addition, a large turbulence structures noise reduction scheme is proposed. Work needed to perform a proof-of-concept demonstration by numerical simulation are discussed.

I. Introduction

Jet noise reduction is, without doubt, one of the most important problem of jet aeroacoustics research and development. In the past, numerous investigators had devoted a good deal of time and effort on this problem. Over the years, progress had been made. However, they were limited. Certainly, there is room for improvement. It is well-known that the most effective way to reduce jet noise is to reduce the jet exhaust velocity. But the jet exhaust velocity is largely decided at the engine system level. It is not a parameter that can be changed by aeroacousticians.

Jet noise reduction effort in the past may roughly be lumped into six main methods. This does not mean that individual and special methods have not be as successful. The six main methods are the use of

(a) tabs
(b) chevrons
(c) fluidic injection
(d) microjets
(e) fluid shield and multi-stream jets
(f) water injection.

It is self-evident that one way to reduce jet noise is to inject disturbances into the jet flow to try to modify the jet flow structures and turbulence is necessary. However, what the disturbances would do after they are introduced into the jet flow is, generally, beyond one's control. One may hope the disturbances would affect the jet flow and turbulence in a positive way that would lead

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to noise reduction. But there is no guarantee. For practical reason, the input of disturbances has to be carried out near the nozzle exit. This is a strong constraint.

It appears that the simplest way to disturb a jet flow is to insert a tab near or at the nozzle exit. This method has been studied by many investigators. Refs. [1] to [10] is a short list of the relevant papers. Tabs are known to generate streamwise counter-rotating vortices. Tabs also modify the shock cell structure in the plume of a supersonic jet. They are quite effective in suppressing jet screech tones. To some extent, they also reduce broadband shock cell noise.

Zaman, Bridge & Huff (Ref. [11]) regarded chevron as a natural evolution from tabs. Chevrons have been extensively investigated experimentally and computationally by numerous investigators (e. g. Refs. [12] – [21]). Chevrons are known to introduce an array of longitudinal vortices in a jet flow. They are somewhat effective in reducing low frequency noise. However, its presence could also increase high frequency noise. Chevrons have now been installed in the nozzles of a number of commercial jet engines. They include the engines of Boeing 737 Max, 747-8, 787 and Bombardier CRJ900 aircraft.

Fluidic injection, sometimes referred to as fluidic chevrons, as a means for reducing jet noise has been investigated well over sixty years by now. There is a rich history of this method. Fluidic chevrons are created by fluid injection at a regular interval around a nozzle. The injection direction may be parallel to the wall or at a slightly inward angle. The injection, generally, creates an array of longitudinal vortices as in the case of mechanical chevrons. There have been numerous publications on the subject. The following is a selected short list of references, [22] to [31].

Microjets are similar to fluidic chevrons. Significant injected mass-flow rate of a system of microjets could have a noticeable impact on jet noise. The parameter formed by the ratio of microjet mass-flow rate to main-jet mass-flow rate has proven to be capable of assessing and optimizing jet noise reduction. One main advantage of microjets, compared to mechanical chevrons is the possibility of their being turned off during cruise. This limits thrust loss to during take-off alone. A short list of references to this subject includes references [32] to [42].

The use of fluid shield and multi-stream jets is motivated by an entirely different thinking when compared with the methods mentioned above. A fluid shield works by redirecting the direction of radiation. Noise radiating in the upward direction from a commercial aircraft would cause no discomfort to anyone. One of the schemes that have been considered is to create a nonuniform gas layer below the jet. Because of refraction, the acoustic rays are made to bend to the upward direction. Instead of using an additional gas layer, a multi-stream jet can be arranged to have the same effect. For a deeper technical understanding of this method, readers may consult references [43] to [50].

Rocket launches, invariably, create high intensity noise fields at the launch pad. To deal with the situation, NASA, in the early days of the space age, developed a water injection system capable of significantly reducing the noise levels. This success has encouraged a number of investigators to consider using water injection to reduce jet noise. There had been a good deal of interest in such a possibility in the past (see references [51] to [57]). Clearly, many hurdles need to be overcome to make such a system feasible for commercial aviation. Chief among them is the weight of water that has to be carried by the aircraft.

Jet noise consists of multiple components. For supersonic jets with Mach number up to two and temperature ratio up to seven (jets with afterburner), their noise is made up of two components of turbulent mixing noise i.e. the large turbulence structures noise and the fine scale turbulence noise Ref. [58], [59], two components of broadband shock-cell noise (one generated by the interaction of large turbulence structures and the shock cells and the other by the passage of blobs of fine scale turbulence through the compression and expansion regions created by the shock-cell structure) Ref. [60], [61]. In addition, there are screech tones which are driven by feedback loops. For jets operating under afterburner condition, strong entropy noise could be generated by the passage of entropy waves (hot and cold spots) from the afterburner through the internal shocks of the nozzle (see Ref. [62]). Because the noise generation mechanism of each of these components is different, it is unlikely one suppression method could reduce the noise of all components. Therefore, a different approach is to develop methods targeting a specific noise component. For instance, if one wishes to suppress screech tones, one may develop a way to cutoff the feedback loop. On the other hand, if one wishes to reduce broadband shock-cell noise, one may try to reduce the strength of the shock cells. The use of chevron appears to be quite effective for this purpose. In this project, our primary objective is to reduce the mixing noise associated with the large turbulence structures of the jet flow. Experiments have found that this is the most dominant noise component radiating in the downstream direction.

To reduce the large turbulent structures noise, it seems that an obvious first step is to find out where the dominant sources of this noise component are located. Once this is known, one may find a way to introduce disturbances into the jet flow that can reach this location to modify the turbulence level or the mixing process there. If one is able to exert some degree of control on the disturbances introduced, one may be able to use this capability to reduce the turbulence level there or try to spread out the turbulent mixing process. In this way, one may be able to reduce jet noise significantly.

Laufer, Schlinker and Kaplan [63] in 1976 used an elliptic mirror microphone to measure the lengthwise noise source distribution of supersonic jets. Fig. 2 shows the measured distribution of relative noise source strength per unit length along the jet axis. The Mach number of the jet is 1.47 and the direction of radiation (exhaust angle) is 90 deg. In this figure, L_1 is at the end of the potential core of the jet. L_2 is at the end of the supersonic core. The dominant noise source is located at approximately 8.8 jet diameters downstream from the nozzle exit. This is more or less the end of the potential core.

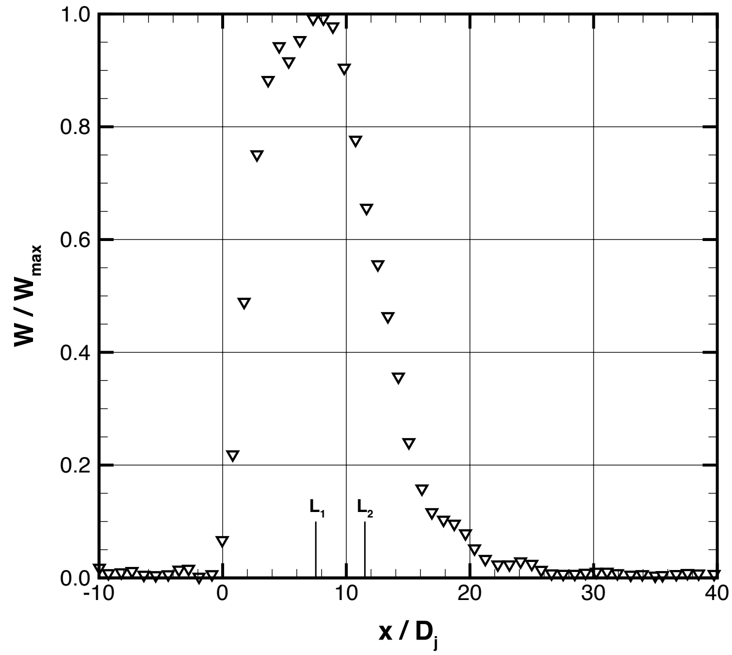

Figure 1. Apparent noise source strength per unit length distribution along the jet axis; M_j=1.47, Direction of radiation (exhaust angle) = 90 deg

Figure 2 is a similar plot for the same jet but at a radiation direction of 32.5 deg. (exhaust angle). For this direction the dominant noise source moves slightly downstream to 10.0 jet diameters. In other words, the dominant noise source is located downstream of the potential core of the jet. The important message is that the dominant noise source is not located near the nozzle exit but near or downstream of the end of the potential core.

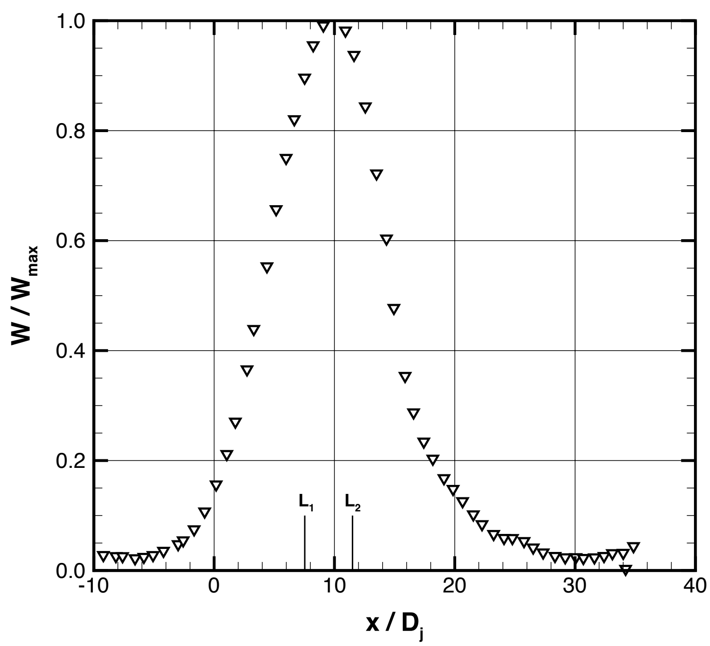

Figure 2. Apparent noise source strength per unit length distribution along the jet axis; M_j=1.47, Direction of radiation (exhaust angle) = 32.5 deg.

Recently, Tam et al [64] studied the near field noise and source distribution of a solid-propellant rocket. They analyzed the measured noise spectra by means of the two similarity spectra of turbulent mixing noise of high-speed jets (see Refs. [61,62]) The pulses of noise corresponding to spectra that fit the fine scale noise similarity spectrum well, generally, have short duration. The pulses of noise corresponding to spectra that fit the large turbulence similarity spectrum well have much longer duration (larger pulses spatially). The result of their analysis is summarized in figure 3. In the experiment the rocket plume pointed upward. This is one of the innovation of the experiment. It was found, from the nozzle exit to a downstream distance of about 12 diameters, all the noise spectra fit the fine scale turbulence similarity spectra well. Thus, the noise emitted from this part of the rocket plume consists mainly short high frequency pulses. Beyond about 19 diameters downstream, all the noise spectra were found to fit the large turbulence structures similarity spectra well. Hence, the sound pulses radiated from this part of the rocket plume have lower frequency and longer pulse duration. In other words, large turbulence structures noise is effectively emitted only downstream of the core of the rocket plume. For jet noise reduction purpose, this is the noise source region of interest.

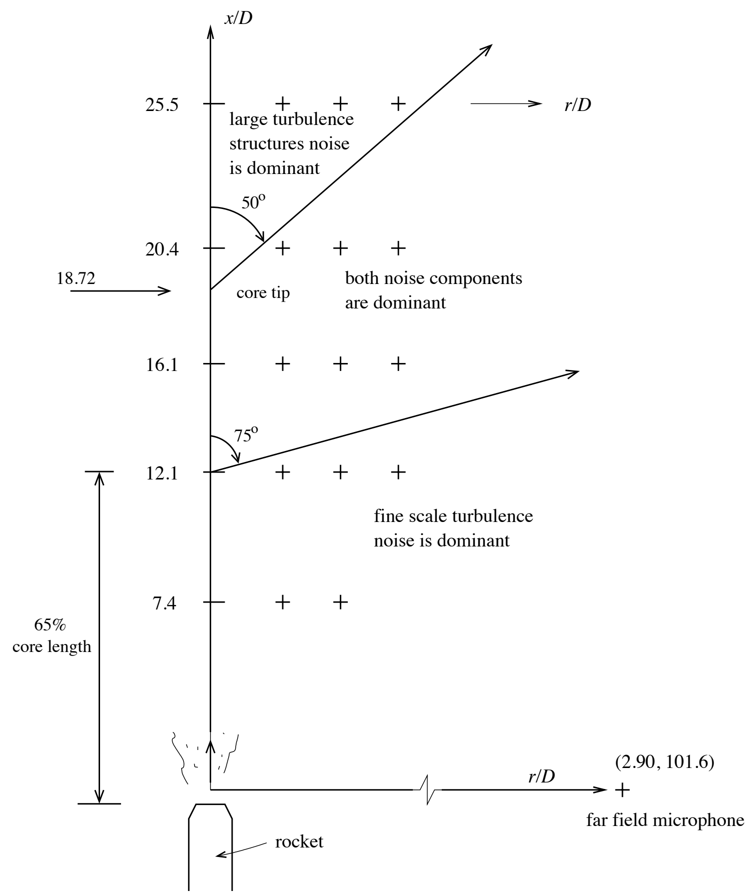

Figure 3. Distribution of dominant noise sources in a rocket plume at low burn.

The rest of this paper is as follows. In section II, the results of a computational aeroacoustics (CAA) large eddy simulation investigation of the noise source distribution in a slightly heated over-expanded supersonic jet are reported. This study offers direct observation of the noise source location of the dominant turbulent mixing noise of the jet. Evidence is provided that the dominant noise source is, indeed, the large turbulence structures of the jet flow. In section III, a new jet mixing noise reduction scheme is proposed. Future work and conclusion are discussed in section IV.

II. A CAA-LES study of the noise source distribution and its characteristics in a supersonic jet.

To supplement the experimental studies of the locations of the dominant jet noise sources performed in Refs. [63] and [64], we have carried out a fairly comprehensive computational investigation. Our investigation uses a Computational Aeroacoustics (CAA) Large Eddy Simulation (LES) computational code. We would like to point out that there are many significant differences between CAA and CFD methods. In the present work, the CAA methods used are fully documented in the book entitled "Computational Aeroacoustics: a wavenumber approach", Ref. [65]. Here we wish to highlight several distinctly CAA methods that have been incorporated in our computer code.

1. A structured multi-size grid conforming to a cylindrical geometry is employed. It is believed that this is one of the best grid for computing the flow and sound field of a circular jet. In cylindrical coordinates, the governing equations have several apparent singularities at the cylindrical axis, r = 0. We use the method developed in Ref. [65] specifically for treating this problem. Many investigators use a Cartesian grid in the center of the jet and adopt an overlapping grid methodology to transition to a cylinder grid.

2. For time marching purpose, a 7-point stencil Dispersion-Relation-Preserving (DRP) scheme is used. The DRP scheme is a high resolution, high accuracy, large stencil scheme. It has the distinction of being a scheme that guarantees mathematically that the computed wave speed (sound speed for jet noise) is identical to that of the governing partial differential equations.

3. The present code has shock-capturing capability. But the shock-capturing scheme is based on a very different design than the those used by CFD codes. Limiters or TVD ideas are not used in the present CAA method. The method we use is given in Chapter 8 in Ref. [65].

4. At the exterior boundaries of the computational domain (see Fig. 4) radiation or outflow boundary conditions are imposed. The radiation boundary condition allows the outgoing sound waves to exit the computational domain with little reflection. This avoids contamination of the computed solution by the reflected waves. In addition, a new capability has been added to the radiation boundary condition. This new capability allows the radiation boundary condition to hold the ambient pressure to a prescribed value. This is particularly important for simulating imperfectly expanded jets. For these jets the nozzle exit pressure is not the same as the ambient

pressure. In fact, it is the difference of these two pressures that determines the shock-cell structure and its strength inside the jet flow. In turn, the shock cells affect the screech tone and the broadband shock-cell noise radiated by the jet.

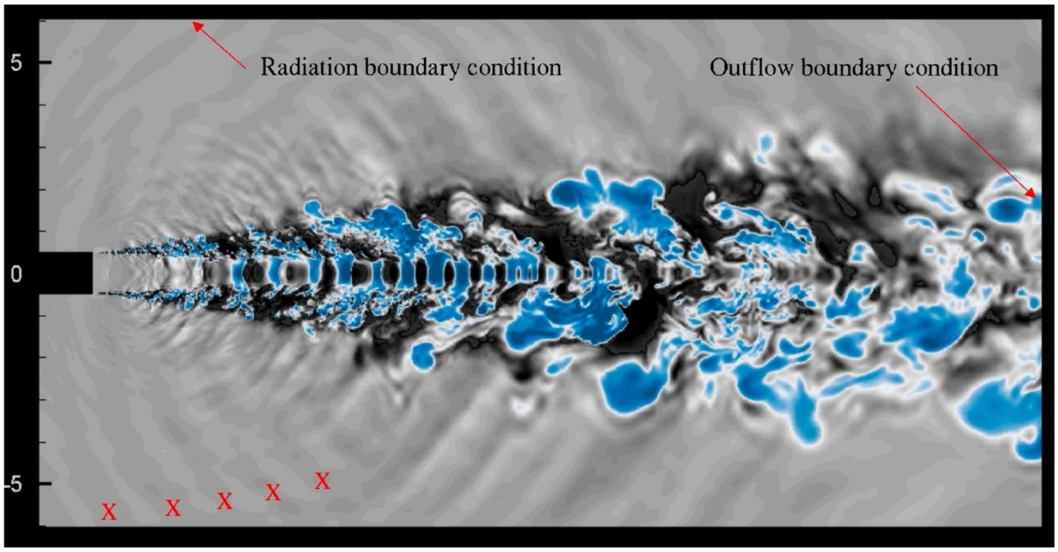

Figure 4. Radiation and outflow boundary conditions imposed at the exterior boundaries of the computational domain.

In our CAA code, the computational domain consists of a cylinder with a diameter equal to 12 times the nozzle exit diameter, D, and a length of 35 D. The Reynolds number of the simulation is 570,000. A video of an overexpanded supersonic jet issued from a C-D nozzle of designed Mach number 1.5 but operated at an exit Mach number 1.358 with NPR = 3 and NTR = 2 has been made. This video allows us to validate the computer code by comparing the measured data with the corresponding experimental data of Professor Ephraim Gutmark of the University of Cincinnati (see Ref. [66]). Our goal is to use this video to first validate the code. Then, it is used to investigate the locations of the dominant sources of turbulent mixing noise inside the jet and the characteristic features of the radiated sound pulses. Jet noise characteristics at the sound-pulse level have seldom been studied or reported in the literature. [Note: sound pulses are emitted directly by a jet and measured by microphones as raw data. It is the tradition of the aeroacoustics community to process the microphone data into spectra. Most jet noise studies are carried out at the spectrum level. Information contained uniquely at the sound-pulse level are rarely investigated.]

Fig. 4 is a snapshot taken from the video. Notice that at the lower left corner, there are bands of sound pulses. They are marked by red X's. These are sound pulses of a screech tone. To facilitate the measurement of the wavelength of the screech tone, red lines are added to the figure. This is shown in Fig. 5. Since the computation uses dimensionless variables, it is straight forward to scale the wavelength to the same scale as the experimental facility of the University of Cincinnati (UC). Sound speed in the ambient is 340 m/s. By dividing the sound speed by the average wavelength of the screech tone, it is found that the tone frequency of the simulated jet is 16.4 kHz.

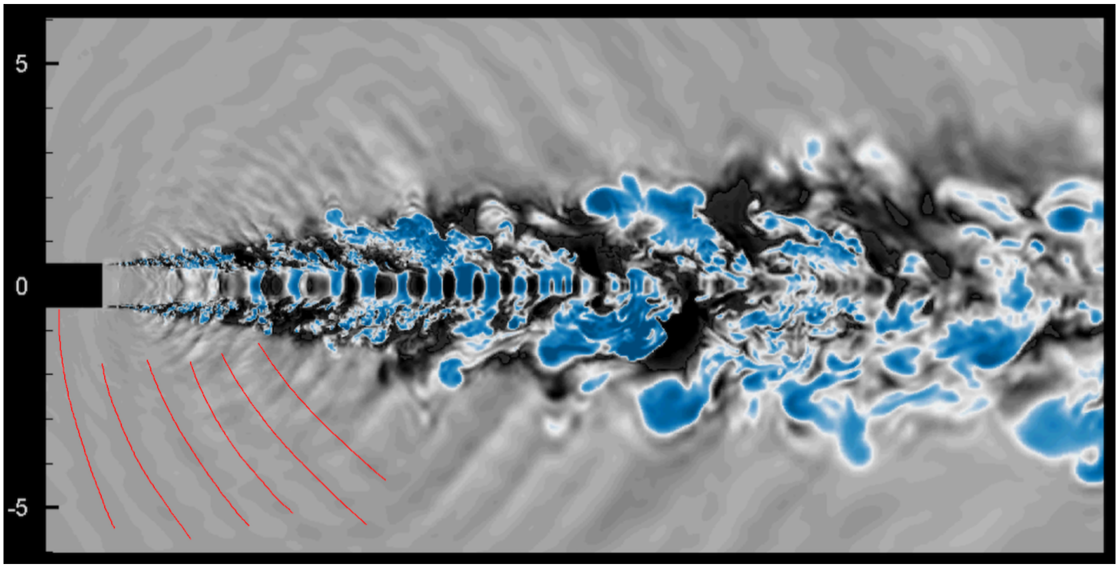

Figure 5. Red lines are inserted in the figure to mark the bands of acoustic waves of a screech tone.

Fig. 6 is a spectrum measured experimentally at 90^0 at the University of Cincinnati. The tone with amplitude at 120 dB is the dominant tone. The tone frequency is found to be 16.4 kHz. This is in good agreement with that of the simulated jet. Screech tone is a fairy complex phenomenon. It involves the interaction of the large turbulence structures and the shock cells inside the jet flow. In addition, the screech tone is driven by a feedback loop. The fact that the screech tone frequency of the simulated jet is in good agreement with experiment offers us a good deal of confidence in the quality and accuracy of our CAA computation code.

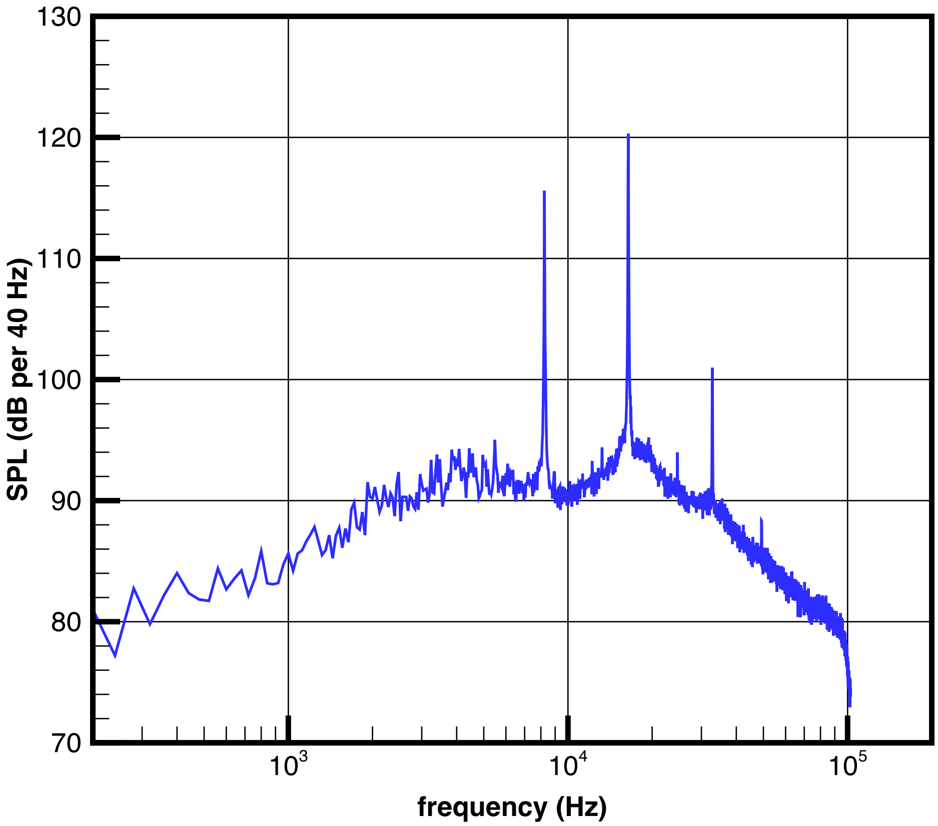

Figure 6. Noise spectrum at 90^0 measured by the UC experiment. The dominant tone with amplitude 120 dB has a frequency of 16.4 kHz.

Figs. 7 and 8 are snapshots taken from the video at different times. The radiated sound pulses are in the form of Mach waves (see ref. [67]). We have added green lines to mark the Mach waves. The inlet angle, θ, is defined as in Fig. 7. θ is found to differ only slightly by 1 to 2 degrees between snapshots. The average is 58 degrees. Since the dominant radiated sound waves are Mach waves, one would expect the most intense noise radiation in the far field is in the direction normal to the Mach lines i. e. $(58^0 + 90^0) = 148^0$. Also, by measuring the average wavelength of the Mach wave pulses, it is possible to find the expected peak frequency of the far field noise spectrum. This frequency is found to be 5.3 kHz.

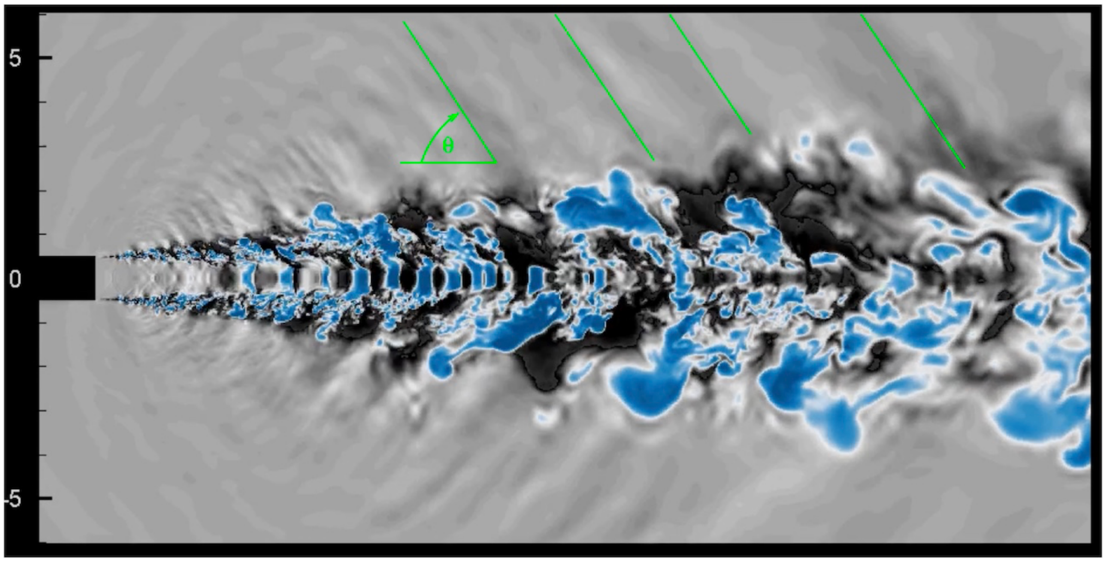

Figure 7. Radiation of large acoustic pulses from the jet in the region downstream of the end of the potential core in the form of Mach waves. The Mach waves are marked by green lines.

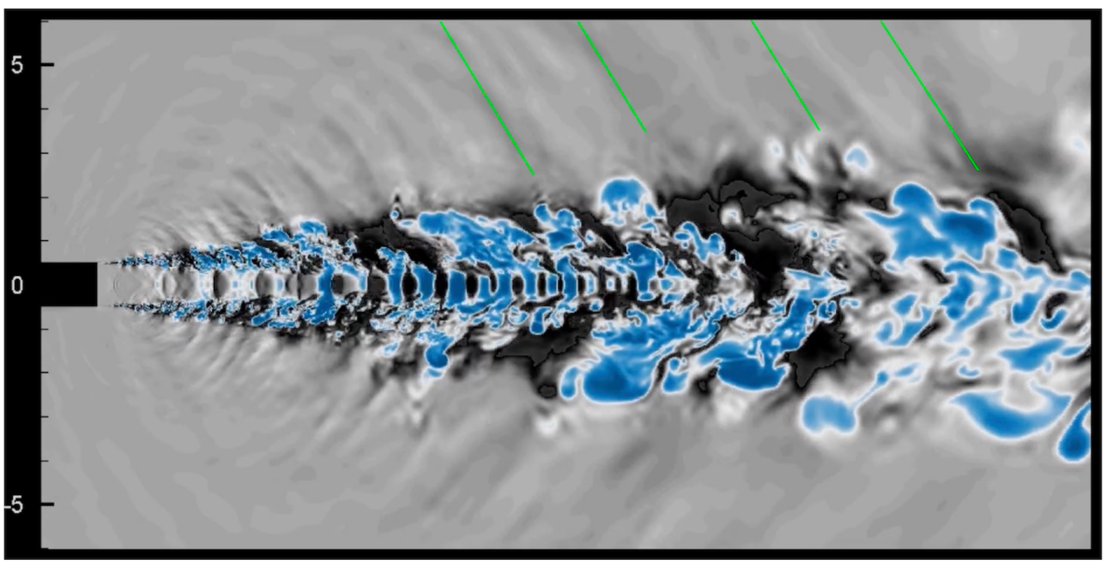

Figure 8. Another snapshot from the video showing the radiation of large acoustic pulses in the form of Mach waves.

Fig. 9 is a superposition of three far field noise spectra at 144^0, 148^0 and 152^0 based on the University of Cincinnati data. The 148^0 spectrum is the green spectrum. This spectrum appears to have one of the highest peaks. In Fig. 9 the red arrow points at the 5.3 kHz frequency; the frequency of Mach wave radiation of the simulated jet. This peak frequency from computer simulation is very close to the experimental value of 5.0 KHz. The good agreements in the direction of peak noise radiation and peak frequency in the noise spectrum provide us with additional confidence in the quality and accuracy of our CAA code.

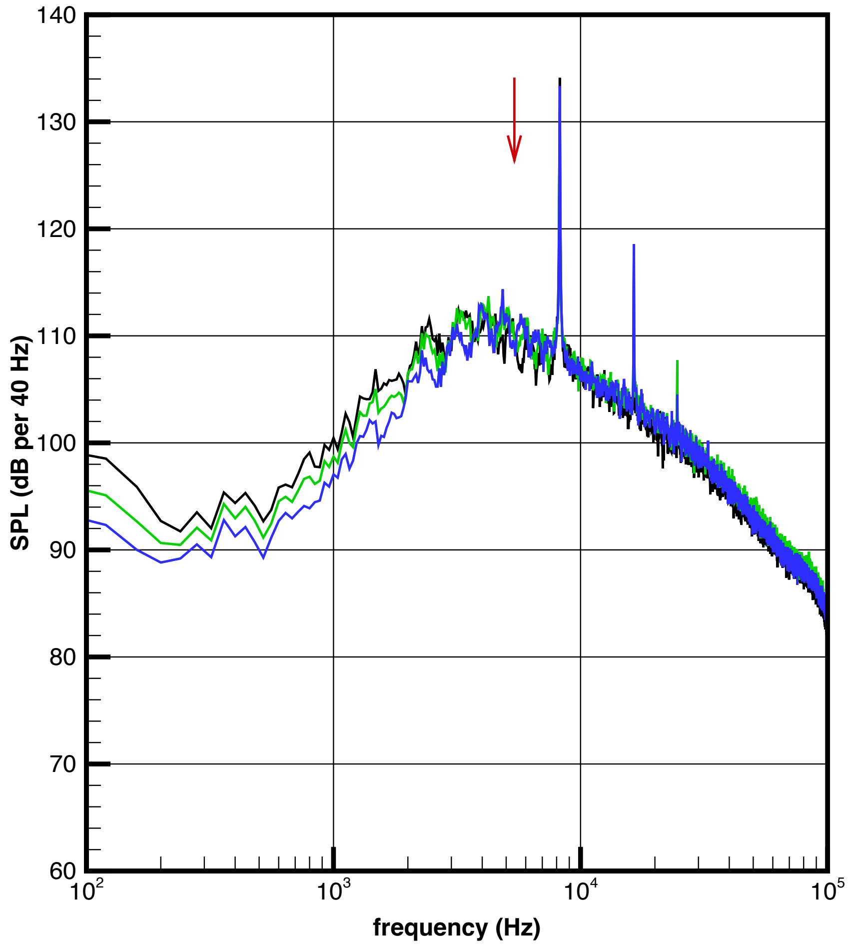

Figure 9. Superposition of three noise spectra at directions of 144^0, 148^0 and 152^o. The green curve is the spectrum at 148^o direction. The red arrow points at the frequency of 5.3 kHz. The frequency at the peak of the spectrum is 5.0 KHz.

Fig. 10 is another snapshot taken from the video. A blue dash line has been inserted in the picture. The dash line separates the sound field into two regions. They are the high frequency and the low frequency regions. To the left of the dash line, the sound pulses have short wavelengths, and the sound has high frequency. To the right of the dash line, the sound pulses are much larger. They form a low frequency sound field. This large pulse sound field is located downstream of the end of the jet potential core. The information provide by this figure is consistent with that observed in the near field of a solid propellent rocket (see Fig. 3). Thus, to reduce large turbulent structures noise of a supersonic jet, a method to reduce large sound pulses downstream of the end of the potential core (marked by a red 'X') would be necessary.

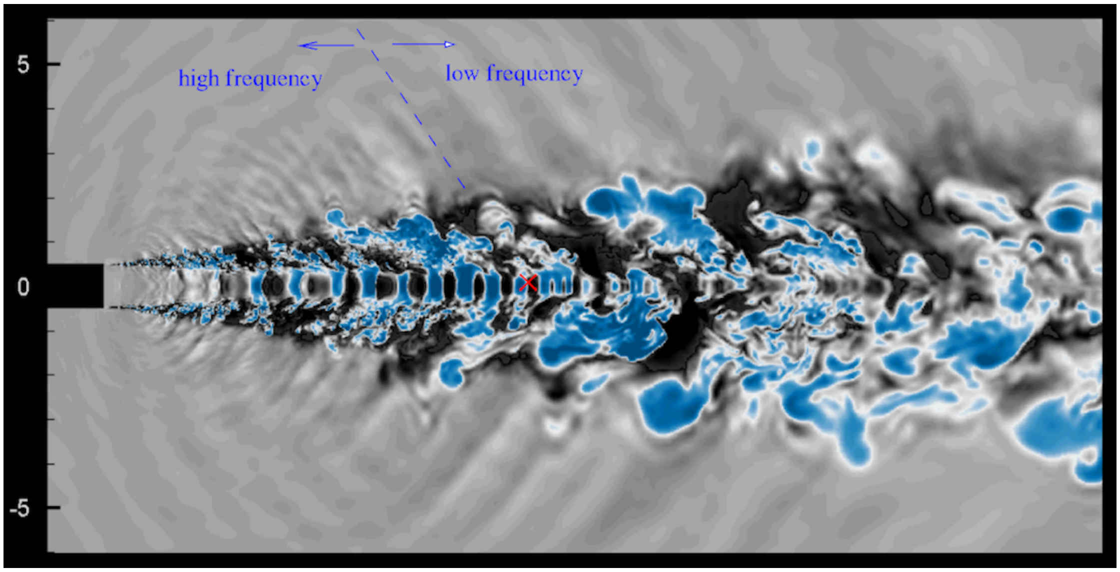

Figure 10. A snapshot from the video. The blue dash line in this figure separates the high frequency short wavelength region from the low frequency large sound pulse region. The transition from one region to the other takes place near the end of the potential core of the jet.

Fig. 11 is another snapshot taken from the video. Notice that there are three acoustic pulses marked A, B, and C in upper part of this figure. By running the video backward, it is found the pulses all emerge from the jet flow downstream of the location marked ‘D’. This establishes firmly that the large Mach wave pulses are emitted by the jet flow downstream of the potential core.

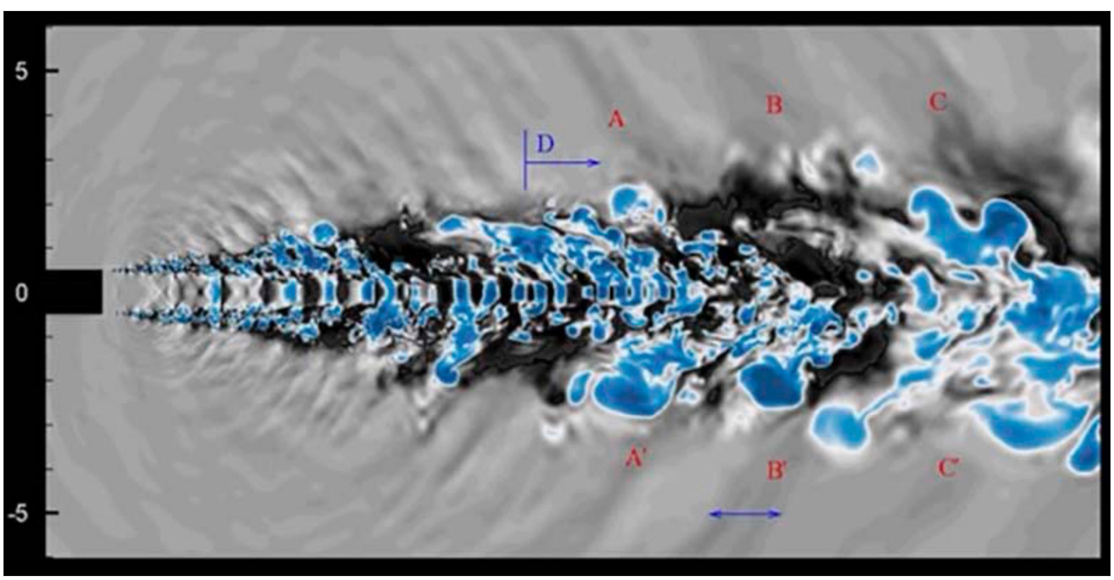

Figure 11. A snapshot from the video showing three large sound pulses A, B, and C radiating from the jet. Showing also are three mirror image pulses A’, B’, and C’. D marks the location downstream of which is the region of the jet from which large acoustics pulses are emitted.

In Fig. 11 on the lower side of the jet, there are three pulses marked by A', B' and C'. These three pulses are mirror image of the pulses A, B and C on the other side of the jet. The fact that the jet emits symmetric sound pulses indicates that the sources of sound pulses are axisymmetric with respect to the jet flow under the present jet operating condition. Furthermore, the size of pulse B', indicated by the blue line nearby is large. It is about a quarter of the local diameter of the jet. For Mach wave radiation the size of the source and the emitted sound pulse must have nearly the same size. Thus, the source of sound are not localized point sources. They are definitely not point quadrupoles as hypothesized by Acoustic Analogy theories. We believe they are large turbulence structures as first observed by Brown and Roshko [68] and later by others e. g. Ref. [69, 70, 71]. In the turbulence research community they are referred to as large turbulence structures. For the present jet, the large turbulence structures seem to have the form of a row of toroidal donut-shape vortices.

III. A proposed turbulent mixing noise reduction scheme for supersonic jet.

It is self-evident that to reduce jet noise one has to disturb the jet flow in some way. One hopes that the disturbances introduced into the jet flow would interact with the jet turbulence resulting is a decrease in noise generation. For practical reasons, the input of disturbances into a jet has to be carried out near the nozzle exit as shown in Fig. 12. Now, we know the sources of large turbulence structures noise are located downstream of the end of the potential core. Surrounding the core is a turbulent shear layer. Thus, the input disturbances have to pass through this turbulence field to reach the noise sources. The energetic, random motion of turbulent fluid, invariably, would destroy any coherent input disturbances. Therefore, it is likely that little of the disturbances introduced into the jet flow would reach the source region of the large turbulence structures noise. This explains why most of the noise reduction effort in the past have not been considered effective.

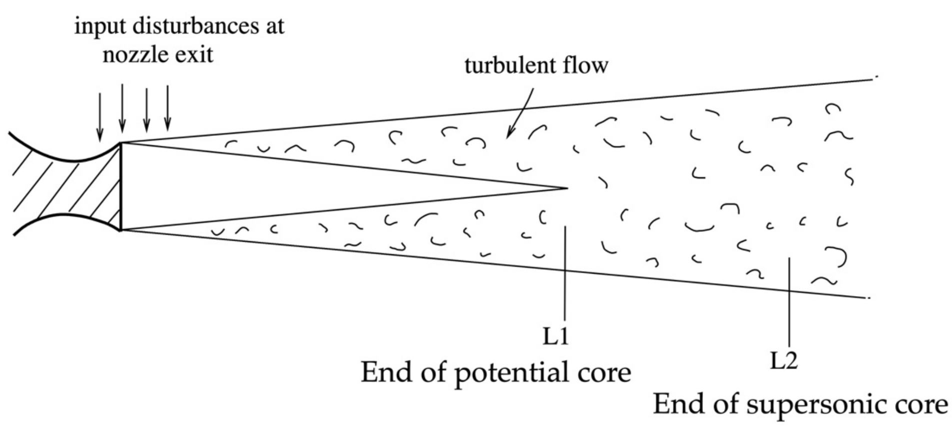

Figure 12. A schematic diagram showing the input disturbances at the nozzle exit and the turbulence field the disturbances have to pass through to reach the source of the large turbulence structures noise.

Fig. 13 is a shadowgraph showing a Mach 1.71 cold jet undergoing large scale oscillations induced by Kelvin-Helmholtz instability. The oscillations driven by the instability wave can easily be seen. Simple measurements reveal that the clear strong oscillations extend well over fourteen jet exit diameters downstream. This is well beyond the length of the jet potential core.

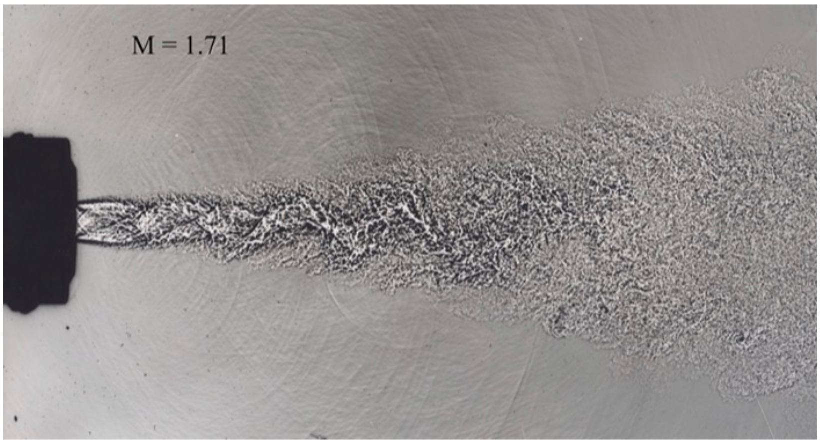

Figure 13. Shadowgraph of a Mach 1.71 cold jet undergoing large scale oscillations driven by Kelvin-Helmholtz instability.

Fig. 14 is a shadowgraph of a Mach 2.6 cold jet. It is well-known that at higher jet velocity the spatial growth rate of Kelvin-Helmholtz instability is reduced. We believe it is for the reason that the jet does not exhibit any oscillations in the initial part of the jet flow downstream of the nozzle exit. However, beyond about ten jet diameters, clear jet oscillations appear. The oscillations continue to about sixteen jet diameters before they become blurred. This confirms that the spatial growth rate of Kelvin-Helmholtz instability is weaker at high jet velocity. It takes time and hence propagating distance for the oscillations to become large enough to be observable. Measurements confirm that readily observable oscillations extend beyond sixteen jet diameters downstream. This distance easily puts the influence of natural instability wave beyond the end of the potential core of the jet.

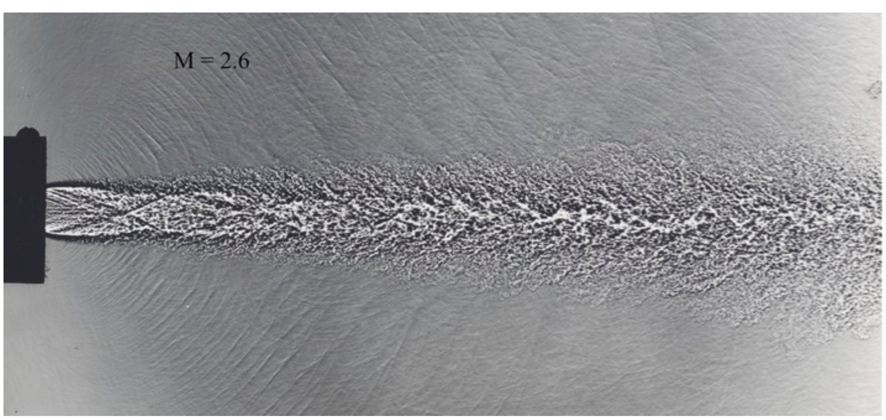

Figure 14. Shadowgraph of a Mach 2.6 cold jet. Jet oscillations cannot easily be observed in the initial part of the jet. Oscillation becomes visible at about ten jet diameters downstream of the nozzle exit. Oscillations extend to about 16 jet diameters before becoming blurred.

Figs. 13 and 14 make it clear that for supersonic jets natural Kelvin-Helmholtz instabilities can extend their influence from the nozzle exit to distances beyond the end of the jet potential core. This is so despite the jet flow is turbulent. Based on this observation, we believe that the natural jet instability waves could be used for jet noise reduction purpose.

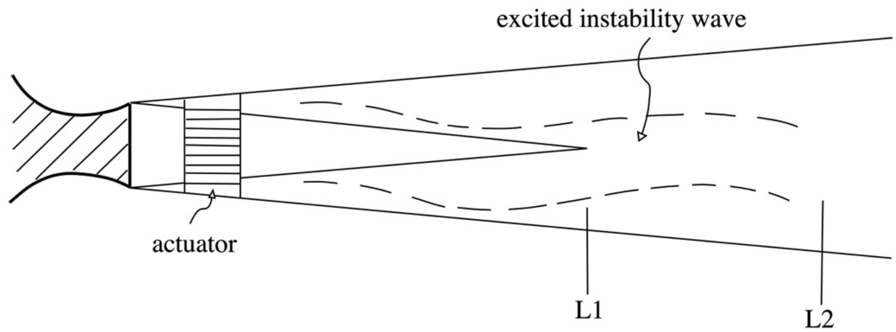

Figure 15. Schematic diagram showing the use of an actuator to excite a carefully chosen instability wave to exert influence/control over the turbulent mixing process downstream of the end of the jet potential core.

Fig. 15 shows schematically our proposed supersonic jet noise reduction scheme. We envisage the installation of an instability wave actuator near the nozzle exit. In an experiment the actuator could be housed inside the nozzle or be a part of the nozzle wall. It is shown outside in Fig. 15 because it is easier to install such an actuator computationally. By exciting an instability waves at a frequency and mode number with the largest total spatial growth (between the nozzle exit and the end of the potential core) it would be possible to exert effective influence on the turbulence and the mixing process downstream of the potential core of the jet. This will represent a first step in exercising control of the source of the large turbulence structures noise. Once effective influence/control is established, the second step is to learn/devise how to optimize the control to maximize jet noise reduction. The learning process is not a simple one for the turbulence mixing process is quite complex. In addition, one has to deal with a number of variables such as jet Mach number, temperature ratio, the presence of a shock-cell structure and other factors like the presence of an afterburner.

IV. Conclusions and future work

Previous experiments have indicated that the sources of large turbulence structures noise are located downstream of the jet potential core, Refs. [63, 64]. To supplement this experimental finding, in this work a numerical simulation study is carried out. A high quality, high resolution CAA code is employed. Snapshots are taken from a video made from the numerical results of a LES simulation of an overexpanded supersonic jet. These snapshots offer new understanding and insight into the noise generation processes and the characteristics of the source of sound. The snapshots show that the acoustic near field is made up of large sound pulses emitted from the jet flow downstream of the potential core. This confirms the experimental result of Ref. [64]. For the jet under consideration, the sound pulses are in the form of Mach waves. In most observations, the Mach waves form two rows of pulses on opposite side of the jet. The pulses are symmetric with respect to the jet axis. This means that the noise source is axisymmetric most of the time. The sound pluses are large. Their size is approximately equal to one quarter of the local jet diameter. Since in Mach wave radiation, the size of the acoustic pulse and that of the source are nearly the same, it is believed that the actual sources are large turbulent toroidal vortical structures. In the turbulence research community these structures are referred to as large turbulence structures. The above findings are new. It is our expectation that they could be very useful in the next phase of this project.

In section III a supersonic jet noise reduction scheme is proposed. However, before the scheme can be implemented experimentally, it appears that several tasks have to be carried out first. These tasks are:
(a) Development of a numerical instability wave actuator.
(b) Determining the best frequency and mode number of the natural instability waves of the jet to excite.
(c) Performing a computational proof-of-concept demonstration by a CAA code.

In this paper, one of our goal is to look at jet noise reduction from a different perspective. Whether our proposed noise reduction scheme is viable, of course, remains to be proven. It is, however, our hope that more capable minds would join in the pursue of jet noise reduction.

Acknowledgement

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