RESPONSE OF MULTI-PANEL ASSEMBLY TO NOISE FROM A JET IN FORWARD MOTION

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Abstract

A model of the interaction of the noise from a spreading subsonic jet with a 4 panel assembly is studied numerically in two dimensions. The effect of forward motion of the jet is accounted for by considering a uniform flow field superimposed on a mean jet exit profile. The jet is initially excited by a pulse-like source inserted into the flow field. The pulse triggers instabilities associated with the inviscid instability of the jet shear layer. These instabilities generate sound which in turn serves to excite the panels. We compare the sound from the jet, the responses of the panels and the resulting acoustic radiation for the static jet and the jet in forward motion. The far field acoustic radiation, the panel response and sound radiated from the panels are all computed and compared to computations of a static jet. The results demonstrate that for a jet in forward motion there is a reduction in sound in downstream directions and an increase in sound in upstream directions in agreement with experiments. Furthermore, the panel response and radiation for a jet in forward motion exhibits a downstream attenuation as compared with the static case.

1. Introduction

This paper describes the results of a numerical simulation of jet noise in the presence of four flexible aircraft-type panels in a panel-stringer assembly. The simulation is based on a model which fully couples the fluid dynamics of the jet flow to the panel motion and the resulting acoustic radiation while accounting for the forward motion of the jet. The primary objective is to determine the role played by forward motion on installation effects from the nearby flexible structure and on the response and the acoustic radiation from the structure.

In previous work[18] we have computed the far field sound, panel response and radiation from a static jet with a two panel model. Computations with a static jet model the response of a jet on the ground. However, the acoustical behavior of a static jet is not sufficient to determine the behavior for a jet in flight. The noise radiated from the jet in the downstream direction should decrease with an increase in the forward velocity from its static level due to the reduced shear resulting from the lower relative velocity between the jet and its surroundings. The effect of forward motion on panel response and radiation has not yet been completely determined. We describe here the effect of forward motion on the response and radiation of the panels. We note that the results presented here do not include the effect of the boundary layer on panel excitation in the forward motion case. It is possible that for some parameter range, the boundary layer can result in enhanced loading on the panel with increasing forward velocity.

The problem of simulating the behavior of a jet in flight has previously been studied analytically and experimentally. Analytic methods generally begin with a formulation of the exact sources,[15, 25] and models of the sources to account for flow effects.[10, 15] Models of the Lighthill sources have been applied within a convective wave equation formulation to develop scaling relations between static measurements and measurements in flight.[22] These analyses demonstrated reduction in noise emmision downstream of the jet together with amplification in the forward direction under certain circumstances.

There have also been extensive experimental studies of forward motion effects. Measurements on a moving structure, the Bertin Aérotrain, have been reported.[9] These results, obtained for locations fixed on the ground, showed a general reduction in level along the jet axis, but under certain conditions there was sound amplification in forward directions. Measurements of a jet in flight[5] and wind tunnel measurements, in which the forward motion effect is simulated by co-flowing air streams and measurements are taken at points fixed with respect to the jet, have also been obtained for both subsonic and supersonic jets.[6, 24, 26] A comparison of sound produced by a moving jet with wind tunnel measurements was performed (i.e., receivers fixed with respect to the ground and receivers fixed with respect to

the jet) and indicated that both methods gave qualitatively similar results.[23]

An important feature of our model is the direct computation of at least some of the natural sources of jet noise, namely fluid dynamical instability waves which develop due to instability of the jet shear layer. Experiments have demonstrated the existence of large scale structures or instability waves in jets.[7, 14, 19] These structures are believed to act as sources of sound, a point also confirmed by analytical studies[4, 13, 21, 20] and computations.[1, 17, 19]

Various approaches have been employed to determine the panel response to jet noise or to other sources which can not be easily calculated. In one important approach the sources in the flow field can be taken from experimental measurements, (e.g., [8]). The panel response could then itself be computed via solution of the resulting panel equation from the measured sources as in [8]. In the approach adopted here, the panel sources are computed from the fluid dynamics and acoustics of the jet and employed in a fully coupled manner to compute panel response.

The geometry of our computational model can be seen in Figure 1. We solve the Euler equations in two domains, the jet domain and the radiation domain simulating the aircraft cabin. Panel response and radiation are also computed and are fully coupled to the fluid dynamics in the sense that the fluid dynamics computation provides the pressure difference across the panels while the computation of the panel displacement provides a boundary condition for the fluid computation. The jet is initially excited by a starter pulse, represented as a finite duration source in the Euler equations. The initial pulse propagates through the jet flow field, thus allowing a study of propagation effects with forward motion. The pulse also excites instability waves in the jet. These waves are sources of sound radiating into the far field, leading to sustained acoustic activity in the jet. Thus, since our model allows computation of these important natural sources of jet noise, the forward motion effect on these sources is computed rather than modeled. In addition, the excitation of the panel (i.e., the pressure difference across the panels) is computed directly from the Euler equations and fully coupled to the motion of the panels so that no modeling of the panel excitation is employed.

The paper is organized as follows. In section 2 there is a description of the model and a discussion of the numerical method and boundary conditions. In section 3 we present our results. In section 4 we summarize our results and provide conclusions.

2. Problem Formulation

The computational domain is shown in Figure 1. Unsteady pressure, density and velocities are computed in two domains, that which contains the jet, exiting from a nozzle of width D,

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and the domain on the other side of the wall boundary. We will refer to the two domains as the jet and radiation domains respectively. The wall boundary is a rigid wall containing 4 adjacent flexible panels (denoted as panels 1-4 in Figure 1) with rigidly clamped boundaries. The panels vibrate in response to excitation from jet noise and radiate sound into both domains. We focus primarily on acoustic radiation into the radiation domain, as the radiation into the jet domain is small compared to the large disturbances already present in the jet.

The numerical method involves coupling the computation of a nonlinear equation governing the panel responses (the beam equation) to an Euler computation performed in both the jet and radiation domains. The panel vibration is fully coupled to the fluid dynamics in that at each timestep the pressure difference across the panels, computed from the Euler computations, serves as a forcing term for the beam equation. Similarly, the displacement obtained from the beam equation is differentiated in time and is imposed as a boundary condition for the Euler computations. The numerical method has been described in detail.[18] The presentation here will be brief.

The nonlinear beam equation is

$$D_b \frac{\partial^4 z}{\partial x^4} - N_x \frac{\partial^2 z}{\partial x^2} + \rho_b h \frac{\partial^2 z}{\partial t^2} + \gamma \frac{\partial z}{\partial t} = p^+ - p^-, \tag{1}$$

where z represents the beam transverse deflection, ρ_b the mass per unit volume of the beam, h the beam thickness, γ the physical damping, and $D_b = Mh^3/12(1 - \nu^2)$ is the stiffness of the beam where M is the modulus of elasticity and ν is the Poisson ratio of the beam material. The coefficient N_x of the nonlinear term represents the tension created by the stretching of the plate due to bending. The pressures in the radiation and jet domains are p^+ and p^- respectively. The solution of (1) is obtained at each timestep using an implicit finite difference method. The panels are assumed clamped at both ends.

The coupling of the beam computation to the Euler computation occurs through the forcing term given on the right hand side of equation 1. The pressures p^+ and p^- are obtained from the Euler computation using an explicit scheme. The displacement at the new time level is then obtained from solving (1) one time step. The normal velocity, v, is then obtained from differentiating z and employed as a boundary condition to complete the update to the Euler computation. Since this procedure is employed at each timestep, the fluid and structural calculations are fully coupled.

The Euler equations are solved in conservation form for the vector

$$\hat{\mathbf{w}} = (\rho, \rho u, \rho v, E)^T,$$

where ρ is the density, u, v are the x and y components of the velocity respectively and E is

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the total energy per unit volume,

$$E = \frac{1}{2}\rho(u^2 + v^2) + c_v\rho\tilde{T},$$

where $\tilde{T}$ is the temperature and c_v is the specific heat per unit volume. The pressure, p, is obtained from the equation of state. The Euler equations are solved separately in both the jet and radiation domains.

In the jet domain the Euler equations are modified to account for the jet flow. We assume a straight pipe of width D from which the jet exits. The solution is computed both within and exterior to the pipe. The Euler equations are modified to account for two different source terms.[18] One source serves as a starter pulse to excite the jet. It corresponds to a localized source of mass injection at the location (x_s, y_j), where y_j is the location of the jet axis (approximately $6D$ from the wall) and x_s is approximately $1.2D$. The second source term is designed so that in the absence of the starter pulse the solution to the Euler equations would be a stationary profile corresponding to a spreading jet. The inclusion of this source term separates the computation of the disturbance, in particular the resulting instability waves, from the computation of the mean flow (i.e., the spreading jet). Thus, the resulting system of equations allows for the simulation of instability waves and the resulting sound generation, together with the bending of acoustic waves in the jet flow field without requiring the computation of the spreading jet itself. Although this is a simplified model, the resulting system captures many of the observed features of instability wave generated jet noise and permits high resolution computation of the coupling of jet noise with the flexible panels and the resulting radiation from the panels. In particular, the model allows for computation of the natural sources of jet noise (the instability waves) together with the sound radiated by these sources.

The initial conditions are taken to be the mean state $\hat{\mathbf{w}}_0$ in the jet domain and ambient data in the radiation domain. The boundary conditions are as follows (refer to Figure 1):

1. Bounding wall - rigid conditions are imposed except for the flexible panels which are treated as described above.

2. Pipe - rigid on interior, impedance on exterior. The use of impedance boundary conditions on the exterior of the pipe simulates the use of an absorbing material to absorb waves incident on the pipe from the exterior.

3. Inflow for the pipe - characteristic conditions. Specifically we linearize the Euler equations about the ambient state, assumed to hold far upstream in the pipe, and impose the three incoming characteristics,

$$p + \rho cu, \ v, \ c_\infty\rho - p/c_\infty$$

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to be the values that they would have far upstream. It has been shown[19] that this boundary condition is valid for the lowest propagating mode in the pipe. The boundary condition can lead to reflections on higher modes, however any such reflections do not effect the data outside the pipe for the time intervals considered here.

4. All other boundaries in the problem are artificial. Non-reflecting (radiation) boundary conditions are imposed to prevent spurious reflections from propagating into the interior. These boundary conditions are based on a far field expansion of the solution.[2, 3]

When there is forward motion, two additional boundary conditions should be imposed at inflow. We impose the conditions

$$c_\infty \rho - p/c_\infty = c_\infty \rho_\infty - p_\infty/c_\infty,$$

simulating isentropy at inflow, and

$$u_y - v_x = 0,$$

simulating irrotational flow at inflow. For the values of the forward motion motion considered here these boundary conditions have a negligible effect on the solution.

We employ a finite difference scheme which is fourth order accurate in space and second order in time. The scheme is a generalization of the second order MacCormack scheme to allow higher order accuracy in space.[11] The scheme is discussed in detail in other publications.[17, 19]

3. Results

We consider a configuration as indicated in Figure 1. The jet exits from a straight nozzle of width $D = 2$in. The infinite wall is located approximately $6D$ above the jet and parallel to the nozzle. The wall is assumed rigid, except for four regions where flexible, aluminum, aircraft-type panels with clamped boundaries are located. The panels are of length $5D$, thickness $0.01D$ and are centered at $x = 0D$, $x = 5.22D$, $x = 10.44D$, and $x = 15.66D$ respectively. We refer to these panels as Panels 1, 2, 3 and 4. Other parameters of the panels are typical of aluminum. The parameters of the starter pulse have been reported previously.[18] The peak frequency is close to 1000 Hz.

The origin of coordinates is chosen to be the horizontal location of the nozzle exit for x and the vertical location of the rigid wall for y. Both the jet and radiation domains extend $48D$ downstream from $x = 0$, $36D$ in the upstream direction and $48D$ in the y direction. We employ a grid of 811×501 points in the jet domain and 441×301 points in the radiation domain. The grid in the jet domain is stretched to improve resolution of the jet shear layer

and source region. The grid in the radiation domain is uniform. The computations have been validated by grid refinement.[18]

We consider two computations. In the first computation we assume a static jet with exit velocity $U_j = 0.65\,c_\infty$. We refer to this computation as the static computation. In the second computation we model a forward motion effect with a uniform flow of speed $U_f = 0.20\,c_\infty$ in the $x-$direction superimposed on the jet mean flow. The Mach number for the mean jet profile is 0.45 so that the exit velocity from the nozzle is still $0.65\,c_\infty$, but the jump in velocity across the jet boundary is now $0.45\,c_\infty$. We refer to this computation as the forward motion computation. This models a wind tunnel experiment of forward motion effects. We note that in the forward motion computation, we compute the sound at points which are fixed with respect to the jet, simulating measurements at a fixed location in a wind tunnel.

Our results are presented in three parts; the jet domain, including the flow and acoustic radiation from the jet, the responses of the panels and the acoustic radiation from the panels.

3a. Jet Flow Domain

Nonstationary behavior in the jet is triggered by the pulse starter, which generates a disturbance that propagates through the jet, interacts with the shear layer and then propagates into the farfield as sound. This disturbance is non-circular due to the flow. Additional disturbances due to purely geometric affects, such as reflection from the wall and scattering from the nozzle lip, are also generated. In addition, instability waves are generated due to the interaction of the acoustic disturbance with the shear layer gradient of the jet profile. These instability waves propagate slowly downstream along the jet axis and are sources of sound;[17] indeed they are important natural sources of sound in subsonic jets. After an initial growth, their amplitude decays due to the spreading of the mean velocity.

As the instability waves propagate downstream they act as sources of disturbances which propagate into the far field as sound.[15, 16, 20, 21, 25] These disturbances also trigger additional disturbances from the nozzle lip, leading to a sustained response of the jet. This behavior is also consistent with experimental observations[4, 7] and with previous linear and nonlinear computations.[19, 1] The resulting sound radiation forces the panels into a broadband, sustained response which in turn leads to a sustained radiation of sound from the panels. The acoustic radiation persists after the initial disturbance generated by the pulse starter has propagated a significant distance from the panels and away from the region of interest.

In this section we examine both the total pressure history at given far field locations (i.e., including both the starter pulse and the jet noise generated by the instability waves) and only the jet noise. In the later case we consider a specified interval in nondimensional time

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t $(10 \leq t \leq 15)$ after the starter pulse has passed through the selected points. Changing the selected interval leads to quantitative changes but does not change the qualitative pattern of the far field sound. Examination of the starter pulse permits a study of the effect of forward motion on wave propagation through the jet flow while examination of the long time behavior permits a study of sound generation from the instability waves.

It has been both observed and predicted that forward motion leads to a reduction in sound downstream of the jet and an increase in sound in the upstream direction (i.e., a forward arc amplification[9, 22]). We illustrate this in Figure 2a where we plot the logarithm of the time integrated intensity I, i.e.,

$$I = 10 \log_{10}(\int_0^T \tilde{p}^2 \, dt/T)$$

around a circle of radius $30D$ from the source. The decibel level is normalized to 0 for the static computation at 90°. The results clearly demonstrate the downstream attenuation of sound and upstream amplification in qualitative agreement with experiments and analysis. We note that the forward arc amplification is noticeable only for angles greater than 90°. The level of sound with forward motion is nearly the same as for the static computation at 90^0.

In Figure 2b we plot the analogous figure for

$$\tilde{I} = 10 \log_{10}(\int_{t_1}^{t_2} \tilde{p}^2 dt/(t_2 - t_1)),$$

where $t_1 = 10$ and $t_2 = 15$ thus examining the effect of forward motion on sound generated from the jet. The data is again normalized so that 0 db is at 90° for the static computation. We note that the qualitative effect of forward motion is similar; there is a reduction along the jet axis and a forward arc amplification. We note that there are now significantly larger differences between the computations with and without forward motion, thus indicating a greater effect of forward motion on sound generation from the instability waves than from wave propagation.

In summary these figures indicate that the observed properties of forward motion, namely a reduction in observed sound downstream and an amplification upstream can be explained as both a wave propagation effect, as evidenced by the behavior shown in Figure 2a accounting for the total pressure field, and as a sound generation effect, as shown in the long time behavior in Figure 2b.

Examination of the pressure histories for $\tilde{p} = p - p_\infty$ at various angles, confirm the results in Figures 2a and 2b. In particular, there is an amplification at mid angles both with and without forward motion. There is very little effect of forward motion at 90°. The primary effect of forward motion is to attenuate low frequencies for low to mid-range

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angles downstream. Examination of the spectrum of $\tilde{p}$ indicates that the installation effect, i.e., forward motion, reflections from the wall and coupling between the wall and the jet, significantly alters the spectrum of the far field sound, particularly for low to mid-range angles.

3b. Panel Response

We categorize the panel response by considering (i) the pressure incident on the panels, (ii) velocities of the panels and (iii) transmitted pressure.

In Figures 3a and 3b we consider the pressure at the panel centers on the jet side for panels 1 and 2 (Figure 3a) and panels 3 and 4 (Figure 3b), respectively. Although this data includes the effect of reflections from the panel, these reflections are small compared to the pressure incident from the jet and we refer to this quantity as the incident pressure. All figures are plotted on the same scale. The effect of convection can be seen in that for panel 1 (upstream of the source) the primary arrival is slightly delayed with forward motion, while for the other panels the primary arrival is advanced with forward motion. The time difference between the leading arrivals with and without forward motion increases with distance of the panel from the source location. There is a slight increase in level for panel 1 (consistent with the forward arc amplification observed in Figure 2a for the far field pressure). There is an overall reduction in level for the primary arrivals for the downstream panel, again consistent with the downstream attenuation due to forward motion.

Only very weak additional arrivals are observed for panel 1. In previous calculations we have found that panel 1 is only weakly influenced by sound from the instability waves. Rather, the primary feature of panel 1 is the geometric effect of repeated reflections between the nozzle and the panel. This was pronounced in analogous results without forward motion[18] where the exterior surface of the nozzle was assumed rigid. In the present computations we have employed impedance conditions on the exterior surface of the nozzle in order to deemphasize these reflections which are not of direct interest in this paper.

The effect of additional arrivals, due to additional sound generated from instability waves can first be seen for panel 2, and becomes more pronounced for panels 3 and 4. The time duration of these additional arrivals increases with the downstream distance of the panels, suggesting panel excitation at lower frequencies which is confirmed by the spectral plots below. It is clear from the figures that the amplitude of these additional arrivals is reduced due to forward motion. Furthermore the amount of the reduction increases with the downstream distance of the panels.

The spectra of the incident pressure is shown in Figure 3c for panels 2 and 4. The data in this figure is normalized by the maximum over both panels. It can be seen that the

pressure incident on panel 2 is more broadband than for panel 4 where the spectrum exhibits a more rapid roll off with increasing frequency. Thus the spectrum is more concentrated at lower frequencies as the downstream distance of the panel increases, consistent with the time histories in Figures 3a and 3b. The lowest frequencies are significantly enhanced for panel 4. We believe that the relatively large secondary arrivals in the static case, due to sound generated from instability waves, leads to an interference effect which causes the oscillatory character of the spectrum in this case. These arrivals are weaker with forward motion, thus resulting in a smoother spectrum. In both cases the attenuation due to forward motion can be seen to be concentrated in the low to middle frequency band. There is virtually no attenuation due to forward motion for frequencies greater than 1500 Hz.

In Figure 4a we show time histories of the normal velocities (v) at the panel centers for panels 3 and 4. There is a sustained long time oscillation for v, even after the primary wave of incident pressure has passed by the panel. This is probably due to the low level of damping of the panels and panel excitation by disturbances shed from the instability waves. There appears to be little qualitative difference between the time histories for v as the downstream distance of the panel increases. Furthermore, the time histories with and without forward motion are similar. This suggests that much of the differences observed in the incident pressure due to panel location and to forward motion are not transmitted to the panel motion.

This is supported by analysis of the spectrum of v (not shown), which is relatively discrete. This is consistent with previous results[18] and indicates that the panels act as filters to convert the relatively broadband incident pressure into relatively discrete spectral bands for the panel response. In addition, the peak frequencies appear to be relatively insensitive to panel location and to whether forward motion is present or not. The frequency response is very similar for all panels and for the computations with and without forward motion.

In Figure 4b we plot v along each panel for different values of non-dimensional time, t. The figures are for the time window $7 \leq t \leq 10$. The predominant effect is that of waves propagating in both directions along each panel and reflecting from the clamped edges. The dark spots on the figures correspond to space/time locations where right moving and left moving waves intersect. Generally these intersections occur with a phase lag from panel to panel indicating the convection of disturbances along the panel array. This is particularly noticeable in comparing panels 2, 3 and 4. Due to the restriction to a specific time window, this figure is most useful for assessing panel response in the mid and high frequency range. Low frequency responses would not be brought out in these figures. Also note that each figure is internally scaled so that amplitude effects from panel to panel would not be visible in

these figures. Corresponding figures for the static computation (not shown) are qualitatively similar, confirming the conclusions drawn from the more detailed Figure 4a that differences in incident pressure due to forward motion are manifested primarily in the amplitude of the panel response in the low frequency range.

In Figure 5 we consider the pressure in the radiation domain directly behind the panels (transmitted pressure) and at the panel centers for panels 3 and 4. The transmitted pressure exhibits features of both the incident pressure and the panel velocity. There is an initial disturbance corresponding to the incident pressure wave and a long time sustained response. This response is largely due to the low damping of the panels although the excitation of the downstream panels, particularly panel 4, is also influenced by relatively large later arrivals generated from the instability waves.

Examination of the other panels indicates that the amplitude of the primary disturbance is slightly delayed and enhanced for panel 1, consistent with the behavior of the incident pressure in the jet domain. For the other panels the incident wave arrives earlier and is attenuated with forward motion. Thus, these effects of forward motion are transmitted into the radiation domain. There is a noticeable attenuation in the amplitude of the long time pressure disturbances for panel 4 with forward motion. This may be due to the enhanced low frequency forcing of panel 4.

Examination of the spectral content of the transmitted pressure (not shown) indicates a behavior similar to that observed for v. The spectrum is again composed of relatively discrete frequency bands in contrast to the incident pressure, illustrating the role of the panels as a filter to convert the relatively broadband incident pressure into discrete frequency bands. In the low frequency range, the characteristic frequencies of the bands appear to be relatively insensitive to the panel location or to whether there if forward motion or not. The predominant effect of the transmitted pressure is the large low frequency responses for panel 4, and the relatively large attenuation of this response with forward motion.

In summary these figures indicate that (i) the panels act as filters converting broadband incident pressure into relatively narrow spectral bands, (ii) panels located farther downstream are excited at lower frequencies and (iii) an important effect of forward motion is to attenuate the low frequency forcing for panels farther downstream, resulting in a significant attenuation in panel response and radiation.

3c. Acoustic Radiation from the Panels

We have computed the radiated pressure for various x locations on a line $y = 18D$ (corresponding to 3 ft.) in the radiation domain. Results for 3 different x locations are shown in Figure 6a. The x locations are indicated in feet on the graph. The results show a leading ar-

rival, followed by sustained pressure disturbances, similar to the transmitted pressure shown in Figure 5a. There is a strong attenuation in the pressure for upstream locations, indicating a preferred beaming of the radiated pressure in downstream directions. The convective effect of forward motion is apparent in comparing the arrival times of the primary wave for the 3 x locations. There is a slight delay with forward motion for the upstream location. There is no noticeable time lag or advance when the x location is close to the location of the nozzle exit (we refer to this as the vertical location). The leading wave arrives noticeably earlier for the downstream location when there is forward motion in the jet domain. We also note that forward motion results in a slightly greater response upstream and a significant attenuation downstream, analogous to properties in the jet domain. There is virtually no difference in level for the vertical response (i.e., at 90° from the jet axis). We note that these properties are transmitted via the panel radiation as there is no forward motion in the radiation domain.

The upstream response is significantly smaller than the vertical or the downstream response, indicating a preferred downstream beaming of the radiated sound. This preferred downstream beaming is apparent with and without forward motion and confirms previous results[18] for a two panel computation without forward motion. The primary effect of forward motion is to reduce the downstream sound in the radiation domain. These results are further shown in Figure 6b, where the total integrated intensity is plotted as a function of x along the line $y = 18D$. The data is expressed in decibels and normalized to 0 db for the vertical location with no forward motion. We note that this data is presented along a line, so that there is an effect of cylindrical decay of the waves for large values of x. However, the preferred downstream beaming is apparent, as is the attenuation due to forward motion.

In summary:

1. Convective properties of the forward motion (i.e., delayed arrivals upstream and earlier arrivals downstream) are transmitted to the radiation domain via transmission through the panels.

2. There is a preferred downstream beaming of sound in the radiation domain. This is true with and without forward motion.

3. Forward motion significantly attenuates the radiated pressure in downstream directions (i.e., reduces but does not eliminate this preferred beaming).

3d. Overall Flow Field

In Figure 7 we show the pressure field in both the jet domain and the radiation domain for a fixed instant of time for the forward motion computation. The value of the nondimensional

time is 11.4. Examination of the radiation domain shows propagation of high frequencies, characterized by closely spaced contours upstream, whereas the pressure field downstream is primarily low frequency in nature as seen by the less dense contour distribution. This is consistent with the integrated intensity in Figure 6b because the higher energy levels at downstream locations shown in that figure are at lower frequencies. An important feature of the jet domain is the instability wave, the large scale structure propagating along the jet axis. The incipient generation of acoustic waves from this instability wave and also from the nozzle lip can be seen in the figure. Comparison with an analogous figure for the static computation (not shown) indicates more pronounced radiation downstream for the static case while with forward motion there is more pronounced propagation upstream, consistent with Figures 2a and 2b.

4. Conclusion

We have computed the full flow/acoustic/structure coupling for a model of a 4 panel assembly forced by sound from a jet. The forcing includes both a starter pulse inserted into the jet flow field, and sound generated from instability waves excited by the starter pulse. We have computed the far field sound, the panel response, and the panel radiation for two cases: one involving forward motion of the jet and one involving a static jet. Although our computations involve excitation of the jet via a pulse starter, instability waves are generated due to the instability of the jet shear layer which lead to a continual generation of disturbances in the jet. Thus, those natural sources of jet noise associated with jet instabilities are computed from the model, although at lower levels than the starter pulse.

The far field sound radiation is heavily influenced by the forward motion. There is an attenuation of sound downstream, while a forward arc amplification is observed upstream. These properties are apparent also in the incident pressure on the panels. The incident pressure is relatively broadband, however low frequencies become more dominant as the panel location increases downstream of the nozzle exit. There is a significant attenuation in incident pressure for downstream panels due to forward motion. There is a continual long time excitation of the panels due to sound generated from instability wave sources in the jet.

The panels act as filters converting the broadband incident pressure to relatively narrow spectral bands. The panel response is more sustained than the incident pressure, presumably due to both the small damping of the panels and the continual excitation by instability wave generated sound. The peak frequencies appear to be insensitive to panel location or to the presence of forward motion. The amplitude of the low frequencies increases significantly with downstream distance from the panel. The most pronounced effect of forward motion is

to reduce the enhanced low frequency response of the downstream panels.

The radiated pressure bears similar features to those due to convection in the jet domain. There is a significant low frequency beaming of sound in the radiation domain. The primary effect of forward motion is to reduce the downstream radiated sound.

Finally we note that the response and radiation of the structure is influenced not only by the noise of the jet, but also also by the boundary layer flow loading over the structure. Thus, while the jet noise level on the structure decreases with increases in speed, the boundary layer flow loading on the side wall increases, possibly leading to enhanced radiation from the panels. Thus, there may be parameter regimes where the effect of boundary layers, not yet incorporated in our model, might qualitatively change some of the results.

Acknowledgments

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Figure Captions

Fig. 1 Computational domain.

Fig. 2a Intensity of far field sound for computations with and without forward motion. Data taken on a circle of radius $30D$.

Fig. 2b Intensity of far field sound for computations with and without forward motion. Data taken on a circle of radius $30D$. Long time behavior of pressure field considered.

Fig. 3a Time history of incident $\tilde{p}$ for panels 1 and 2 at the panel centers, with and without forward motion.

Fig. 3b Time history of incident $\tilde{p}$ for panels 3 and 4 at the panel centers, with and without forward motion.

Fig. 3c Spectra of $\tilde{p}$ shown in Figures 3a and 3b for panels 2 and 4.

Fig. 4a Time history of v at centers of panels 3 and 4, with and without forward motion.

Fig. 4b $v(x, t)$ for $7 \leq t \leq 10$ along each panel. Computation with forward motion.

Fig. 5 Time history of transmitted $\tilde{p}$ for panels 3 and 4 at the panel centers, with and without forward motion.

Fig. 6a Time history of $\tilde{p}$ in the radiation domain at $y = 18D$, at 3 different values of x, with and without forward motion.

Fig. 6b Time integrated intensity of pressure in radiation domain along the line $y = 18D$, with and without forward motion.

Fig. 7 Contours of $\tilde{p}$ for forward motion computation, non-dimensional time of 11.3.