Flight Effects on Jet Noise Radiated from Convecting Quadrupoles

R. Dash*
NASA Ames Research Center, Moffett Field, Calif.

Abstract

THE effects of flight on noise radiation from convecting quadrupoles in a jet flow are examined. The theory provides an explicit expression for a newly discovered flight-convective amplification in terms of the characteristic Mach numbers M_c, M_j, and M_f. This analysis shows that as flight velocity increases there is a steadily increasing amplification of the sound that is radiated into the forward arc and a large reduction of the sound that is radiated into the rearward arc. The analysis also shows that flight effects in the fore and aft quadrants for a hot jet, inasmuch as the amplification or reduction over the static case is concerned, are essentially the same as flight effects in the fore and aft quadrants for a cold jet. Finally, the theory shows that the flight effects at $\theta = 90$ deg to the jet axis are virtually absent.

Contents

An approach that takes care of the modifications to Lighthill's theory[1,2] to include the effects of sources convected with the flow and their interactions with the flow was initiated by Lilley[3] and Mani[4,5] who consider a vortex-sheet model jet noise problem. All of these features, however, describe a jet with zero flight velocity. This theory[6] takes into account the triple events of convection, jet flow, and flight which occur simultaneously in a practical environment. The primary contribution of this paper is a generalized inclusion of flight effects.

The analysis is intended to model the situation depicted in Fig. 1a, in which a subsonic jet exhausts at a velocity U_j from a nozzle which is moving in an opposite direction with a velocity U_f, while a point source is convecting with a velocity U_c on the centerline of and in the same direction as the jet flow. For a coordinate system fixed on the nozzle, the whole affair would appear as if the phenomenon were taking place in an atmosphere which is moving in the same direction as the jet. Thus, the situation could be modeled as illustrated in Fig. 1b, which is in consonance with the acoustic environment prevailing in a wind tunnel designed to simulate the effects of flight on jet noise. The mathematical model that describes the vortex sheet theory consists of the following governing equations:

$$\left[\frac{1}{c_j^2}\left(\frac{D}{Dt}\right)_j^2 - \nabla^2\right]p = \frac{\partial^2}{\partial x_i \partial x_j} q_{ij} \quad \text{for inner flow where } r \le r_0$$

$$\left[\frac{1}{c_f^2}\left(\frac{D}{Dt}\right)_f^2 - \nabla^2\right]p = 0 \quad \text{for outer flow where } r \ge r_0$$

with

$$\left(\frac{D}{Dt}\right)_j = \frac{\partial}{\partial t} + U_j \frac{\partial}{\partial z} \qquad \left(\frac{D}{Dt}\right)_f = \frac{\partial}{\partial t} + U_f \frac{\partial}{\partial z}$$

where q_{ij} is the quadrupole point source; U_j and U_f are jet velocity and flight velocity, respectively; c_j and c_f denote the speed of sound in the inner jet and in the outer flow simulating flight. In addition to these equations, we have the usual boundary conditions on the vortex interface at $r = r_0$. These conditions are 1) continuity of acoustic pressure and 2) continuity of normal particle displacement. The latter condition is given by

$$\left(\frac{\partial p}{\partial r}\right)_{r=r_0(+)} (\rho_j/\rho_f)\left[\frac{k_0 + (M_c - M_j)k_3}{k_0 + (M_c - M_f)k_3}\right]^2 = \left(\frac{\partial p}{\partial r}\right)_{r=r_0(-)}$$

where ρ_j and ρ_f are the density of the jet and density of the outer flow simulating flight. However, making use of the usual procedure as detailed in our cited work,[6] we find that a low-frequency model point quadrupole source, convected downstream at Mach number M_c by a jet flow of Mach number M_j issuing from an aircraft with flight Mach number M_f radiates a field for which

$$\bar{p}^2 = \bar{p}^2_{\text{static}}[1 - c_0/c_f(M_c - M_f)\cos\theta]^{-6} \times [1 - c_0/c_f(M_j - M_f)\cos\theta]^{-4}$$

$$\bar{p}^2_{\text{static}} = \left[-\frac{q_{33}^0}{4\pi R}\rho_f/\rho_j(k_0 c_0/c_f \cos\theta)^2 \times \exp\{iRk_0c_0/c_f - i\omega_0 t\}\right]^2$$

It has been shown[6] that this result is more general insofar as the results due to (Berman, Goldstein and) Mani[4] and Lighthill[1,2] can be deduced from this if we do not make allowance for the differences in mean density and speed of sound between the jet flow (marked j) and the external ambient fluid simulating flight (marked f). An interesting feature of the radiation result as just stated is the outcome of a newly introduced "relative intensity amplification" factor I_{RQ} which we define as the ratio of the intensity of acoustic radiation due to a convecting axial quadrupole source in flight to that due to an equivalent, convecting axial quadrupole source without flight. This is given by

$$I_{RQ} = \left[\frac{1 - c_0/c_f M_c \cos\theta}{1 - c_0/c_f(M_c - M_f)\cos\theta}\right]^6 \left[\frac{1 - c_0/c_f M_j \cos\theta}{1 - c_0/c_f(M_j - M_f)\cos\theta}\right]^4$$

This form clearly indicates that $I_{RQ} \gtrless 1$ depending on whether $M_f \cos\theta \lesseqgtr 0$. These two in-flight situations arise when an observer is standing in front of $(\pi/2 < \theta < \pi)$ or behind $(0 < \theta < \pi/2)$ the jet. In physical terms, it is concluded that the effect of flight on jet noise is to amplify noise in the forward arc and reduce the noise in the rearward arc with increasing

Presented as Paper 78-192 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan. 16-18, 1978; submitted Feb. 8, 1978; synoptic received June 5, 1978. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Aeroacoustics; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

*NRC Senior Resident Research Associate.

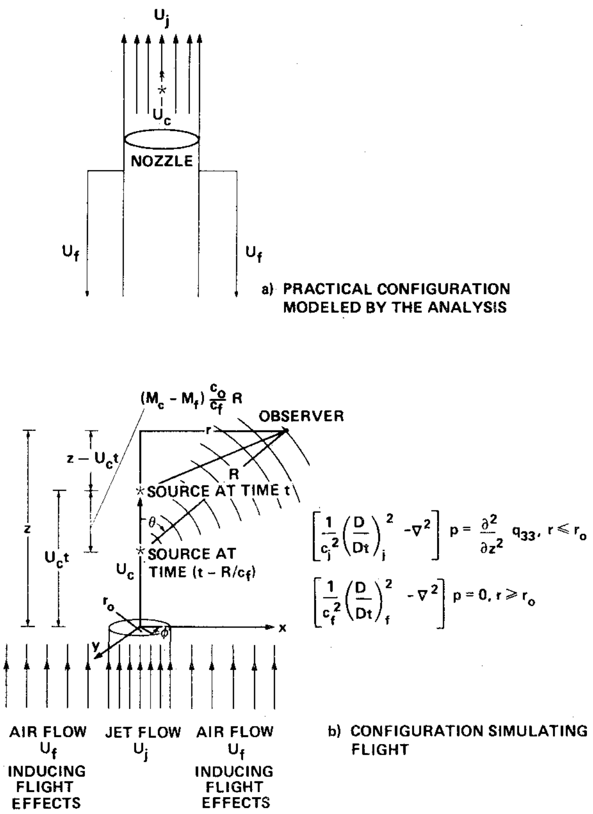

Fig. 1 Vortex sheet model describing source convection in a jet flow in flight.

flight Mach number M_f. This is a major finding reported in this analysis. This will be better appreciated when we look at Fig. 2, which is plotted for $10 \log_{10} I_{RQ}$ vs θ. This illustrates the change in directional distribution of relative intensity amplification I_{RQ}. These curves indicate the amount of amplification or reduction over the static case of the noise at different flight Mach numbers M_f and jet Mach numbers M_j. The static case corresponds to the case when $M_f = 0$; we have also used $M_c = 0.65\, M_j$ in our computations.

Summary

As a result of our investigation, we find the following features arising as manifestations of flight effects on jet noise radiation.

1) Flight effects modify the structure of the so-called convective amplification to produce a newly discovered flight-convective amplification:

$$[1 - c_0/c_f(M_c - M_f)\cos\theta]^{-6}[1 - c_0/c_f(M_j - M_f)\cos\theta]^{-4}$$

2) Flight effects steadily amplify noise radiation in the forward arc, that is, in directions lying ahead of the aircraft at the time of emission of the sound, and steadily reduce the noise radiation in the rearward arc.

3) Amplification in the forward quadrant decreases when jet velocity is increased (up to its critical value) with, however, a stronger attenuation in the aft quadrant.

4) Flight effects at $\theta = 90$ deg to the jet axis are virtually absent.

5) Flight effects on noise radiation in the fore and aft quadrants for a hot jet are essentially the same as flight effects in the corresponding quadrants for a cold jet.

6) The theory also predicts that the streamwise zone of silence is strongly evident despite the presence of flight effects in this vortex-sheet model problem.

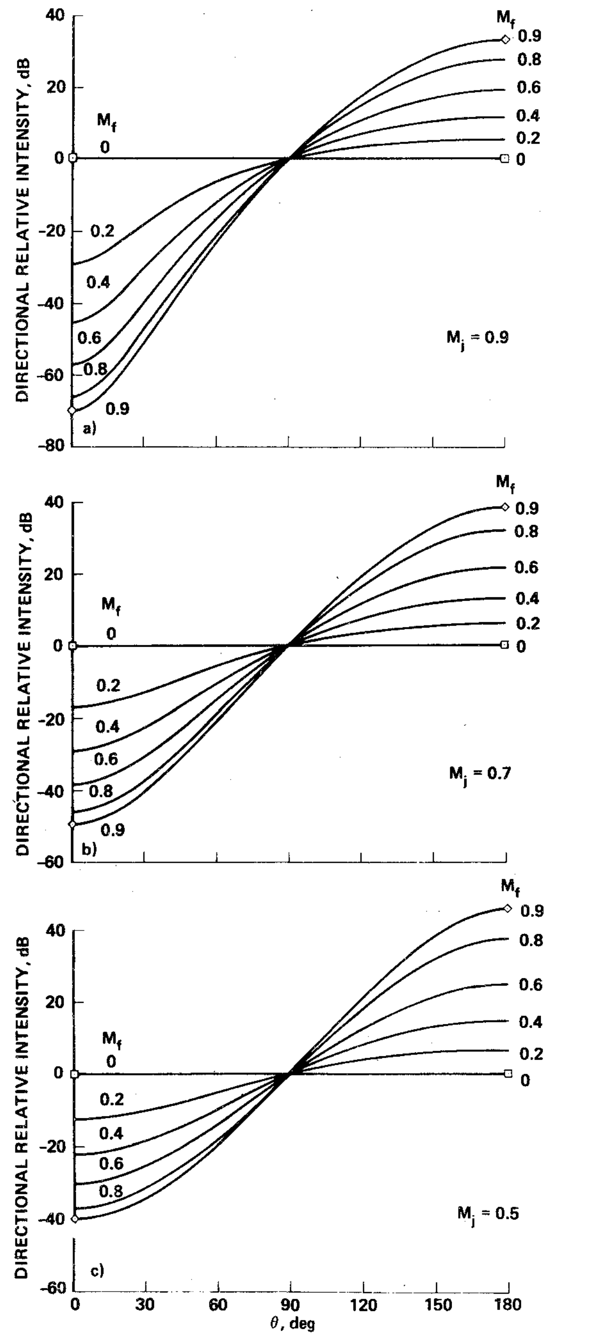

Fig. 2 Change in directional distribution of relative intensity amplification I_{RQ}.

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