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Dipole Modeling and Nondimensionalization of Airframe Noise

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Airframe noise measurements may be correlated and made more physically meaningful by a conversion from a decibel or dimensional form to a coefficient or nondimensional form, in particular for radiation in a single direction, chosen to be directly below the aircraft. For radiation in other directions, a three-dipole model may be used, and three additional coefficients defined. Examples of the coefficients are given for various flight and configuration conditions for both the DC-9-31 and the DC-10-10 aircraft. A significant body of airframe noise data has been published and is available for conversion to nondimensional form, both for the representation of overall sound pressure levels and for any one or more one-third octave band levels.

Introduction

RECENTLY a significant quantity of airframe noise flight data and predictions have been presented in the literature by Fink,[1] Hardin et al.,[2] Munson,[3] Revell et al.,[4] and Bauer and Munson.[5] A current problem is the difficulty in correlating all the results, inasmuch as sound levels are generally presented in decibels, which are related to a dimensional quantity; that is, although decibels are dimensionless, a decibel measurement of noise represents a definite sound pressure, which has the dimensions of force divided by area. Consequently, when airframe noise is plotted in terms of decibels, the benefits of using nondimensional coefficients are lost. If the sound levels were reported in terms of nondimensional coefficients, the task of correlating the past and future results would be simplified. Such a simplification has been very successfully used for the reporting of aerodynamic force coefficients (see Refs. 6 and 7, for example), which were standardized by NACA many years ago. In a like fashion, acoustic force coefficients may be defined.

The comparison between acoustic and aerodynamic force coefficients may be better understood by considering the fundamental differences between acoustic and aerodynamic phenomena. For constant freestream flow conditions, aerodynamic forces are essentially steady and the force coefficients are large and easy to measure close to the airframe; in the far field the coefficients are small, since the forces fall off like R^{-2}, where R is the radius or distance from the airframe. The acoustic forces are unsteady and are difficult to distinguish from aerodynamic effects close to the airframe, but the acoustic sound pressures are easy to measure in the far field, where acoustic pressures fall off like R^{-1}. Hence, aerodynamic force coefficients are generally measured in the near field, but acoustic force coefficients are most easily determined from far field measurements.

Nondimensionalization of Airframe Noise

In Ref. 5 the nondimensionalization is put in the form

$$SPL_c = 10\log(G^2 C_i^2) \tag{1}$$

where the acoustic range angle λ and the sideline angle μ are both 90 deg; that is, where the ground-based microphone is directly below the flight path, where C_i is the dimensionless coefficient, where SPL_c is the sound pressure level corrected for the effects of atmosphere absorption and turbulence, and where the dimensional factors are lumped in the parameter

$$G = \frac{M^{5/2} S_W{}^{1/2} p_a}{4\pi R p_0} \tag{2}$$

where R is the acoustic radius, M is the flight Mach number, p_0 is the acoustic reference pressure (20×10^{-6} Pa) p_a is the atmospheric pressure, and S_W is the reference or wing area.

The nondimensionalization would be equally valid in principle if M were raised to any arbitrary power in Eq. (2). The 5/2 power was chosen in order to minimize the variation of C_i with changes in M. The subscript on C_i may be used to denote the portion of the frequency spectrum represented by C_i; in Fig. 1 the subscript on C is 0, denoting overall sound pressure level (OASPL). Figure 1 shows values of C_0 plotted as a function of M for the eight different configurations that were tested using the DC-9-31 aircraft. Definition of the flight conditions and the configurations are shown in Tables 1 and 2. Figure 1 shows that C_0 is essentially invariant with changes in M, but, as expected, C_0 increases with increased extension of the landing gear or flaps.

The horizontal lines drawn in Fig. 1 are used to show the general invariance of C_0 with M for those configurations where results were obtained at more than one value of M (configurations A, B, C, E, G, and H for the DC-9-31 only). The data scatter for configurations B and E is such that it obscures any variation of C_0 with M. Configurations G and H both give about the same magnitude for C_0. Notice that C_0 is quite a bit smaller for the DC-9-31 clean configuration A than for the DC-10-10 clean configuration, but the opposite is true for the gear and flaps full-down configurations H. The differences in C_0 are attributed to the geometric shape differences between the two aircraft.

The results shown in Figure 1 were obtained using microphones flush with the ground; hence the coefficients are approximately twice as large as would be obtained from freefield conditions.

In general, C_0 is a function of the airframe configuration as well as both M and C_L, where C_L is the airframe lift coefficient

$$C_L = \frac{2W}{\gamma p_a M^2 S_W} \tag{3}$$

where W is the airframe weight and γ is the atmospheric specific heat ratio (1.40). As shown in Table 2, $M^2 C_L$, and hence W were almost constant for all the various flight conditions; hence the variation of C_0 with $M^2 C_L$ cannot be

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Table 1 Configuration list

Configuration	Flap deflection, deg	Gear	Slat extension, %
A	0	Up	0
B	0	Down	0
C	0	Up	100
D	0	Down	100
E	20	Up	100
F	40	Down	100
G	50	Up	100
H	50	Down	100
E′	35	Up	100
F′	35	Down	100

Table 2 DC-9-31 flight conditions

Configuration	Run no.	M	C_L	M^2C_L
A	7	0.327	0.550	0.0588
A	9	0.321	0.591	0.0610
A	11	0.388	0.400	0.0602
A	17	0.449	0.283	0.0571
B	16	0.328	0.538	0.0578
B	24	0.443	0.267	0.0524
B	25	0.450	0.256	0.0518
C	8	0.266	0.826	0.0583
C	10	0.317	0.602	0.0606
D	22	0.383	0.368	0.0541
E	13	0.239	1.041	0.0594
E	15	0.278	0.754	0.0582
E	23	0.347	0.441	0.0532
F	26	0.271	0.700	0.0512
G	27	0.234	0.925	0.0508
H	19	0.270	0.752	0.0547
H	20	0.239	0.953	0.0545
H	21	0.243	0.913	0.0537

determined from the data of Fig. 1. In fact, the power used on M in Eq. (2) is the result of holding M^2C_L essentially constant while M was varied; then, the power was set at 5/2 to minimize the variation of C_0 with M. If we suppose that C_0 might vary in direct proportion to C_L when M is constant, then we would also conclude that C_0 would vary like $M^{1/2}$ when C_L is held constant. Hence, the 5/2 power in Eq. (2) is not necessarily the best choice, and research is needed on the variation of airframe noise with either M or C_L when the other is held constant.

Physical Interpretation of the Noise Coefficients

From Eq. (1), we see that the far field acoustic pressure is

$$p_{ac} = GC_i p_0 \tag{4}$$

for $\lambda = \mu = 90$ deg, and from Eq. (3) we see that the average aerodynamic lifting pressure on the wing surface is

$$p_{ae} = \frac{\gamma p_a M^2 C_L}{2} \tag{5}$$

Hence, the ratio of the two quantities is

$$\frac{p_{ac}}{p_{ae}} = \frac{M^{1/2} S_W{}^{1/2} C_i}{2\pi\gamma R C_L} \tag{6}$$

From Figure 1 and Table 2, we see typically that, for OASPL's, C_0 is an order of magnitude or two smaller than C_L. Also, if we assume that Eq. (4) gives the correct order of magnitude for acoustic pressures in the near field of the aircraft, then we may use Eq. (6) for the correct order of

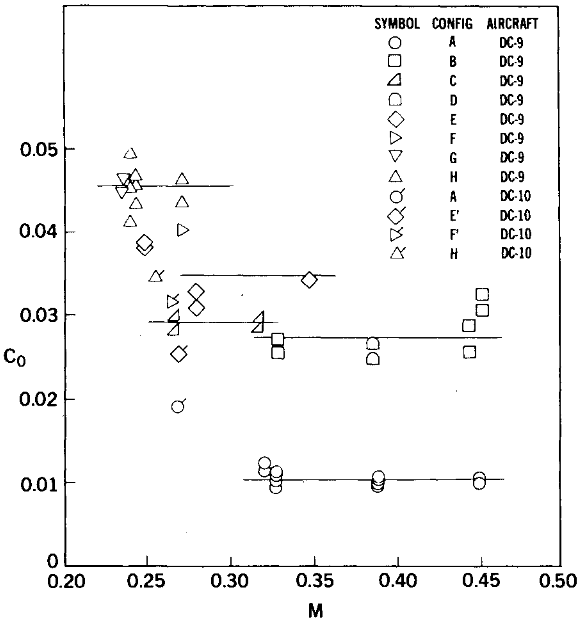

Fig. 1 Overall airframe sound pressure coefficients vs Mach number.

magnitude of p_{ac}/p_{ae} even when R is so small as to be approximately equal to $S_W{}^{1/2}$. Since $M^{1/2}/2\pi\gamma$ is certainly much less than 1, we can conclude from Eq. (6) that p_{ac} is typically about two orders of magnitude smaller than p_{ae} near the airframe surface.

Hence, the OASPL on the airframe surface is about the same order as the pressure fluctuations caused by the turbulent boundary layer flow over a flap plate, as given by Willmarth,[8] who reported the level

$$p_w = 0.005(\gamma p_a M^2/2) \tag{7}$$

Furthermore, for narrow frequency ranges, such as one-third octave bandwidth, the ratio p_{ac}/p_{ae} will be typically another order of magnitude smaller.

Dipole Modeling of Airframe Noise

The above discussions were limited to noise radiated directly below the aircraft ($\lambda = \mu = 90$ deg), but the noise radiated in all directions is of interest. For the vertical plane through the flight path ($\mu = 90$ deg), Munson[3] has shown that a two-dipole model can be correlated with data to model the noise for all values of λ. Mulson also has shown the need for the convective amplification term, represented by $(1-M_r)^{-4}$, and King[9] has arrived at the same conclusion, where M_r is the relative Mach number between the airframe and the microphone. Both Munson[3] and Bauer and Munson,[5] using data from DC-9-31 and DC-10-10 flyovers, have shown that a drag dipole as well as a lift dipole is necessary to match the experimental data. Furthermore, Bauer and Munson have shown that the two-dipole model predicts the variation of the noise with sideline angle μ, and that an additional side force dipole is sometimes needed to match the data. The form of the dipole function is

$$f = \frac{\sin^2\lambda \sin^2\mu + A_i \cos^2\lambda + B_i \sin\lambda\cos\lambda\sin\mu + a_i \sin^2\lambda\cos^2\mu}{(1-M_r)^4} \tag{8}$$

where the coefficients A_i and a_i represent the ratios of the strengths of the drag and the side force dipoles to the lift dipole, and where B_i represents the correlation of the lift and the drag dipoles in the form

$$B_i = \frac{2\overline{\left(\frac{\partial F_I}{\partial t}\right)\left(\frac{\partial F_3}{\partial t}\right)}}{\overline{\left(\frac{\partial F_I}{\partial t}\right)^2}} \tag{9}$$

where F_I and F_3 are the fluctuating forces in the lift and the drag directions. Then the SPL_c is given by

$$SPL_c = 10\log(G^2 C_i^2 f) \tag{10}$$

and the acoustic pressure is

$$p_{ac} = GC_i p_0 f^{1/2} \tag{11}$$

The relation given by Eq. (8) was used in Ref. 5 to match the variations of noise levels with changes in λ and μ. For the DC-9-31 aircraft flying at $M = 0.45$ in Configuration A, the required coefficients were $A_0 = 0.7$, $B_0 = -1.0$, and $a_0 = 0$, where the subscript 0 denotes OASPL's. For configurations with both gear and flaps down, a_0 was found to be about 0.3 to 0.4, which for some reason was not near the value $a_i = 1.0$ required to match the sideline noise data reported by Fethney.[10] For the DC-10-10 aircraft no significant sideline noise measurements were performed, but values of A_0 and B_0 for $M = 0.26$ were as follows:

Configuration	A_0	B_0
A	0.70	−0.41
E′	0.73	−0.33
F′	0.86	−0.35
H	0.68	−0.14

Although the dipole model can apparently be made to fit the sound radiation pattern of any aircraft flying at any subsonic Mach number, more tests of the model usefulness would be welcome. For example, the sensitivity of the coefficients A_0, B_0, and a_0 to changes in Mach number are unknown; no tests of the model have been performed with λ and μ both different from 90 deg; and no tests of the model have been performed using individual one-third octave bands. All three of these tests could be made by using the data from Ref. 11.

Concluding Remarks

A method of nondimensionalizing airframe noise has been presented, and dipole modeling has been used to represent the noise directivity. A comparison of DC-9-31 and DC-10-10 coefficients shows significant differences between the two aircraft; the DC-9-31 has the lower noise coefficient for the clean configuration, but the DC-10-10 has the lower noise coefficient for the gear and flaps full-down configuration. The fluctuating sound pressures near the aircraft are shown to be about two orders of magnitude smaller than typical aerodynamic pressures.

Acknowledgment

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