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Wing Effect on Jet Noise Propagation

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Jet aircraft with engines under the wings may produce higher flyover noise levels than similar aircraft with other engine mounting arrangements. To determine the cause of higher flyover noise of such aircraft, an experimental investigation was performed in an anechoic chamber. Basic experimental apparatus consisted of an ASME 15.24 cm (6 in.) diameter converging nozzle and a wing section which corresponded to the horizontal projection area of a portion of a wing of a typical jetliner. Results of this experiment indicate that the presence of the wing in the vicinity of the jet enhances the noise produced by the jet alone. This noise enhancement may be attributed to two sources. The boundary layer generated on the surface of the wing as the result of entrainment of the air into the region between the wing and the jet is believed to be responsible for the low-frequency noise enhancement. Reflection of jet noise incident on the wing surface contributes to enhancement of noise primarily at high frequency. The jet is found to have considerable effect on noise enhancement at high frequency where strong refraction effects on sound waves occur. The substantial enhancement of high-frequency noise measured in planes at oblique angles to the wing surface may require consideration in aircraft noise prediction and design. Based on static test results, it appears that the wing effect may increase the sideline noise levels of aircraft during takeoff.

Introduction

IT is recognized that jet aircraft with engines under the wing may produce higher flyover noise levels than similar aircraft with other types of engine mountings. The wing of such an aircraft is believed to function as a reflector for engine noise (including jet noise) incident upon it. The engine noise reflected from the wing may interfere with the engine noise which propagates directly to the observer. As a result, higher (or lower) noise levels than that of the engine noise alone may be measured. The situation can be critical for jet noise which is a predominant source of noise in jet aircraft during takeoff.

The high cost of conducting flight tests makes it attractive to predict aircraft flyover noise by measuring engine noise from the ground. A precise definition of *all* contributing noise sources is essential to the success of such prediction techniques. Unfortunately, there seems to be a shortcoming in this particular area. Failure to take into consideration the effect of the wing on the propagation of jet noise has contributed to discrepancies in the results of a number of flyover noise prediction techniques.[1] Until recently, this subject has not been adequately investigated.

The effect of reflection on propagation of jet noise has been studied by several investigators.[2,3] In these investigations, the primary interest was in the effect of ground reflection on the propagation of jet noise. An important problem unique to jet aircraft with engines mounted beneath the wings was not considered. Some of the jet noise reflected from the wing surface must be transmitted through the jet to propagate to the observer. During its transmission through the jet, various frequency components of jet noise are either absorbed, reflected, or refracted by the jet. Hence, the characteristics of the measured noise may depend on the conditions of the jet and the wing surface.

Objectives of the present investigation are to improve the understanding of the wing effect on propagation of jet noise and, should the effect prove to be significant, develop techniques for noise reduction. In particular, the effect of the jet on the propagation of jet noise is investigated.

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Experimental Facilities

Anechoic Acoustic Test Facility

The experiment was conducted at the Anechoic Acoustic Test Facility (AATF) in the Aerophysics Laboratories of Douglas Aircraft Company. The anechoic chamber (Fig. 1) is certified to provide an acoustic free-field environment for sound waves at frequencies above 125 Hz. An attractive feature of the facility is the ventilation flow system. Fans on the roof of the facility are used to supply air to the plenum chamber. From the plenum, the air flows into the anechoic room where it is used to supply the natural entrainment requirements of the jet flow.

The fans were controlled during the test to provide an amount of entrainment flow equal to that of the jet flow in an open-air environment. By this means, the chamber static pressure was kept above that of the outside atmosphere so that the jet flow could move through the exhaust muffler without any contamination from reverse flow. This forced ventilation flow system reduces the level of recirculation within the anechoic chamber to a very low value and provides a better acoustic environment than is possible without the forced ventilation feature. Further information on the facility may be found in Ref. 4.

Experimental Model

The experimental model consisted of a jet nozzle connected to a static jet rig and a wing scaled to 16% of the horizontal projection area of a portion of the wing of a DC-10 jetliner. The wing model, shown in Fig. 2, was truncated at points corresponding to wing chord positions 54 cm (21.2 in.) to each side of the wing engine centerline. The chord length along the centerline was 137 cm (54 in.). For simplicity, the wing surface was made flat rather than the actual DC-10 airfoil shape. The central part of the wing model was removable so that panels with various acoustic surfaces could be mounted on the surrounding frame which was 1.9 cm (0.75 in.) thick. The edge of the wing model was square.

Three different kinds of panels were used in the investigation. The baseline panel was made from 1.9 cm (0.75 in.) plywood covered with aluminum sheet. The second panel was made from a 1.9 cm (0.75 in.) fiberglass blanket covered by wire mesh. The blanket had a density of 0.128 g/cm^3 (8.0 lbm/ft^3). The third wing panel was made from a composite honeycomb structure sandwiched by an aluminum sheet

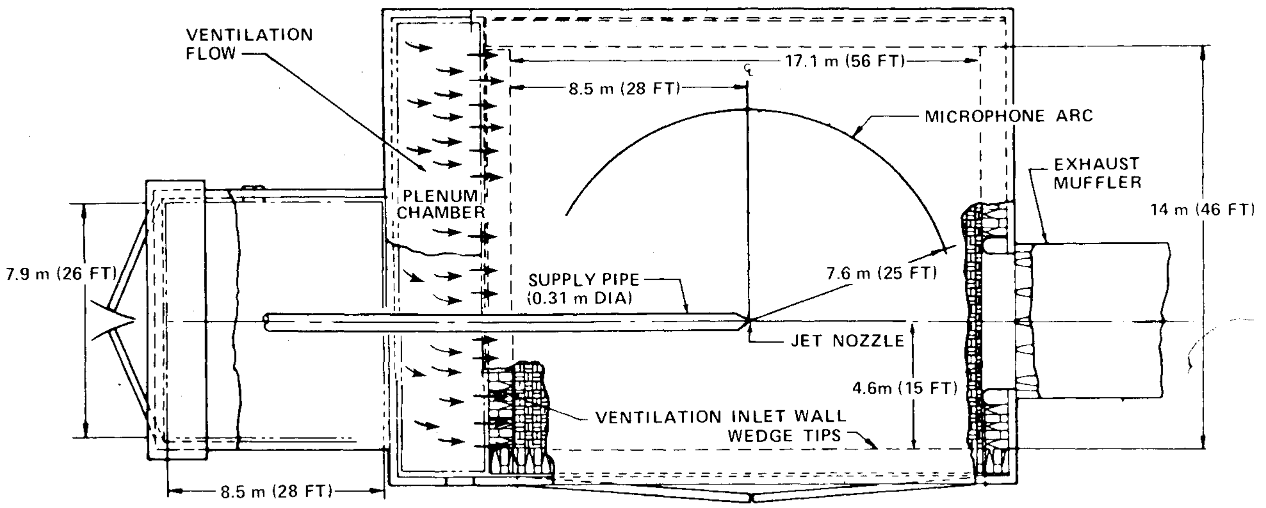

Fig. 1 Anechoic Acoustic Test Facility (AATF) with jet nozzle and supply pipe.

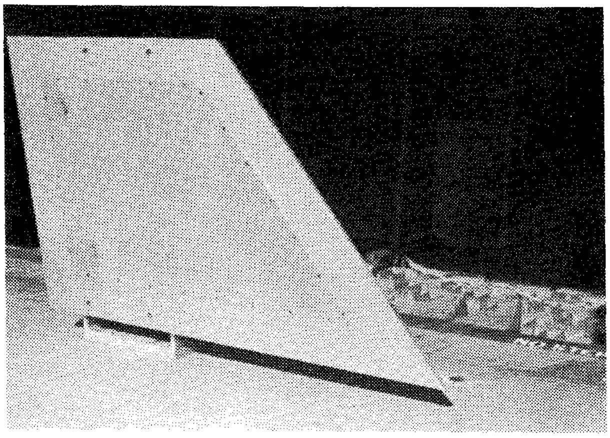

Fig. 2 Wing model.

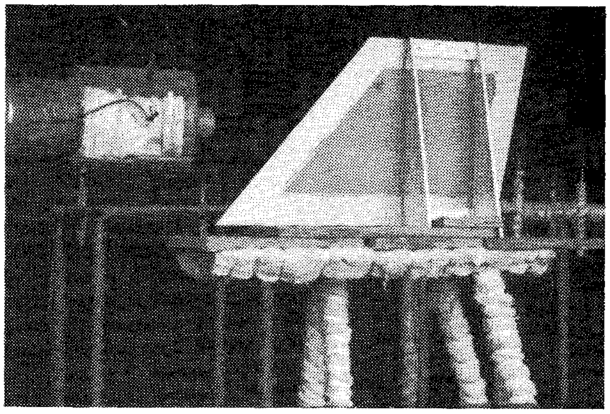

Fig. 3 The wing configuration and its supporting structure in relation to the jet nozzle.

backplate and a 60-cgs-rayl DynaRohr surface. The wing was placed vertically on a slotted table so that it could be moved horizontally in directions either parallel or perpendicular to the jet axis.

The jet nozzle used in the investigation was an ASME converging nozzle with a diameter of 15.24 cm (6 in.). The cross-sectional area of the nozzle was equal to 16% of the primary nozzle area of the CF6-50 engine used on the DC-10 aircraft. For part of the experiment, the distance from the jet axis to the wing was 27.6 cm (10.8 in.), corresponding approximately to the DC-10 scaled position. Noise measurements were also taken for another distance from the jet axis to the wing. To simplify the experiment, the pylon between the jet nozzle and the wing was omitted from the model. Figure 3 is a photograph of the wing configuration and its supporting structure in relation to the jet nozzle. The jet pipe, the microphone poles, and the frame structure are all wrapped in fiberglass blankets to avoid reflection.

It should be noted that the experimental model used in this investigation was not a scale model of a DC-10. However, it was felt that the experimental model was sufficiently similar to provide useful information on the noise characteristics of the full-scale aircraft.

Data Acquisition System

Acoustic measurements were made using B&K type 4135 0.64 cm (0.25 in.) microphones at the locations shown in Fig. 4. Microphones 1 through 8 were located in the plane through the jet axis and perpendicular to the wing surface. This plane will be referred to as the *normal reference plane*.

Microphones 13 through 16 were in planes passing through the jet axis and at angle ϕ with respect to the normal reference plane, as shown in Fig. 4. Table 1 shows the angular relationships of microphones 13 through 16 with the normal reference plane and the jet axis. All microphones were 7.62 m (25 ft) from a point on the jet axis five nozzle diameters downstream of the nozzle exhaust plane. The angle between a line through this point to a given microphone and the jet axis is denoted by θ in Fig. 4. All noise data were reduced to one-third octave band spectra.

Experimental Procedures

Major experimental parameters are:

1) the distance (H) from the jet axis to the wing surface (see Fig. 4),

2) the relative positions of the wing with respect to jet nozzle in the direction parallel to the jet axis, as shown in Fig. 5,

3) the exhaust velocity of the jet, and

4) the type of acoustic treatment used on the wing panel.

Since the jet rig was stationary, investigations of various relative positions between the wing and the jet nozzle were achieved by moving the wing. Noise measurements were taken for the wing at two distances (H) from the jet axis—27.6 cm and 42.8 cm. For each of the two distances, noise measurements were taken for five wing positions along a line parallel to the jet axis (Fig. 5). When the wing was at position 3, the relation between the wing and the nozzle corresponded to that of the DC-10. Measurements were taken for three jet exhaust velocities—183 m/s (600 fps), 244 m/s (800 fps), and 305 m/s (1000 fps). For a given wing configuration and test

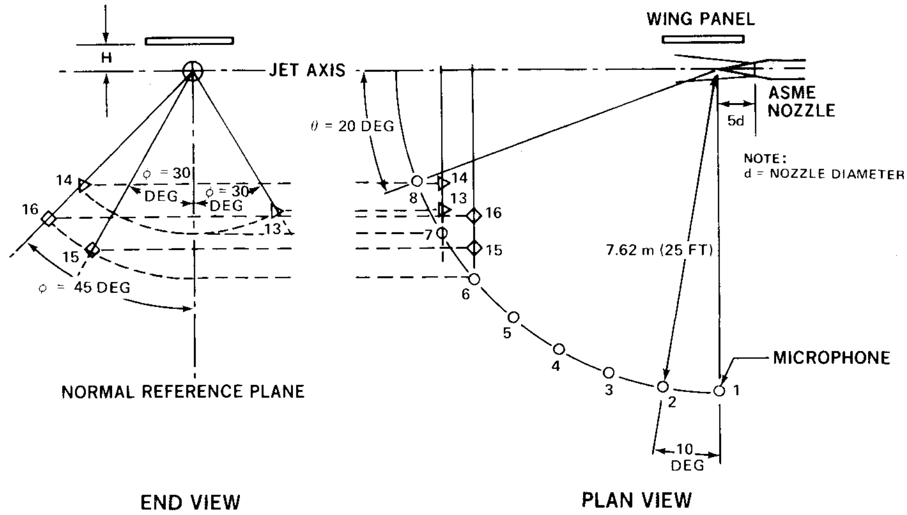

Fig. 4 Relationship of microphone positions to wing and jet nozzle.

Table 1 Angular relationship of microphones with normal reference plane and jet axis[a]

Microphone number	ϕ, deg	θ, deg
6	0	40
15	−30	40
16	−45	40
7	0	30
13	30	30
14	−45	30

[a] ϕ = the angle of a plane with respect to the normal reference plane; θ = the angle with the jet axis.

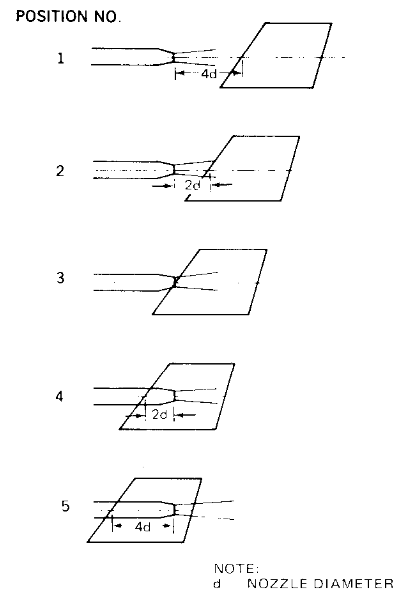

Fig. 5 Axial positions of the wing relative to the nozzle.

condition, the effect of the wing was established by comparing measurements with the wing installed to those with the wing removed.

Prior to acoustic measurement, all microphones were calibrated with a B&K pistonphone. Next, the exhaust velocity and the ventilation flow rate were set to the desired values. When both the jet and the ventilation flow were stabilized, the gains for the on-line channels were adjusted to appropriate values. Finally, the Acoustic Data Acquisition System (ADAS) of the AATF was activated to take environmental, performance, and acoustic data. Acoustic signals measured by the selected microphone channels were recorded simultaneously.

Results and Discussion

Wing Effect as Measured in the Normal Reference Plane

Figure 6 gives the one-third-octave-band spectra of the noise measured for a jet exhaust velocity of 183 m/s (600 fps) and wing position no. 3. To show the effect of the wing, each of these spectra is plotted along with the corresponding jet noise spectra measured when the wing was not present. The noise measured when the wing was present is in general at a higher level than that of the jet alone throughout the frequency range of interest.

The results given in Fig. 6 can be presented in an alternative way. Figure 7 shows the difference in noise levels between the spectra measured when the wing is present and the spectra measured when the wing is absent. Enhancement of noise due to the wing is observed to be most pronounced at the lower frequency end of the spectra. As shown in Fig. 7, as much as 12 dB of enhancement was measured.

Enhancement of noise measured by each microphone can be seen to decline as frequency increases. At the higher frequencies, except for microphones near the perpendicular direction to the wing surface, the increase in noise level due to the wing effect is small. The frequency at which the enhancement is the greatest appears to shift to a higher frequency for the smaller angles between the microphones and the jet axis.

In addition, the enhancement of the noise is observed to be the greatest at microphone 1, where $\theta = 90$ deg. The enhancement diminishes progressively as θ decreases. The extreme condition seems to be at $\theta = 20$ deg from the jet axis, where hardly any increase in noise level over that of the jet alone can be seen. This result shows that the enhancement due to wing effect has a directional pattern.

The results as given above were measured by microphones placed in the normal reference plane, which contains the jet axis. The noise which propagates from the region between the wing surface and the jet must pass through the jet to reach these microphones.

Wing Effect as Measured in Oblique Planes

The enhancement in noise measured by microphones located in planes at angle ϕ with respect to the normal reference plane was found to be quite different from that measured by microphones in the normal reference plane where $\phi = 0$ deg. Figure 8 shows typical results measured by microphones 13–16, two in planes with $\phi = 30$ deg and two in planes with $\phi = 45$ deg. Substantial noise enhancement can be observed not only at low but also at high frequencies. This result is in marked contrast to that measured by microphones

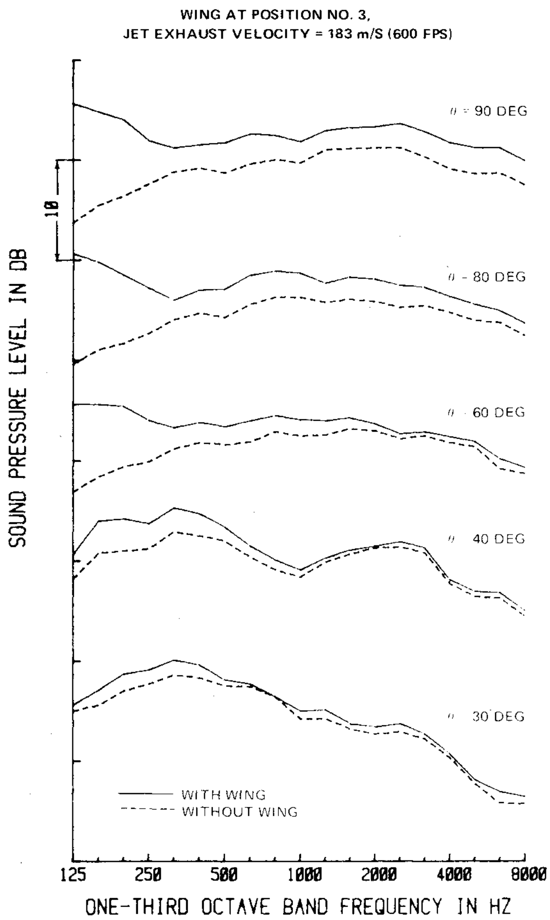

Fig. 6 Comparison of noise spectra measured with and without the wing installed.

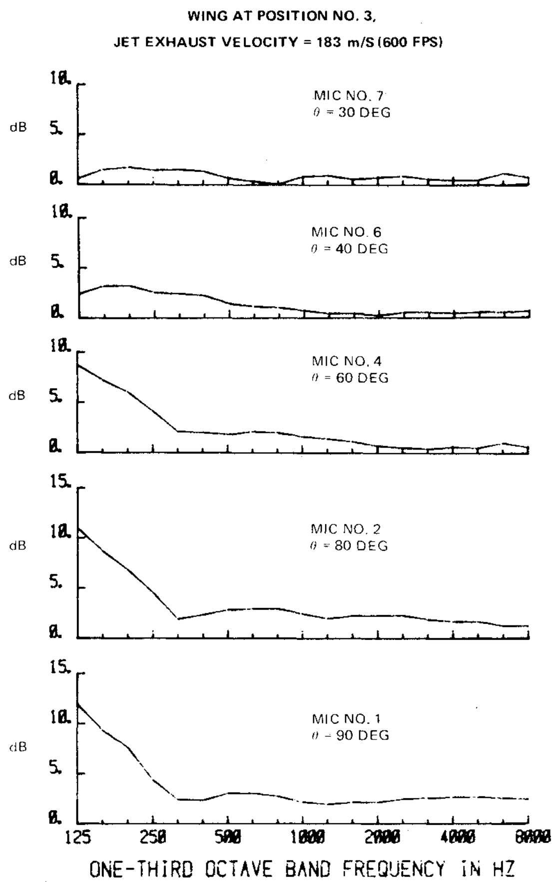

Fig. 7 Enhancement of noise due to wing effect.

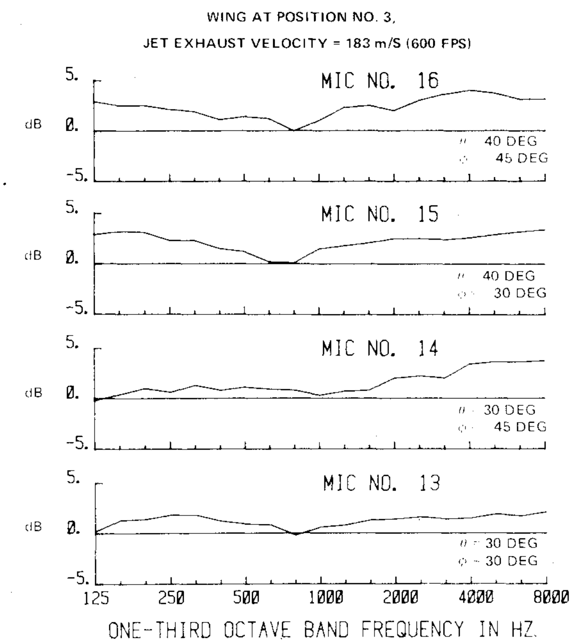

Fig. 8 Enhancement of noise measured by microphones in oblique planes.

in the normal reference plane where little high-frequency noise enhancement is measured.

It is of particular interest to compare the result measured by microphone 6 ($\phi = 0$ deg) with those measured by microphones 15 ($\phi = 30$ deg) and 16 ($\phi = 45$ deg). Note that all three microphones are at the same angle, $\theta = 40$ deg, with the jet axis. Figure 9 presents such a comparison for three different jet exhaust velocities. The difference in enhancement measured by the three microphones in different planes is in general rather small at frequencies below 1000 Hz. However, at higher frequencies the enhancement measured by microphones 15 and 16 is substantially stronger than that measured by microphone 6 in the normal reference plane. Furthermore, at high frequencies, microphone 16 at $\phi = -45$ deg measures slightly stronger enhancement than microphone 15 at $\phi = -30$ deg. Similarly trends can be observed from Fig. 10 for microphones 13, 14, and 7 which are all at an angle $\theta = 30$ deg with the jet axis, but in different planes.

These results clearly indicate the strong influence of the jet on the noise propagating from the region between the wing and the jet to the far-field. This noise certainly includes the jet noise reflected from the wing surface. It is believed that the refraction effect of the jet plays an important role in what is occurring. Obviously, in order that the noise may propagate to microphones in the normal reference plane, it must be transmitted through the jet. During this transmission process, it is more difficult for the high-frequency components of the noise, which are the most susceptible to refraction and reflection by the jet flow, to be transmitted and propagate to micróphones in the normal reference plane. Therefore, enhancement in noise measured by microphones in the normal reference plane is primarily at low frequencies since the jet is ineffective in either reflecting or refracting sound with a longer wavelength than the dimension of the jet.[5-10]

Since the noise propagating from the region between the wing and the jet does not have to be transmitted through the jet to propagate to microphones in oblique planes, these microphones measure noise enhancement at both low and high frequencies. This also explains why the enhancement measured by microphone 15 in the plane at 30 deg with the normal reference plane is not as strong as that measured by microphone 16 in the plane with $\phi = 45$ deg. By simple

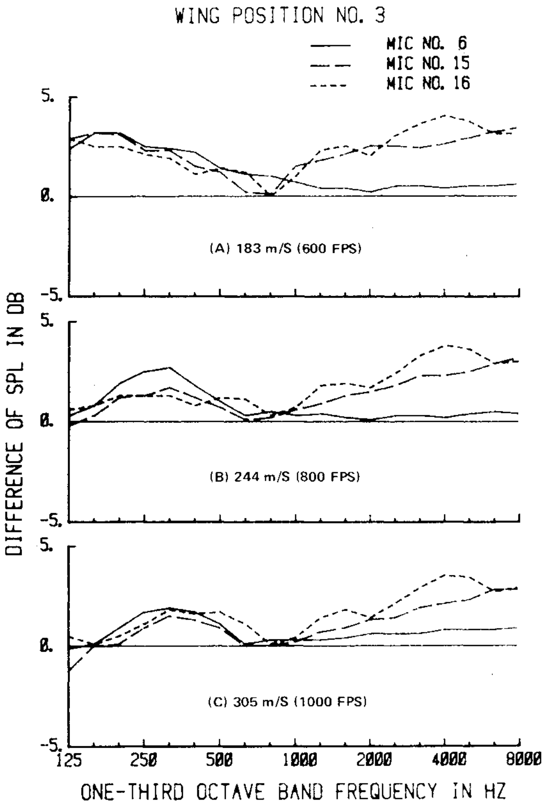

Fig. 9 Comparison of enhancement patterns measured by microphones in three different planes at three jet exhaust velocities.

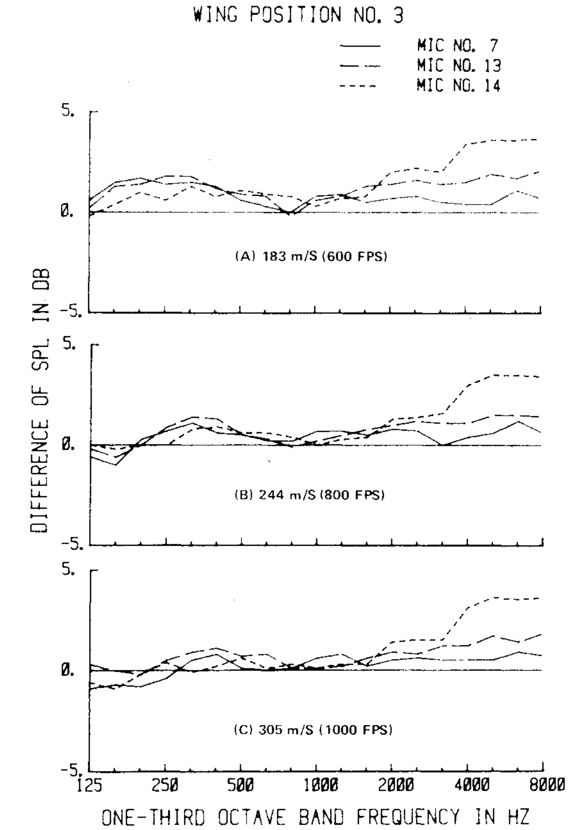

Fig. 10 Comparison of enhancement patterns measured by microphones in three different planes at three jet exhaust velocities.

geometry, it can be shown that propagation of the noise originating between the wing and the jet to microphone 15 ($\phi = 30$ deg) may be partially obstructed by the jet.

A question which arises is whether it is appropriate to compare the results measured by microphones in different planes, for instance microphones 15, 16, and 6. If noise enhancement is due to reflection of noise from the wing surface, the noise measured by microphones in different planes will be those with different angles of incidence and reflection with respect to the wing surface. Theory for plane acoustic waves shows that, for oblique incidence, the reflection coefficient of a solid surface is a function of the angle of incidence.[11] However, for an angle of incidence of less than 45 deg with the surface normal, the reflection coefficient is a weak function of the angle of incidence. It is therefore justified to compare results measured by microphones placed in different planes.

It is of interest to note that the results obtained here may be related to the problem of the twin-jet-shielding effect.[12-15] If the wing surface is a perfect reflector, one can consider that the jet noise reflected from the wing radiates from an image jet. The noise due to the image jet can be thought of as being shielded by the real jet. The results of this study suggest that shielding will be most evident at high frequencies.

Influence of Jet Exhaust Velocity

In Fig. 11, the noise enhancement measured at the three different jet exhaust velocities is presented for three microphones in the normal reference plane. The exhaust velocity of the jet is found to have a significant effect on enhancement of noise.

Perhaps the most interesting observation is the trend in the variation of noise enhancement with the jet exhaust velocity at the low-frequency end of the spectra measured by microphones 1 and 4. At very low frequencies, higher jet exhaust velocities are found to lead to weaker enhancement, but at slightly higher frequencies the trend with exhaust velocity is reversed. This trend reversal is found to be most

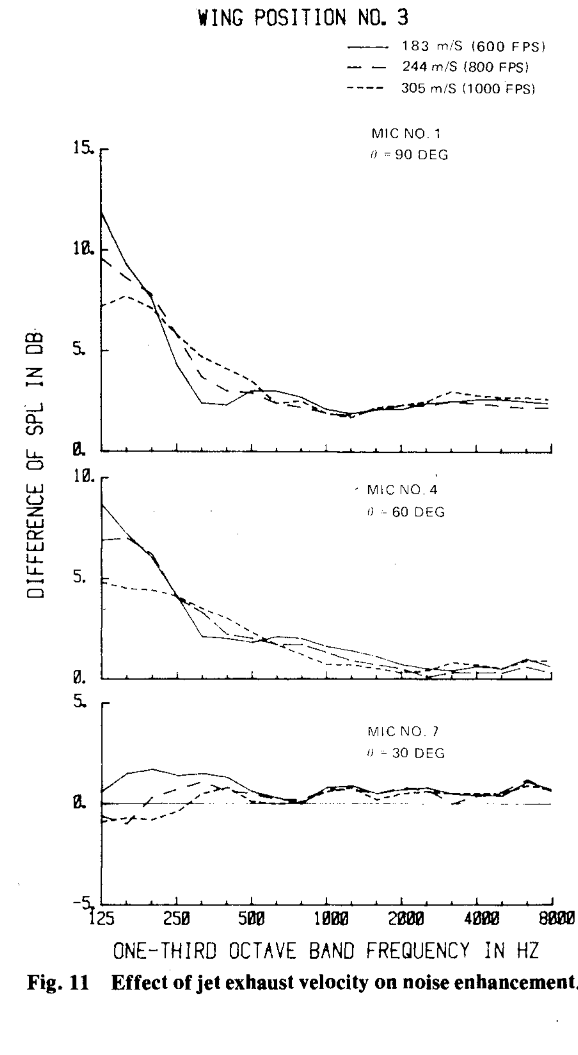

Fig. 11 Effect of jet exhaust velocity on noise enhancement.

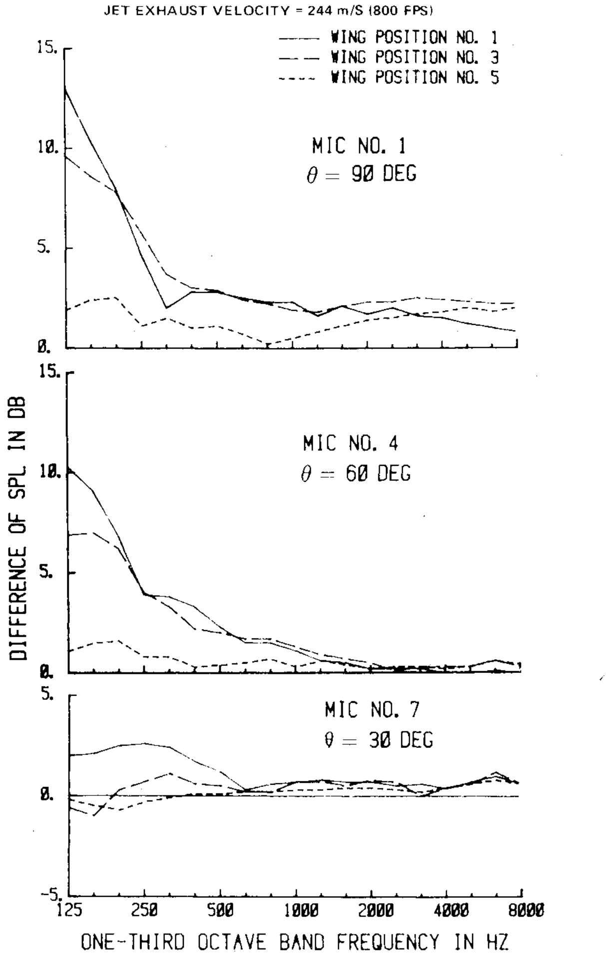

Fig. 12 Effect of wing positions with respect to the nozzle on noise enhancement.

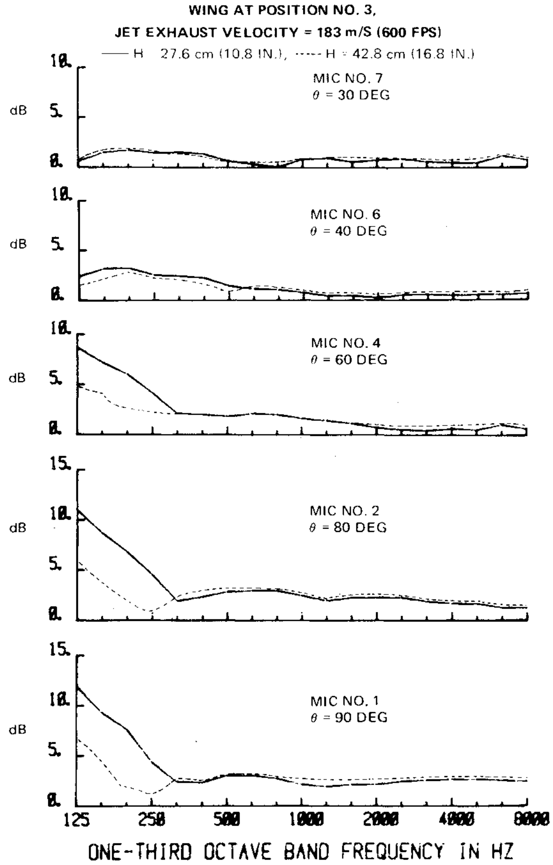

Fig. 13 Effect of distance between the wing and the nozzle axis.

pronounced in the results measured by microphone 1 at $\phi = 90$ deg.

The explanation for this is as follows. As the exhaust velocity of the jet is increased, the velocity of the air entrained by the jet into the region between the wing and jet is also increased. The higher velocity of the entrained flow shifts the frequency distribution of the generated noise into higher frequency ranges.[16] But the increase in higher frequency content in the noise spectra due to increased flow velocity is accompanied by corresponding reduction in the low-frequency content, thus explaining the trend.

Effect of Axial Wing Position

The effect of axial wing position with respect to the jet nozzle is shown in Fig. 12. The results indicate that the effect is most significant at the low-frequency end of the spectra. As the wing is moved from position 1, the extreme downstream position relative to the nozzle, to position 5 where the nozzle is near the trailing edge of the wing, noise enhancement is found to decrease. The low-frequency enhancement in noise is believed to be attributable to flow entrainment. Moving the wing from position 1 to 5 reduces the entrainment, and thus the low-frequency enhancement. As the nozzle approaches the trailing edge of the wing, more of the noise-producing region of the jet moves out of the region where the wing effect is significant.

Effect of Distance Between the Wing and the Jet

Typical results measured for the two distances between the wing and the jet axis are compared in Fig. 13. The results clearly show that wing effect diminishes with increase in the distance from the wing surface to the jet axis. Differences in noise enhancement are found mainly at low frequencies. Also, the largest differences are found to be measured by microphones near $\theta = 90$ deg. All these results suggest that entrainment of air into the region between the wing and the jet contributes to the low-frequency enhancement.

Effects of Various Wing Surfaces

The enhancement in noise measured by microphones in oblique planes for the three different types of wing panels are compared in Fig. 14. At high frequencies both the honeycomb-backed panel and the fiberglass panel produce substantially less enhancement than the baseline aluminum panel. These results indicate that the reflection effect of the wing is important and can be modified by absorption at the wing surface.

Source of Noise Enhancement

In view of the results of this study it is concluded that enhancement of noise due to the presence of a wing near a jet can be attributed to two major sources. One of the sources, as indicated in the results for various wing panels, is the reflection effect of the wing on the noise incident to it. The jet reflected by the wing surface certainly contributes to the higher noise levels. However, there is no evidence of interference between the jet noise reflected from the wing and that directly radiated from the jet.

The other possible source is the boundary layer generated on the surface of the wing as the result of entrainment of the air into the region between the jet and the wing. This source of noise appears to be responsible for the enhancement observed at low frequencies. The directivity of the low-frequency enhancement of noise, which peaks in a direction perpendicular to the wing surface, is similar to that of a dipole. Further effort in this area will be required to define with greater precision the contribution of noise radiated from the boundary layer.

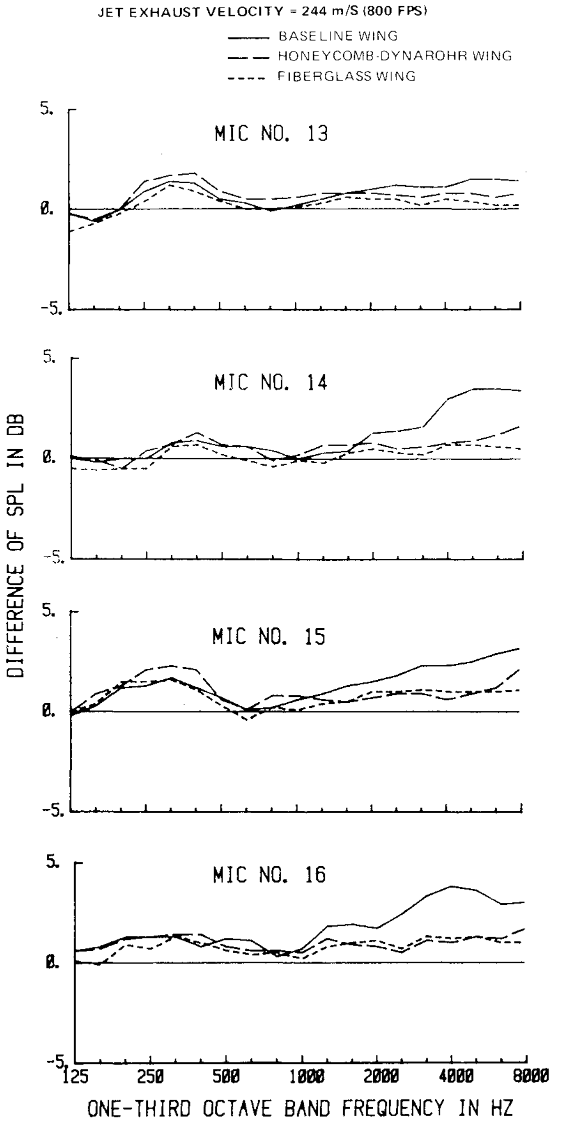

Fig. 14 Effect of various wing surface conditions on noise enhancement.

Practical Implications of the Wing Effect

It is of considerable interest to know how the wing effect influences aircraft flyover noise. Although, as pointed out earlier, the present experiment is not that of a precisely scaled model, the results can still be scaled to the full-scale aircraft to provide an estimate of the wing effect.

Assuming the temperature is constant and the exhaust velocity of a full-size jet is about 1100 fps, the scaling factor for frequency based on the same Strouhal number is approximately 0.2. Thus the approximate frequency relationship between the model used in the present investigation and that of the full-size aircraft is as follows (frequency in Hz):

Model	125	250	500	1000	2000	4000	8000
Full size	25	50	100	400	400	800	1600

For full-scale aircraft, the range of frequency where there is substantial low-frequency enhancement is well below 100 Hz. However, the frequency range in which substantial "high-frequency" enhancement is measured in oblique planes will be somewhere between 200 and 2000 Hz. Therefore, the wing effect may increase sideline noise levels of the aircraft. Nevertheless, the flight effect which tends to stretch the mixing length of the jet may move the noise-producing region downstream of the wing trailing edge and thus reduce the wing effect.

Concluding Remarks

The results of the experimental investigation have shown that the wing has considerable effect on the far-field measured jet noise. When the wing is placed near the jet, the measured noise over a range of jet exhaust velocities is generally found to be of a higher level than that of the jet alone. With few exceptions, enhancement in noise can be observed over the range of frequency of interest.

Experimental evidence indicates that the wing serves as a reflector for jet noise incident upon it. The reflected jet noise contributes to the higher noise levels. However, it is not evident that there is interference between the jet noise reflected from the wing and that radiated directly from the jet.

The boundary layer on the wing surface as the result of entrainment of air by the jet into the region between the wing surface and the jet is believed to be responsible for the substantial enhancement of noise at low frequency. This is supported by the directivity pattern of noise enhancement at low frequency, e.g., 125 Hz, which is that of a dipole.

Enhancement of noise over the frequency range of interest is strongly influenced by the jet. The different enhancement patterns measured by microphones in various planes, which contain the jet axis but at different angles with the wing surface, demonstrate the magnitude of this effect. The effect of the jet is most evident at high frequencies where the wavelengths of the noise are small compared to the dimension of the jet. The result agrees with previous investigations on the refraction effect of a jet on sound waves.

The enhancement at high frequencies measured in planes at oblique angles with the wing surface may require consideration in aircraft noise prediction and design. When scaled to full-size aircraft, the frequency range where substantial "high-frequency" enhancement of noise occurs will be somewhere above 200 Hz. Therefore, the wing effect may increase the sideline noise levels of aircraft during takeoff.

Several techniques may be used to reduce noise enhancement due to the wing effect. For instance, the jet engine may be positioned so the major source distribution of the jet noise would be downstream of the trailing edge of the wing. Surface treatment is quite effective in reducing high-frequency noise enhancement, but this technique does not seem practical for it could have negative impact on the aerodynamic performance of the aircraft.

The noise enhancement observed in the experiment under static conditions may not be a problem at all for aircraft during flight. The flight effect which tends to stretch the mixing length of the jet may reduce the wing effect. In addition, the atmospheric attenuation may also cause significant reduction of the noise enhancement at high frequencies. Further investigation will be necessary in the area of application to full-scale vehicles during flight.

Acknowledgments

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