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ACOUSTIC INVESTIGATION OF THE ENGINE-OVER-THE-WING CONCEPT USING A D-SHAPED NOZZLE

by Meyer Reshotko and Robert Friedman
Lewis Research Center
Cleveland, Ohio

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ACOUSTIC INVESTIGATION OF THE ENGINE-OVER-THE-WING CONCEPT USING A D-SHAPED NOZZLE

Meyer Reshotko* and Robert Friedman**
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

Small-model experiments were conducted of the engine-over-the-wing concept using a D-shaped nozzle in order to determine the static-lift and acoustic characteristics at two wing-flap positions. Configurations were tested with the flow attached and unattached to the upper surface of the flaps. Attachment was obtained with a nozzle flow deflector. In both cases, high frequency noise shielding by the wing was obtained. Configurations using the D-shaped nozzle are compared with corresponding ones using a circular nozzle. With flow attached to the flaps, the static lift and acoustic results are almost the same for both nozzles. Without the nozzle flow deflector, (unattached flap flow), the D-nozzle is considerably noisier than a circular nozzle in the low and middle frequencies.

Introduction

Recent studies of the engine-over-the-wing (EOW) concept have shown it to be a favorable contender for quiet aircraft.(1-8) The acoustic advantage of the EOW concept is that the wing shields the region under the aircraft from much of the middle and high frequency noise generated by jet mixing. Two experimental EOW configurations which have shown both good acoustic performance and powered lift capabilities are a circular nozzle with flow deflector and a high aspect ratio slot nozzle.(6) The circular nozzle with deflector in the EOW configuration was about 10 dB quieter than an engine-under-the-wing externally-blown-flap configuration of comparable size, also with a circular nozzle.(8) However, both the circular and slot nozzle may have either aerodynamic, structural or operational disadvantages for EOW aircraft. A possible compromise configuration being considered is a wing-mounted engine with a semicircular or D-shaped nozzle.

In the present work, conducted at the NASA Lewis Research Center, a preliminary experimental study using a small model was conducted in order to measure the noise levels and directivity patterns, as well as the static lift characteristics, of an EOW configuration with a D-shaped nozzle. Although powered lift applications were of primary interest, a model with potential conventional lift application was also tested. A 2-in. equivalent diameter, convergent D-nozzle was placed over a wing section such that the exhaust flow was attached to the upper surface of the wing. Tests were run with the flow attached to the flaps for powered lift application, and also unattached for conventional lift application. Flow attachment to the flaps was obtained with a nozzle flow deflector.

A two-flap wing section having a 13-in. chord was used. The flaps could be positioned at either 10°-20° or 30°-60°, which are assumed to be representative of takeoff and approach settings respectively. Static lift and acoustic measurements were taken at jet exhaust velocities over a range of 600 to 950 ft/sec. Data are primarily presented with the flap-slots closed for powered lift applications, and flap-slots open for conventional lift applications. Acoustical measurements were made at azimuthal angles corresponding to flyover and sideline. Results are compared to corresponding data obtained with a circular nozzle.(2,6)

Apparatus and Acoustic Analysis

Model Description

The D-shaped nozzle, so called because of its shape at the exit plane (Fig. 1), had an area equivalent to a 2 in. circular nozzle. The wing-flap system consisted of a wing segment with a double-slotted flap. The wing section had a chord length of 13 in., with the flaps retracted, and a span of 2 ft. The flaps could be placed in one of two positions: (1) leading-flap chord-line 30° from the wing chord line, trailing flap 60°; and (2) leading flap 10°, trailing flap 20°. The D-nozzle was mounted on the wing surface in such a manner that the wing chord line made a 5° angle with the nozzle axis. A sketch of the model with a flow deflector in place is shown in Figure 2. The deflector was used for powered lift applications to attach the flow to the upper surface of the flaps. The deflector is a simple canted rectangular plate displaced downstream of the exit plane of the nozzle. For the configuration shown, the presence of the deflector did not reduce the nozzle flow. The acoustic tests were conducted with the slots between the flaps open and with them completely covered with cloth tape.

Test Setup

Lift-thrust facility. - The amount of flow turning by the flaps was determined by measuring the static-lift and thrust of the over-the-wing model. The facility and over-the-wing model testing are described in references 9 and 6 respectively. The EOW models were mounted at the exit of a 6 in. diameter plenum suspended from overhead (Fig. 3). The plenum was supplied with pressurized, ambient temperature air and was isolated from solid supports by means of flexible couplings. This enabled the model and plenum to move freely in the horizontal plane. Forward thrust was measured by a load cell on the nozzle axis upstream of the plenum. Lift force, on the vertically-mounted model, was measured by a second load cell acting in a horizontal direction and perpendicular to the nozzle axis.

Lift and thrust measurements were taken over a nozzle-exit velocity range of 600 to 950 ft/sec.

* Aerospace Research Engineer, Jet Acoustics Branch, V/STOL and Noise Division; Member, AIAA.
** Aerospace Engineer, Operations Branch, V/STOL and Noise Division; Member, AIAA.

In order to normalize the nozzle-wing lift and thrust data, the thrust of the D-nozzle alone was also measured.

Acoustic facility. - The outdoor acoustic facility(6) is shown in Figure 4. Dry pressurized, ambient temperature air was supplied to the nozzle-wing assembly through a control valve and a valve-noise quieting system, which consisted of a perforated plate, a four-chamber baffled muffler, and approximately 15 ft of 4-in. piping.

Acoustic data were taken by fourteen 0.5-in. condenser microphones, located on stands in the same horizontal plane as the nozzle, on a 10 ft radius circle (Fig. 4). The nozzle was 5 ft above the smooth asphalt surface. As shown in Figure 5(a), when the wing was oriented vertically (90° to the microphone plane), measurements corresponded to an aircraft flyover mode. Rotating the wing and nozzle to an angle of 26.5° with the microphone plane represented a sideline mode (Fig. 5(b)). Acoustic measurements were taken over the same range of nozzle-exhaust velocities as the lift-thrust measurements, 600 to 950 ft/sec.

Both facilities used sharp-edged orifice plates with appropriate static and differential pressure taps and thermocouple probes to measure airflow. Nozzle total pressure was measured by a total-pressure tube at the plenum. Exit velocity was calculated by one-dimensional isentropic equations using the total to atmospheric pressure ratio and the total temperature of the flowing air.

Acoustic Analysis

Microphone output signals were analyzed by a 1/3-octave-band spectrum analyzer. The analyzer determined sound pressure level (SPL) spectra referenced to .0002 microbar (2×10^{-5} N/m^2). Overall sound pressure levels (OASPL) and integrated sound power levels (PWL) referenced to 10^{-13} watts were computed from the SPL data. Three noise data samples were taken at each microphone location for each pressure ratio. An atmospheric attenuation correction was applied to the average of the three samples to give lossless sound pressure level data at 10 ft. No ground reflection corrections were made to the noise data.

Aerodynamic Results

The measured values of static lift and thrust, and the turning angles of the exhaust flow are shown in Figure 6. Lift force and forward thrust are normalized by the nozzle alone thrust. The angle shown is that made by the turned flow with respect to the nozzle axis, and the magnitude of the radius represents a static turning efficiency. Data are also shown for corresponding tests with a circular nozzle.

Without a flow deflector, the flow-turning angles of the D-nozzle configuration were less than 7° for both flap positions. This indicated that the flow was attached to the wing but unattached to the flaps.

When the nozzle flow deflector (Fig. 2) was deployed, good attachment to the flaps was achieved. At the 10°-20° flap setting, the flow turned approximately 30° with a turning efficiency of 0.8. At the 30°-60° flap setting, good attachment was also achieved and the flow turned approximately 65° with a turning efficiency of 0.7. These results for the D-nozzle are almost the same as those of an equivalent area circular nozzle with deflector.(5,6)

These static-lift and thrust results are the same whether the flap slots are open or closed. However, with forward velocity, flap slot covering may be a factor in the turning effectiveness of the system.

Acoustic Results

The acoustic results obtained from tests of the engine-over-the-wing concept using a D-shaped nozzle are separated into three categories: nozzle alone; attached flow (where the flow is attached to the upper surface of the wing and flaps); and unattached flow (where the flow is attached to the wing but unattached to the flaps). For each category comparisons are made with similar EOW configurations using an equivalent area circular nozzle.

Nozzle Alone

In order to evaluate the acoustic benefits associated with the EOW concept, the measured noise data are compared to the noise of the nozzle alone. The acoustic characteristics of the D-shaped nozzle are presented in Figure 7 and are compared to those of a circular nozzle for the flyover orientation. The sound pressure level spectra (Fig. 7(a)) shown for the D-nozzle are at velocities of 610, 765 and 940 ft/sec and measured at 100° from the nozzle inlet. The spectra of the "D" and the circular nozzle are about the same at low frequencies, but there is a tendency for the D-nozzle to produce higher values at the high frequencies. At the lowest velocity (610 ft/sec), the D-nozzle data above 3150 Hz is 3 dB noisier than the circular nozzle data, especially at the lower velocities.

The radiation pattern for the D-nozzle and comparison with the circular nozzle are presented in Figure 7(b) in terms of overall sound pressure level. The OASPL's of both nozzles are essentially the same, except at 610 ft/sec where the D-nozzle is noisier by 2 dB at all angles. It should be noted that although the upper and lower surfaces of the D-nozzle are not symmetrical (Fig. 1), the resulting noise radiation patterns in the flyover mode are.

Attached Flow

Nozzle exhaust flow attachment to the upper surface of the wing and flaps was obtained for powered lift simulation by use of a deflector (Fig. 2). All data are for the flyover position and covered flap slots unless otherwise indicated.

Basic noise data. - One-third octave band SPL spectra for the EOW configuration are shown in Figure 8 for a nozzle exhaust velocity range of 625 to 945 ft/sec. Data are presented for the 10°-20° and 30°-60° flap positions. The spectra shown were measured at 100° and 80° from the nozzle inlet, for the respective flap positions. At an exhaust velocity of 945 ft/sec the spectra at the two different flap positions are very similar. However, at exhaust velocities of 765 and 625 ft/sec the SPL values above 1000 Hz are about 4 dB greater for the 30°-60° flap position.

The noise radiation patterns for both flap positions are shown in Figure 9 at an exhaust velocity of 765 ft/sec. In the region in front of and under the wing, 20° to 100° from the nozzle inlet, the OASPL values at the 10°-20° flap position are 2 to 3 dB less than those at the 30°-60° flap position. Above the model, between 200° and 330°, the noise levels at the two flap positions are almost the same. Similar results were obtained at the other jet velocities used herein.

Noise generation and shielding. - The effect of noise generation and shielding by the wing for the attached-flow EOW configuration with a D-nozzle is shown in Figure 10. For this particular case, the flaps are set at 10°-20° with a nozzle exhaust velocity of 765 ft/sec. The sound power level is plotted versus frequency in Figure 10(a). Considering the nozzle alone as a baseline noise level, the addition of the flow deflector causes a large increase in noise power generation at the middle and high frequencies. The addition of the wing causes no further increase in high frequency noise, but generates a large amount of middle and low frequency noise. This noise increase is caused primarily by the flow passing over the trailing edge of the last flap. It should be noted that with the nozzle flow deflector configuration used (Fig. 2), the flow in the plane of the exit of the deflector plate is probably no longer D-shaped in profile (possibly more like an open-sided slot flow).

The effect of wing shielding is shown in Figure 10(b) where SPL is plotted versus frequency for an angle of 100° from the nozzle inlet. The noise data show that adding a deflector to the nozzle alone causes an increase in high frequency noise just as in the power generation case. However, at this location below the wing, the addition of the wing causes a large noise decrease in the high frequency region and a large increase in the low frequency region. The wing thus acts as a good shield for the high frequency noise causing the flap noise below 2000 Hz to dominate. Similar results were obtained at the other jet velocities and at the 30°-60° flap position.

Effect of velocity. - The effect of exhaust velocity on the flyover noise for the EOW model with attached flow is shown in Figure 11. Acoustic data for both flap positions and the nozzle alone are included. The OASPL values are for a common microphone angle of 100°. The data for both flap positions follow the sixth power velocity relationship, which is in agreement with previously reported flap noise data.(8,10) The 10°-20° flap position is quieter than the 30°-60° by one to two dB. The nozzle-alone data follow the eighth power velocity relationship, which is in agreement with most nozzle data. Similar results were obtained at other angles below the wing.

Effect of flap slot covering. - The effect of flap slot covering on noise spectra with a D-shaped nozzle in the EOW configuration is shown in Figure 12. Data taken with open and fully covered flap slots are compared at the 30°-60° flap position for a nozzle exhaust velocity of 765 ft/sec. The noise level is very sensitive to whether the slots are open or closed. Opening the flap slots caused the peak SPL to increase by six dB and the OASPL to increase by three dB. This noise increase is caused by the interaction of the jet exhaust with the wing trailing edge and the leading and trailing edges of the flaps. As the jet velocity decreases the noise difference between that of the open and closed flap slots increases. Because of this adverse effect of open flap slots on noise, all the other results in this section on attached flow have been presented for configurations having fully covered slots.

Sideline noise. - In addition to the acoustic measurements taken at simulated flyover, noise data were also taken at a simulated sideline location. The sideline noise data were taken with the nozzle and wing-flap system making a 26.5° angle with the microphone plane (Fig. 5(b)). A comparison of flyover and sideline noise with attached flow using a D-shaped nozzle is shown in Figure 13. Data are presented at exhaust velocities and microphone angles appropriate to each flap position. At sideline, the values of SPL are less at all frequencies with a three dB decrease in OASPL at a jet exhaust velocity of 945 ft/sec.

Comparison with circular nozzle EOW model. - Many of the small model configurations previously tested(1-6) used a circular nozzle with deflector to explore the acoustic advantages of the engine-over-the-wing concept. A spectral comparison of the "D" and the circular nozzles are shown in Figure 14. The data are for the 10°-20° flap position taken at 100° from the nozzle inlet and shown at all three velocities. These data are also presented in reference 6. Below 1000 Hz the D-nozzle configuration is one to three dB noisier than that of the circular nozzle at all velocities, and above 5000 Hz two to three dB quieter at the velocities of 765 and 945 ft/sec but showing no difference at 625 ft/sec. Except for these differences the two configurations have very similar spectra.

A comparison of the noise radiation patterns for the D-nozzle and the circular nozzle at an exhaust velocity of 765 ft/sec is shown in Figure 15. The values of OASPL for the two configurations are the same below the wing (at angles of 20° to 120° from the nozzle inlet), however, above the wing (from 180° to 330°) the D-nozzle is from zero to five dB noisier.

Unattached Flow

A one-third octave band SPL spectrum of the D-nozzle configuration without a deflector is shown in Figure 16(a) in comparison to results for the nozzle alone. The data are for open flap slots at 10°-20°, a nozzle exhaust velocity of 765 ft/sec, and a microphone angle of 120°. The 120° angle was selected because the flyover noise is a maximum for both flap positions when flap flow attachment is absent. The lift-thrust measurements for these data (Fig. 6) indicate that the flow is unattached to the flaps (flow is attached to the wing). The presence of the wing reduces the noise above 5000 Hz, but causes a large noise increase below 5000 Hz. The noise attenuation at high frequencies is due to wing shielding, and the noise increase at low frequencies is due to the scrubbing of the flow over the wing surface and its interaction with the wing trailing edge.

Figure 16(b) shows the variation of noise with velocity. The noise for the D-nozzle and wing configuration follows a velocity to the sixth power relationship. This is unlike the case of the circular nozzle in unattached flow which behaves as V^8.(8) However, over-the-wing attached-flow noise and externally-blown-flap noise do behave as V^6 as shown in Figure 11 and references 8 and 10. This means that although the flow is unattached to the flaps with the D-shaped nozzle, there is a flow interaction with the wing surface and its trailing edge which causes the noise to be generated in the same manner as flap noise.

A spectral comparison of the D-shaped and circular nozzles with open and closed flap slots for the EOW model is shown in Figure 17. For the circular nozzle without deflector, the flow is unattached to the wing as well as the flap. For the D-shaped nozzle without deflector, only the flow over the flaps is unattached. Although both configurations have the same SPL values above 10 000 Hz, the D-nozzle is considerably noisier below this frequency. The increase in low frequency noise with the D-shaped nozzle with flap slots closed (Fig. 17(a)) is due to the scrubbing noise of the flow attached to the wing. With the flap slots open (Fig. 17(b)), there is an additional noise contribution from the flow over the wing trailing edge. At 500 Hz the D-shaped nozzle is 9 dB louder than the circular for both open and closed flap slots.

Summary of Results

A preliminary small model experimental test was conducted in order to measure the static lift and acoustic characteristics for D-shaped nozzles in the engine-over-the-wing configuration.

With a nozzle flow deflector, good flow attachment to the flaps was achieved. The flow turned approximately 30° and 65°, for flap positions typical of takeoff and approach respectively. Without a deflector, the flow turning was only about 7° at both flap positions.

For the attached flow situation the deflector was a source of middle and high frequency noise, while the flap trailing edge contributed low and middle frequency noise. The wing shielded the high frequency noise, leaving the flow over the trailing edge of the last flap as the dominant noise source. Comparisons of configurations with attached flow using the D-shaped nozzle over the wing with ones using a circular nozzle indicated that the aerodynamic and acoustic results were about the same for both at angles of interest.

For unattached flap flow, the D-nozzle configuration tested (with attached wing flow) was considerably noisier in the low and middle frequencies than one using a circular nozzle (unattached wing flow).

Concluding Remarks

In conclusion, it is of interest to discuss the implications of these preliminary model test results with respect to aircraft applications. It has been shown in previous studies that small model engine-over-the-wing noise data, when scaled up properly, can predict large scale results quite well.[8] Therefore the results obtained from this small model experiment are an indication of the acoustic characteristics of D-shaped nozzles over-the-wing when applied to full-sized aircraft.

The main advantage of the EOW concept, as described herein, is the shielding of the high frequency jet noise by the wing. In order to approach a full sized aircraft a scale factor of 15 or more must be applied to the data. This scales the shielded noise spectra to lower frequencies, such that there is a favorable effect on perceived noise level. The accompanying increase in the very low frequency noise, however, may create structural vibration and material fatigue problems to the aircraft, as well as annoyance to the community.

On the basis of the preliminary results presented herein for the EOW concept with powered lift, it can be concluded that the use of a D-shaped nozzle produces no acoustic penalty when compared to a circular nozzle. Thus, other installation or performance considerations could predominate in the selection of nozzle shape. Furthermore, the static-lift results indicate that a flow attachment device is necessary for powered lift applications. In an aircraft application, the simple external flow deflector used in this study can be replaced by an internal deflector which would be an integral part of the D-shaped nozzle. Such a design would provide good turning efficiencies while providing minimum aerodynamic drag. However, refinements such as these were considered beyond the scope of this exploratory investigation.

Additional noise attenuation, including a reduction of jet-flap interaction noise, may possibly be obtained with an acoustically treated flap system.[11] However, flap treatment will be acceptable only if the loss in augmented lift will not significantly affect the desired aerodynamic performance.

Although this experiment was primarily intended for powered lift applications, a conventional lift model was obtained by removal of the flow attachment device. Although good shielding of the high frequency noise was achieved, the low and middle frequency noise was loud because of the flow interaction with the upper surface of the wing. Perhaps with configuration refinements this additional noise can be reduced somewhat.

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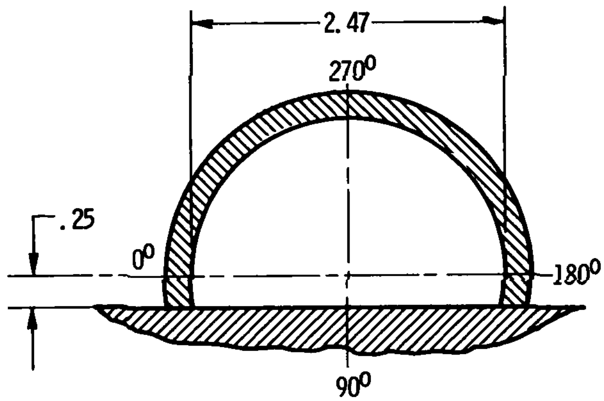

Figure 1. - Exit view of D-shaped nozzle. (Dimensions in inches.)

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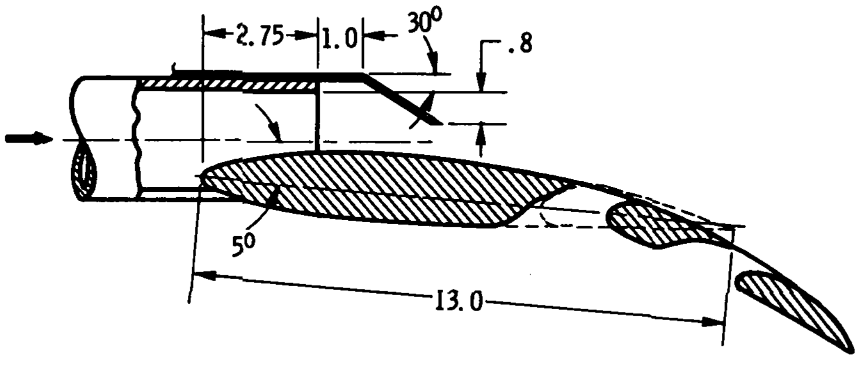


Figure 2. - D-shaped nozzle with deflector mounted over the wing. 10°-20° flap setting illustrated. (Dimensions in inches.)

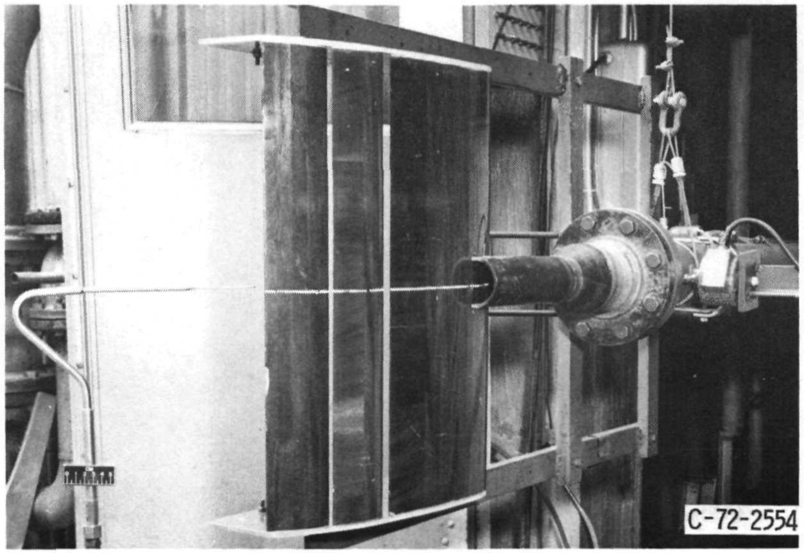


Figure 3. - D-shaped nozzle over the wing without deflector in the lift-thrust facility. 10^0-20^0 flap setting.

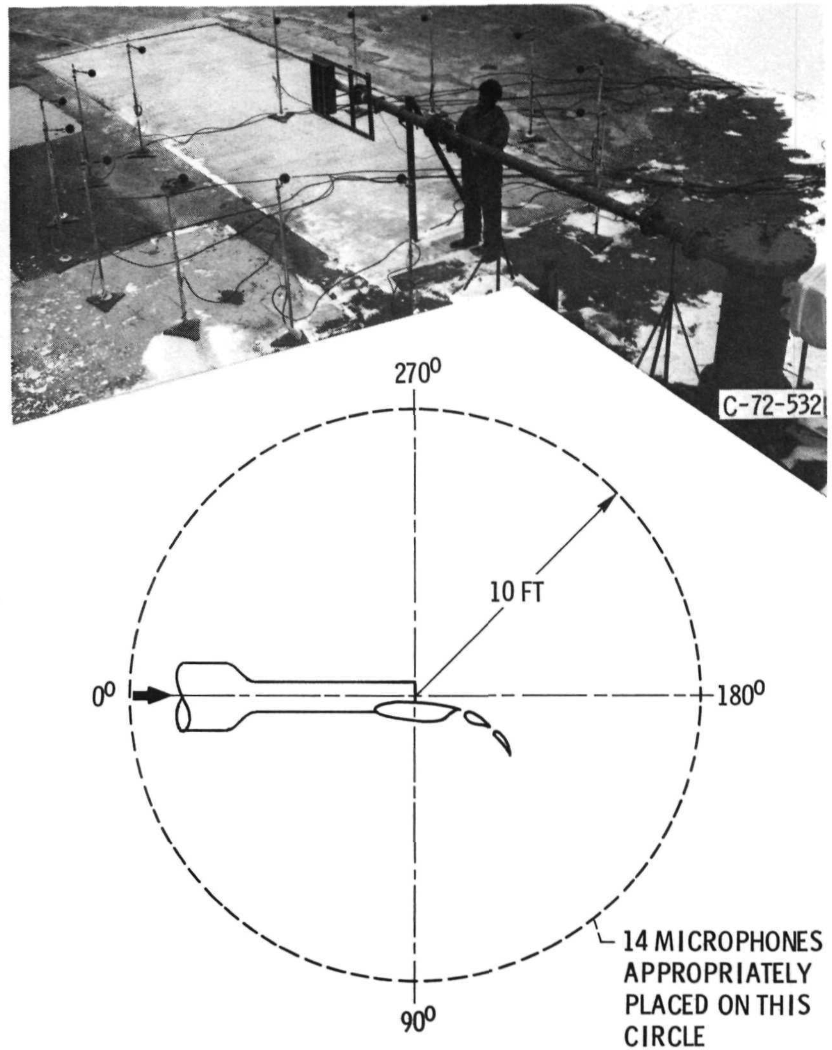


Figure 4. - A typical setup for performing noise tests on the engine-over-the-wing model at the outdoor acoustic facility.

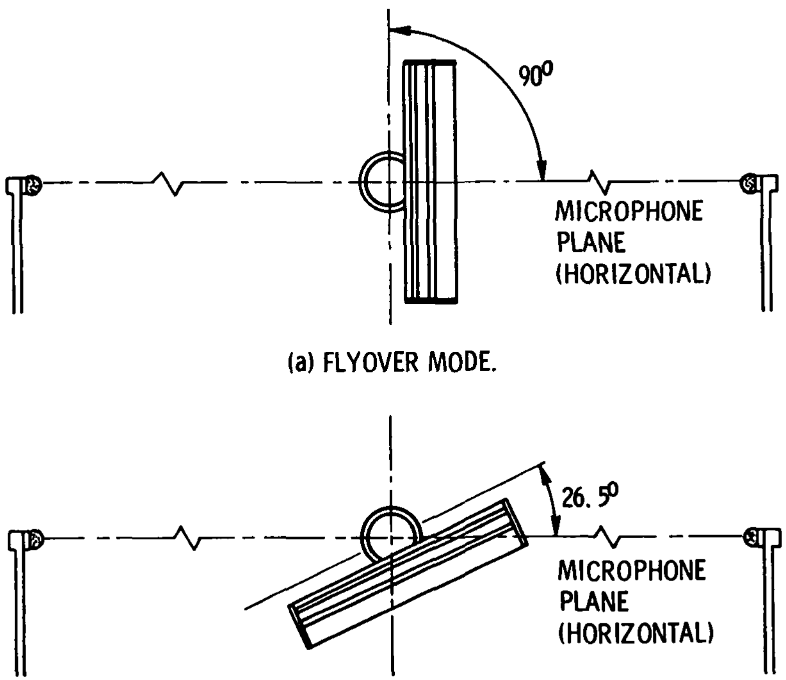


Figure 5. - Orientation of the engine-over-the-wing model for acoustic tests.

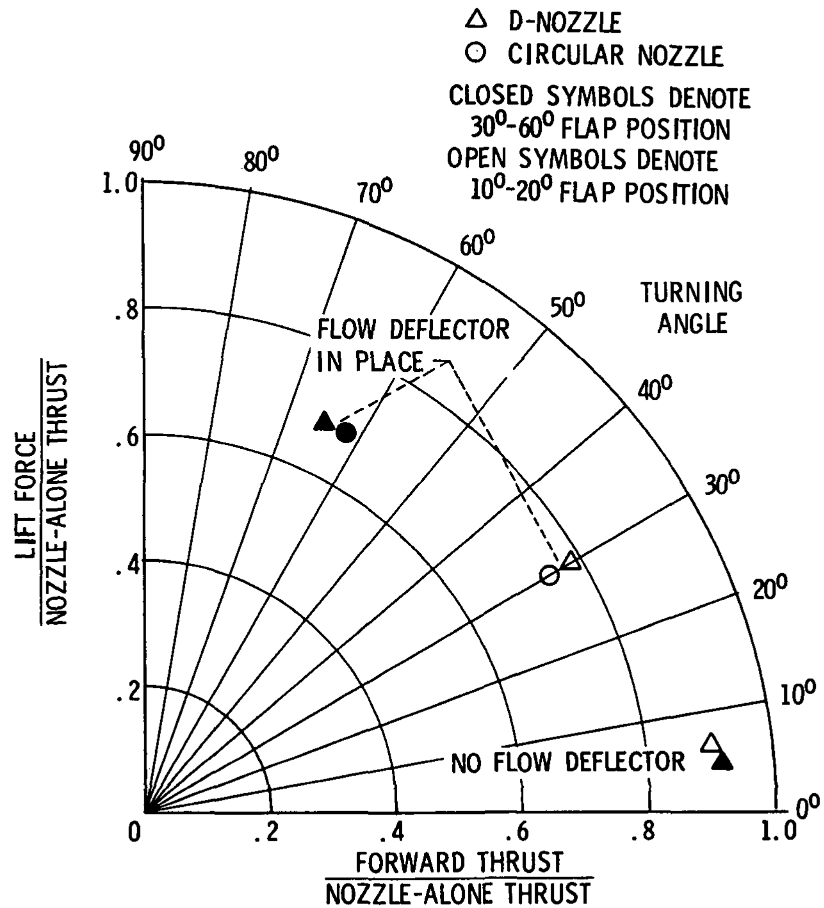
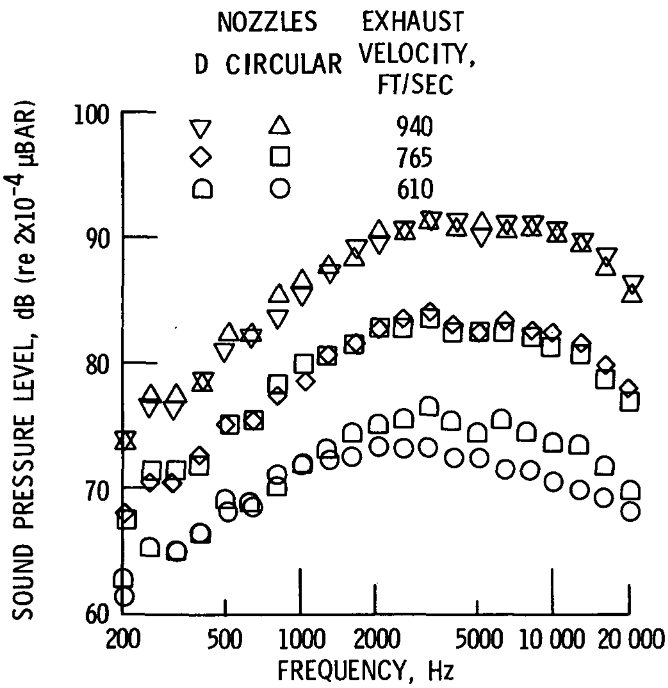
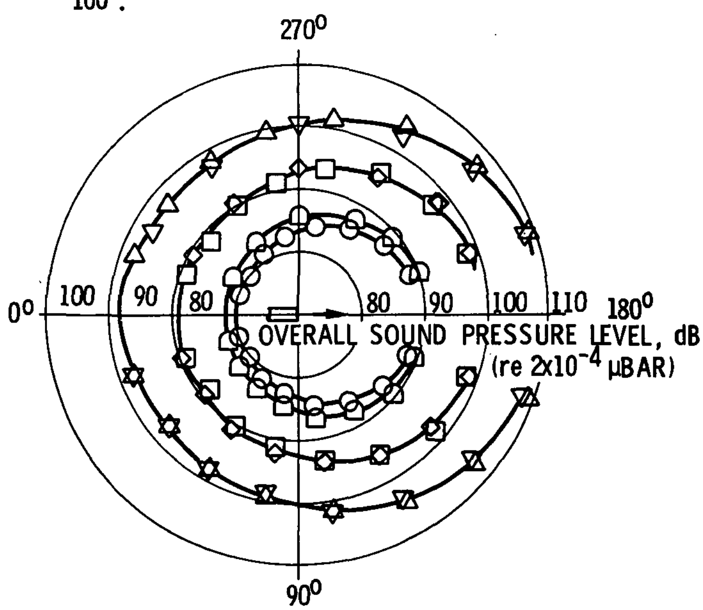


Figure 6. - Static turning effectiveness of the engine-over the wing configuration using a D-shaped nozzle. Nozzle exhaust velocity range, 600 to 950 ft/sec.



(A) NOISE SPECTRA. MICROPHONE ANGLE, 100°.



(B) NOISE RADIATION PATTERN.

Figure 7. - Noise comparison for D-shaped and circular nozzles.

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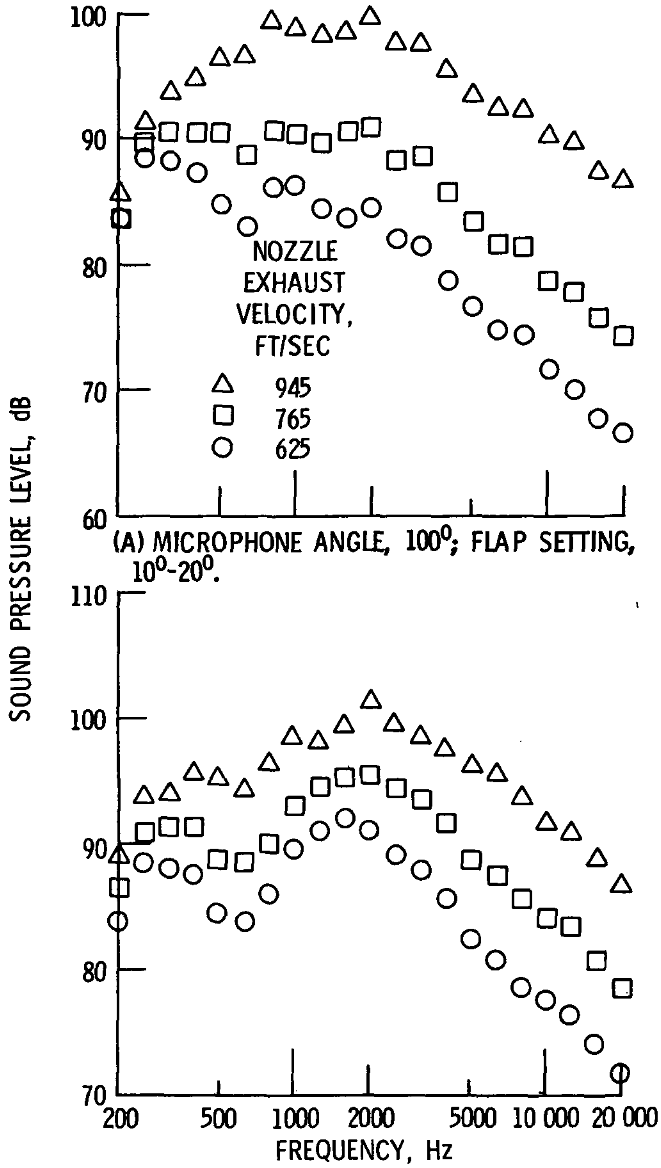

(A) MICROPHONE ANGLE, 100°; FLAP SETTING, 10°-20°.

(B) MICROPHONE ANGLE, 80°; FLAP SETTING, 30°-60°.

Figure 8. - Sound pressure spectra for the EOW configuration with a D-shaped nozzle and attached flow. (Flow deflector in place.)

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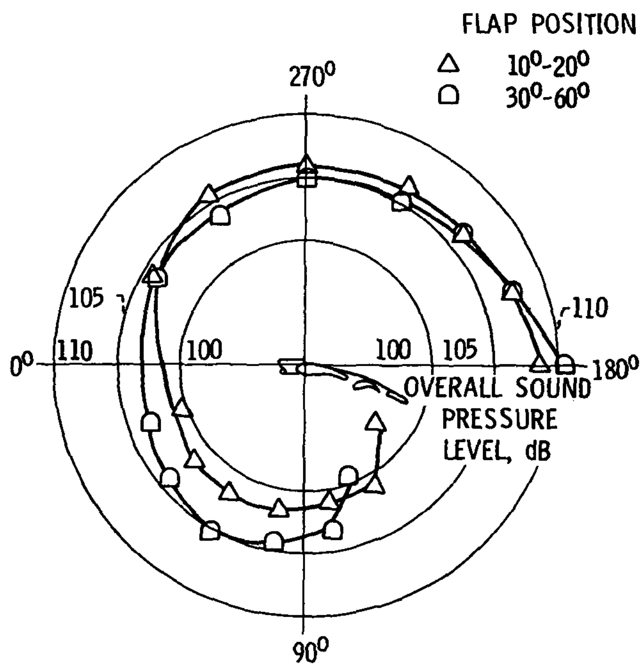

Figure 9. - Effects of flap position on the noise radiation pattern with a D-nozzle and attached flow in the EOW configuration. Nozzle exhaust velocity, 765 ft/sec.

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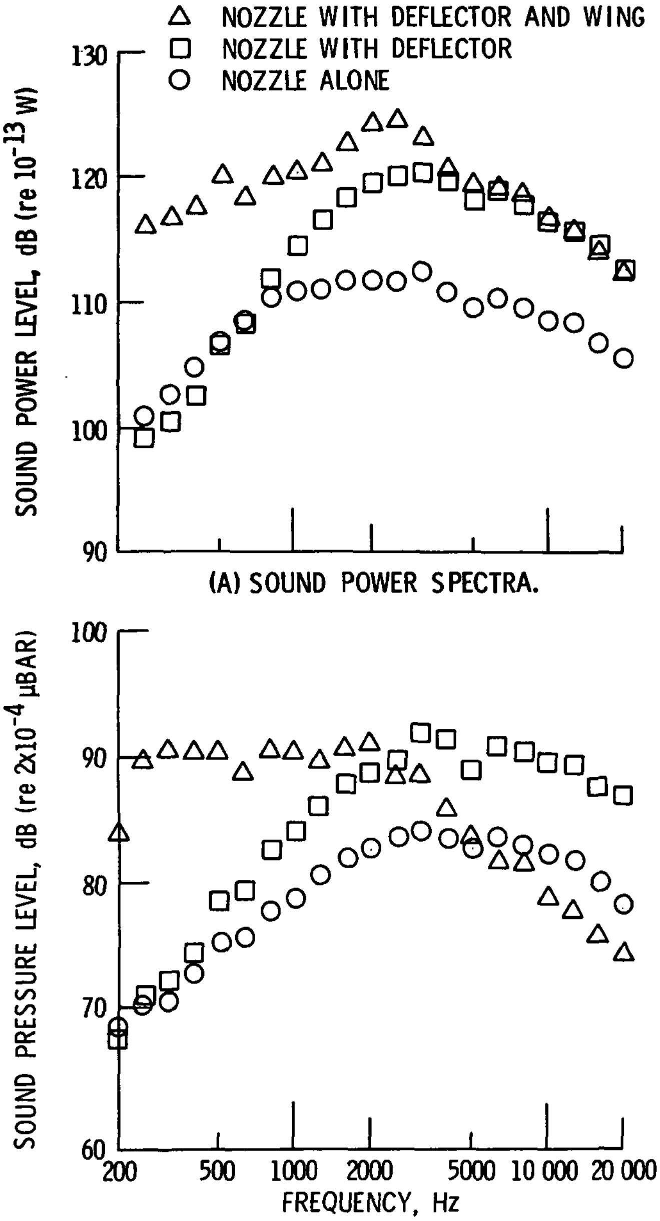


(B) SOUND PRESSURE SPECTRA. MICROPHONE ANGLE, 100^0.

Figure 10. - Effect of noise generation and shielding by the wing on the EOW configuration with a D-nozzle and attached flow. Flap setting, 10^0-20^0; nozzle exhaust velocity, 765 ft/sec.

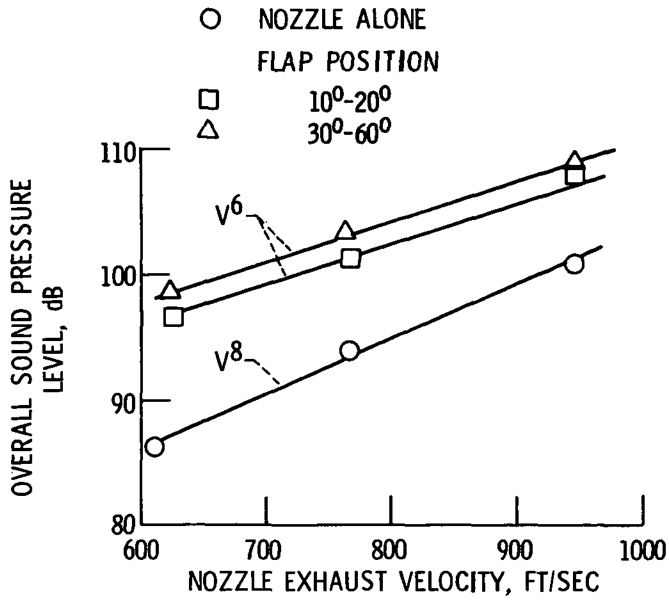


Figure 11. - Effect of exhaust velocity on noise for the EOW model with a D-shaped nozzle and attached flow. Microphone angle, 100°.

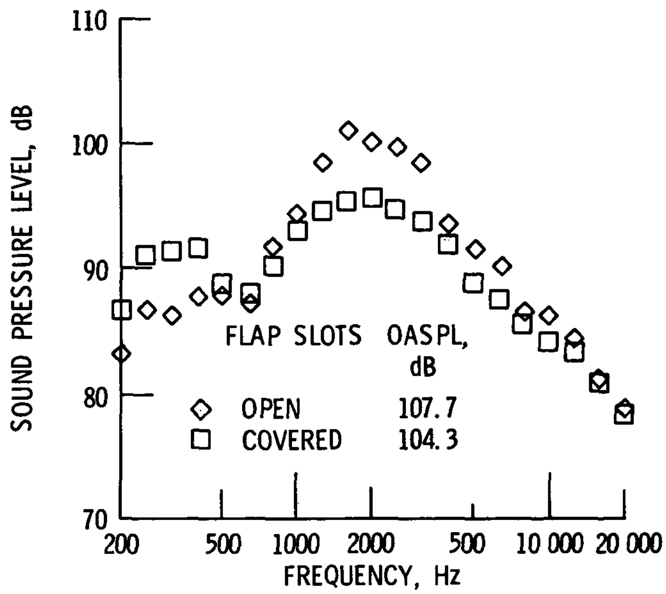
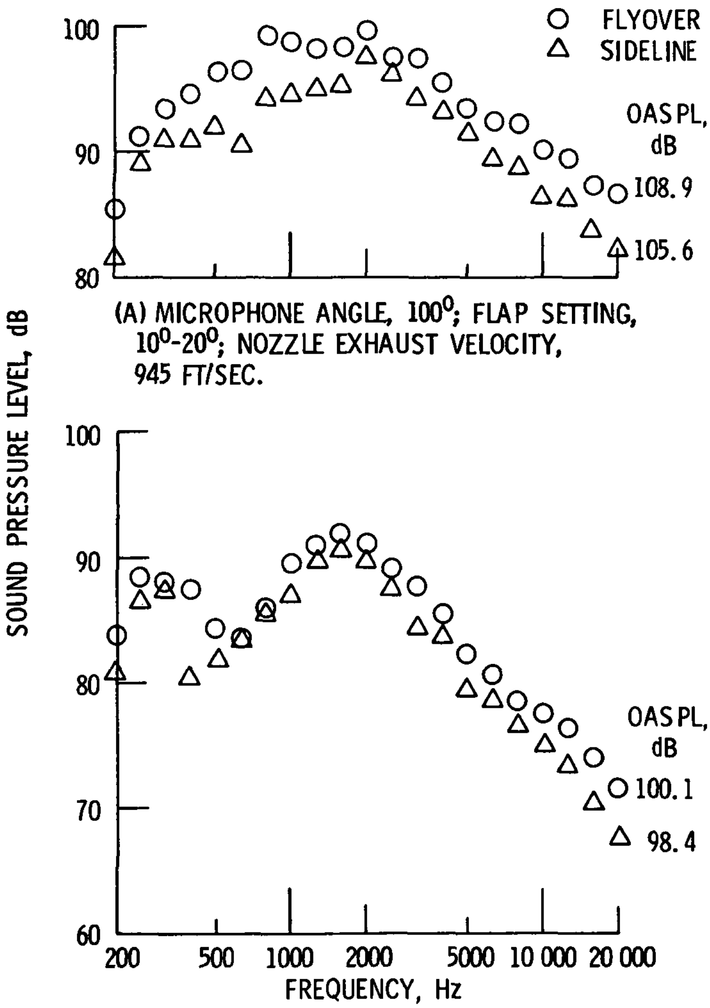


Figure 12. - Effect of flap slot covering on noise spectra with a D-shaped nozzle in the EOW configuration and attached flow. Flap setting, 30°-60°; nozzle exhaust velocity, 765 ft/sec; microphone angle, 80°.



(A) MICROPHONE ANGLE, 100°; FLAP SETTING, 10°-20°; NOZZLE EXHAUST VELOCITY, 945 FT/SEC.

(B) MICROPHONE ANGLE, 80°; FLAP SETTING, 30°-60°; NOZZLE EXHAUST VELOCITY, 625 FT/SEC.

Figure 13. - Comparison of flyover and sideline noise for a D-shaped nozzle in the EOW configuration with attached flow.

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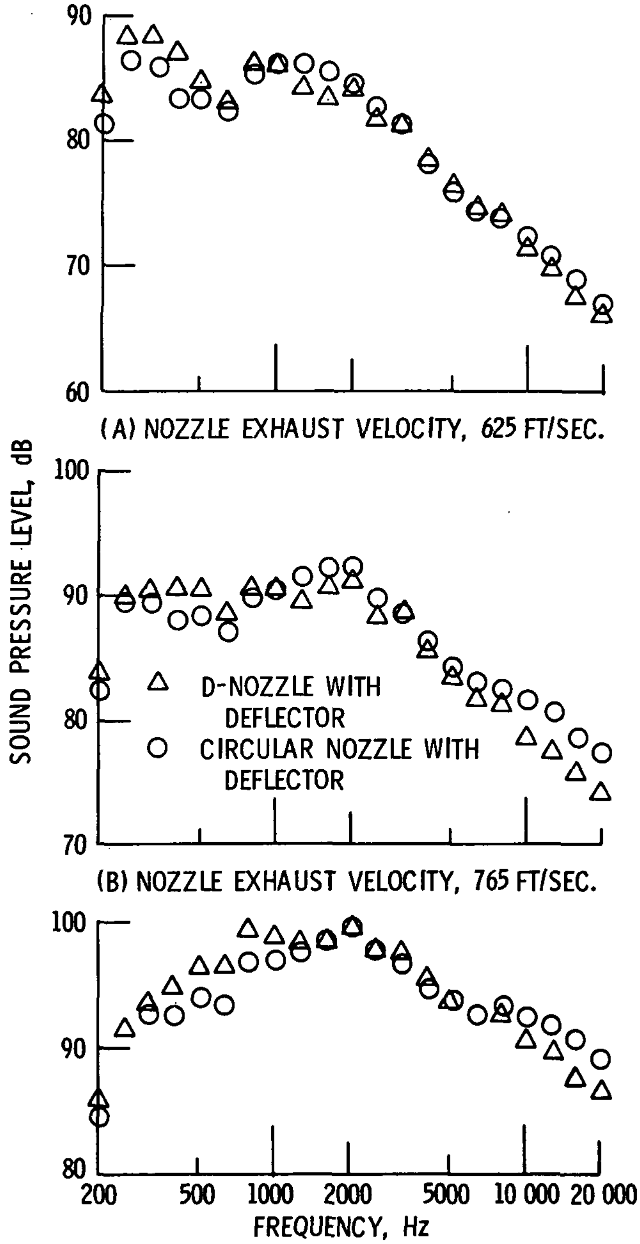

Figure 14. - A spectral comparison of D-shaped and circular nozzles in the engine-over-the-wing configuration with attached flow. Flap setting, 10°-20°; microphone angle, 100°.

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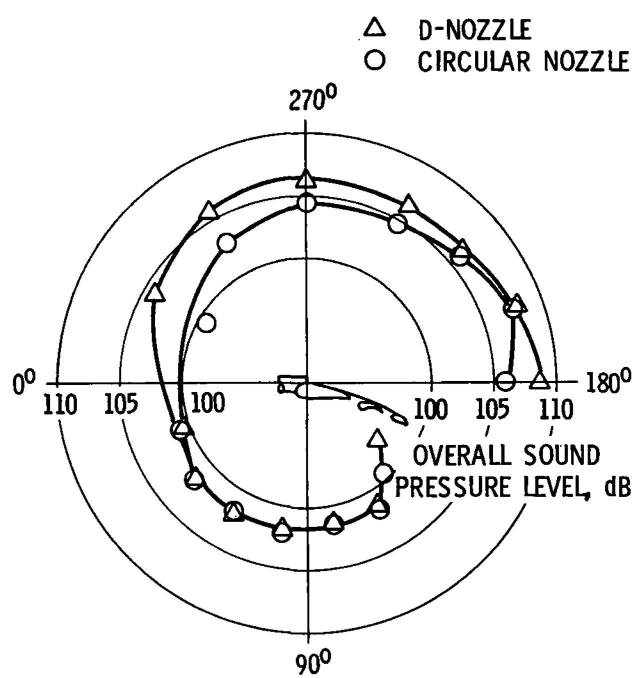
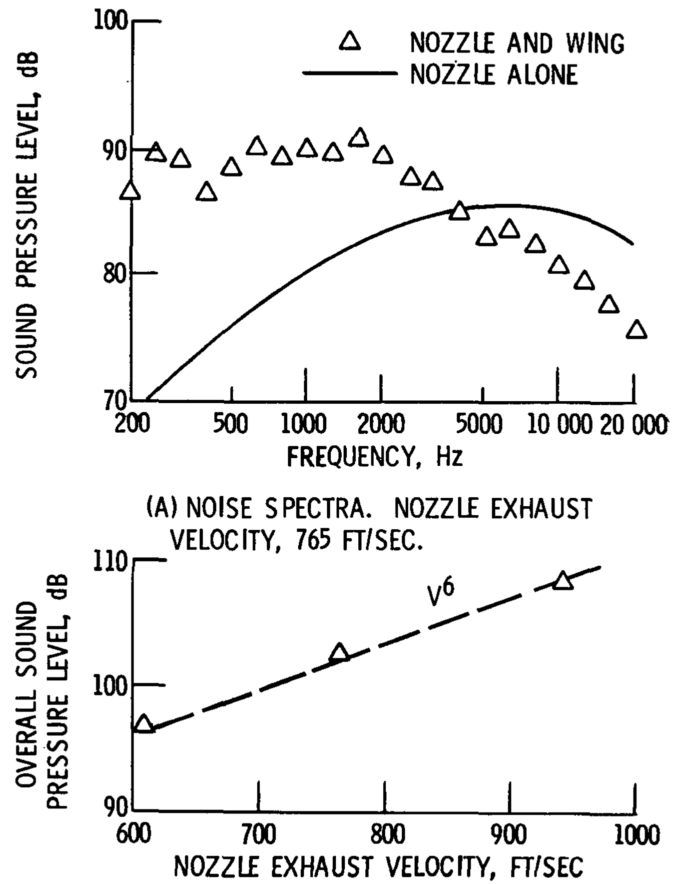


Figure 15. - A comparison of noise radiation patterns for D-shaped and circular nozzles in the EOW configuration with attached flow. Flap setting, 10^{0}-20^{0}; nozzle exhaust velocity, 765 ft/sec



(A) NOISE SPECTRA. NOZZLE EXHAUST VELOCITY, 765 FT/SEC.

(B) EFFECT OF VELOCITY.

Figure 16. - Noise characteristics of the D-nozzle in the engine-over-the-wing configuration with unattached flow (no deflector). Flap setting, 10^{0}-20^{0}; microphone angle, 120^{0}; flap slots open.

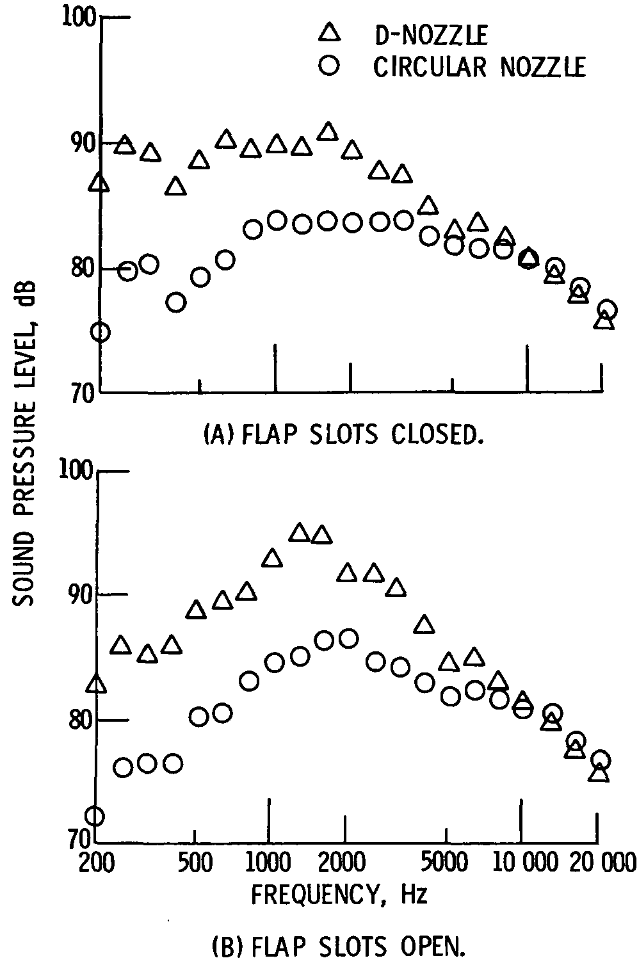


Figure 17. - A spectral comparison of D-shaped and circular nozzles for the EOW model with unattached flow. Flap setting, 10°-20°; microphone angle, 120°; nozzle exhaust velocity, 765 ft/sec.

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