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FORWARD VELOCITY EFFECTS ON JET NOISE WITH DOMINANT INTERNAL NOISE SOURCE

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ABSTRACT

Acoustic data, with and without forward velocity, were obtained with a circular nozzle using a quiet flow system and one dominated by a low frequency internal noise source (analogous to combustion noise). Forward velocity effects were obtained by installing the test nozzle in a free jet. Far-field noise data were obtained at jet pressure ratios from 1.3 to 1.7 and forward velocities up to 260 ft/sec. With a quiet flow system, jet noise is reduced by forward velocity. With a dominant low frequency core noise source, the portion of the noise spectra dominated by this source was not appreciably affected by forward velocity.

INTRODUCTION

When jet noise is reduced by the use of high-bypass ratio turbofan engines with low jet exhaust velocities, engine core noise (internal noise) can become a dominant far-field noise source. A prime contributor to engine core noise is the combustor. The combustor constitutes a pressure loss device that has inherent flow-related and flame instability noise. In addition, the combustor and other internal components can create swirl and turbulence that can also influence the external jet shear flow region and core structure of the jet, thereby altering or adding to the external noise generation processes.

In reference 1, it is shown that combustors, lit or unlit, can contribute to the noise field. With the flame on, a significant increase in low frequency noise occurred as shown in figure 1, taken from reference 1. (All symbols are defined in Nomenclature.) In addition, the flame presence reduced the high frequency noise radiation. It should also be noted that the larger burner (small pressure drop device) did not generate as much noise (cold flow) as the smaller burner (large pressure drop device). This may, in part, explain the differences in noise level between the two burners.

Engine core noise can also provide a floor for jet noise suppression in the range of conventional jet exhaust velocities. For example, the contribution of internal noise (engine core noise) for the JT8D engine is sufficient to impose a constraint on the noise suppression of the engine (ref. 2). With high-bypass ratio turbofan engines, such as those being considered for quiet STOL aircraft, and their associated lower jet velocities this constraint will become even more significant.

Finally, in order to predict inflight propulsion system noise, the forward velocity effects on the aircraft noise level must be established. The ability to predict this noise level is important in determining the approach and takeoff flight paths for minimum aircraft noise over a community. The attenuation effects of forward flight (velocity) effects on pure jet noise are given in reference 3 for a variety of nozzle geometries. However, the effect of forward velocity on jet noise with internal flow-related (combustion) noise remains to be established.

In the present study, conducted at the NASA Lewis Research Center, the effect of forward velocity on subsonic jet noise with flow-related internal noise that simulated the engine situation with core combustion noise was examined. The core combustion noise characteristics were simulated with a cold-flow air jet rig that included an internal noise source; namely, the flow control valve. The rig could be operated with or without internal noise being the dominant noise source by use of a suitable muffling system. An outdoor free jet surrounding the test nozzle exhaust flow was used to provide forward velocity. Far-field noise data for a convergent circular nozzle (ref. 3) obtained with a quiet flow system (pure jet noise) are compared with that obtained with a low-frequency dominant internal noise flow system. Jet velocities of 680 to 940 feet per second were used in the tests. The free jet was capable of providing free stream (forward) velocities up to 260 feet per second. The results are presented in terms of sound pressure level and sound power spectra, acoustic radiation angles (directivity) and total sound power.

APPARATUS

Internal flow-related noise with characteristics similar to combustion noise is frequently encountered in a jet noise test rig using a laboratory air supply. The dominant internal noise source (fig. 2) generally is the flow control valve. The peak noise for such a rig is frequently 30 dB or more higher than the pure jet noise (i.e., jet noise with a quiet flow system). The valve noise can be reduced well below the pure jet noise by means of perforated plates and mufflers downstream of the valve. The perforated plates change the valve noise to one of much higher frequencies that can be attenuated easily by a dissipative muffler using conventional acoustic absorbent materials. If the perforated plates are left out of the muffling system, the high frequencies in the valve noise spectra are still attenuated by the muffler; however, the low frequencies are unaffected. This yields the noise spectrum shown by the dashed line in figure 2. When the spectrum is suitably tailored, by the design of the muffler, it is analogous and representative of the combustor generated noise spectra shown previously in figure 1.

Details of the free jet and the specific nozzle flow systems are given in the following sections.

Free jet. - A 13-inch diameter free jet (fig. 3) was used to provide forward velocity. For this rig, dry cold air (at about 520° R) was supplied to a 16-inch diameter gate valve from the Center's 125 psia air supply system by way of a 24-inch diameter underground pipe line. A 10-inch diameter butterfly valve was used to control the flow. The nozzle centerline was 12 3/4-feet above grade.

A muffler system installed in the line downstream of the flow control valve attenuated internal noise caused primarily by the flow control valve. Essentially, the muffler system consisted of perforated plates and dissipative type mufflers. The first perforated plate was located immediately downstream of the flow control valve (40-percent open area plate, 1-inch diameter holes). The other perforated plates were located at the entrance and exit of the first dissipative mufflers (20-percent open area plates, 1/8-inch diameter holes). Both dissipative mufflers were sections of pipe that contained splitter plates oriented at right angles to one another so that the flow divided into four channels. The internal surfaces of the muffler pipes and the surfaces of the splitter plates were covered with 1-inch-thick acoustic absorbent material. The second dissipative muffler was located downstream of the last 45° elbow in the airflow line to take advantage of the reflections caused by turning the flow. In addition the system was wrapped externally with fiber glass and leaded vinyl sheet to impede direct radiation of internal noise through the pipe wall. Two screens (5/16-inch mesh) were placed in the air line downstream of the last muffler to improve the flow distribution to the free jet nozzle.

Test nozzle flow system. - The quiet flow system (ref. 3) for the test nozzle, proceeding downstream, consisted of a flow control valve, two perforated plates, a four-chamber-baffled muffler, a 4-inch inlet pipe and, finally, the test nozzle. This muffling system removed sufficient internal noise so that it was not significant in the measured far-field noise levels (similar to the lower solid curve in fig. 2). Pressurized air was supplied at a nominal temperature of about 520° R.

In order to provide a dominant low-frequency internal noise source, a somewhat different muffler system than that just described was used. This system consisted of a dissipative muffler (ref. 4) without perforated plates. The muffler removed high frequency noise; however, low frequency valve noise, analogous to combustion noise, was substantially unaffected. The net effect was to provide a noise spectrum similar to the dash line in figure 2.

Test nozzle. - The test nozzle consisted of a convergent circular nozzle having a 2.06-inch diameter. This nozzle was mounted on the centerline of the free jet. Pertinent installation dimensions and details are given in figure 3. A photograph showing a typical test nozzle mounted in the free jet is shown in figure 4.

PROCEDURE

Data were obtained at nominal jet velocities for the test nozzle from 680 to 940 feet per second. Free jet velocities ranged from 0 to 260 feet per second. Total pressures and temperatures were measured upstream of the nozzle. Jet exhaust velocities were calculated from the isentropic equations.

Acoustic data were taken with 0.5-inch condenser microphones placed on a 10-foot radius circle centered at the nozzle exit (fig. 5). The microphone horizontal plane and jet centerline were located 12 3/4-feet above grade. The sound data were analyzed by a 1/3-octave band spectrum analyser. The analyser determined sound pressure level (SPL) spectra referenced to 0.0002 microbar. Overall sound pressure levels (OASPL) and sound power level (PWL) were computed from the SPL data. No corrections are made to the data for ground reflections. Most of the cancellations and reinforcements in the data occur at much lower frequencies than the peak noise and are not pertinent to the present study.

RESULTS AND DISCUSSION

In this section, acoustic data are presented for the free jet and for the convergent circular nozzle with and without the internal noise source. The free jet acoustic characteristics are presented briefly first because they establish a noise floor that can limit the useful range of test nozzle jet noise data. The test nozzle acoustic data with and without the internal noise source then are given for zero forward velocity. The effect of forward velocity on jet noise is then shown for a given jet exhaust velocity. A similar development is used to present the sound power data.

Free Jet

Typical sound power spectra for the 13-inch diameter free jet with the test nozzle in place but inoperative are shown by the solid curve in figure 6. The data shown are for a free jet velocity of 260 ft/sec. Also shown in figure 6 are two typical sound power spectra for the test nozzle with a quiet flow system (no internal noise) operating at jet velocities of 925 and 825 ft/sec and with a forward velocity of 260 ft/sec. Below a frequency of about 400 Hz, the free jet is acoustically dominant. At frequencies above 400 Hz sufficient separation (10 dB or greater) exists between the test nozzle jet noise data and that of the free jet, for the velocities shown, to provide valid jet noise measurements. With further decreases in nozzle jet velocity, the acoustic separation becomes less than that shown, until insufficient acoustic separation between the two flows is reached to provide useable noise data.

Operation of the free jet at velocities less than 260 ft/sec resulted, of course, in a decrease in the free jet sound power level. Thus, a wide range of useful combinations of the test nozzle and free jet velocities were available for the present work. Similar acoustic trends were observed for sound pressure level measurements. In general, only jet exhaust noise data separated from the free jet noise level by at least 10 dB and above 400 Hz are included herein.

Sound Pressure Level

Zero forward velocity. - Typical sound pressure level (SPL) spectra for the circular nozzle with zero forward velocity are shown in figure 7 for nominal jet velocities from 680 to 940 ft/sec. The data shown are for acoustic radiation angles of 90°, (representative of sideline and flyover angles of interest) and 155° (near the peak noise lobe) as a function of 1/3-octave band center frequency. The solid curves in these figures are representative of the sound pressure level spectra at the same jet velocities obtained with the quiet flow system (pure jet noise) as part of a comprehensive study reported, in part, in reference 3. The various symbols in this figure denote the SPL spectra with the flow system that includes a low frequency internal noise source analogous to combustor noise as described previously. In general the internal noise source peaks near 500 Hz and that harmonics are evident at 1000 and 2000 Hz; particularly at the lowest jet velocity of 680 ft/sec. The internal noise source appears to be frequency dependent. With a jet velocity of 680 ft/sec, the internal noise source exceeds the jet noise by about 5 dB at 90° and 9 dB at 155°. At the higher jet velocities of 835 and 940 ft/sec, jet noise is the primary noise source; particularly at radiation angles other than 155°.

Above 3000 Hz, jet noise is the dominant noise source as indicated by the coincidence of the data from the two flow systems used in the tests.

The sound pressure level spectra measured at other radiation angles (40° to 140°) are similar to those shown at 90° in figure 7(a) for each respective flow system. The absolute magnitude of the SPL's is a function of the specific directivity angle.

Effect of forward velocity. - Typical changes of sound pressure level spectra for nominal jet velocities of 680 and 940 ft/sec with forward velocities of 0 and 175 ft/sec are shown in figures 8 and 9 at radiation angles of 90° and 155°, respectively, as a function of 1/3-octave band frequencies. The dashed and solid curves in these figures represent the SPL spectra obtained with a quiet flow system (ref. 3) at forward velocities of 0 and 175 ft/sec, respectively. The symbols represent the SPL's obtained using the flow system with internal noise; the circle and square symbols are for forward velocities of 0 and 175 ft/sec, respectively.

In general, the SPL's for pure jet noise are reduced on a broadband basis with forward velocity from those measured statically. The change in SPL for pure jet noise with forward velocity is given by a function of $U_j^2 \, (U_j - U_o)^6$ in reference 3.

With the noisy flow system, the high frequency SPL's where pure jet noise dominates decrease with forward velocity in the same manner as those with the quiet flow system. The low frequency internal noise, however, is not, for the most part, sensitive to forward velocity. Consequently, the low frequency SPL's become dominant with forward velocity and determine the far-field noise level. This is quite evident from the data at the low jet velocity (680 ft/sec) and a radiation angle of 90° shown in figure 8(b). At these conditions, with a forward velocity of 175 ft/sec, the internal noise source is more than 12 dB louder than the peak SPL for jet noise with a quiet flow system. With zero forward velocity the difference, while in the same direction, is only about 5 dB. With a jet velocity of 940 ft/sec, the internal noise level did not significantly affect the far-field noise at zero forward velocity. However, with forward velocity, the internal noise peak SPL was slightly greater than the jet noise peak SPL. Consequently, the internal noise source, for this jet velocity, was about an equal contributor with jet noise to the far-field noise.

With decreasing jet velocity, the internal noise becomes dominant at increasingly higher frequencies. This is particularly evident in figure 9 in which the SPL spectra are shown at a radiation angle of 155° (near the peak noise lobe). Other data trends discussed for the 90° radiation angle also apply to the 155° angle.

Overall Sound Pressure Level

The effect of forward velocity on the overall sound pressure level (OASPL) as a function of directivity angle (measured from the inlet, (fig. 5)) is shown in figure 10. The data are shown for nominal jet velocities of 680 and 940 ft/sec. The solid and dash curves represent the OASPL data for 0 and 260 ft/sec, respectively obtained with the quiet flow system (ref. 3). The symbols are the OASPL data obtained with the noisy flow system. At a nominal jet velocity of 940 ft/sec, the attenuation in OASPL due to forward velocity for the noisy flow system is substantially the same at all radiation angles except near peak lobe where the attenuation is somewhat more. In all cases, the attenuation with the noisy flow system is less than that obtained with the quiet system for comparable jet and forward velocities.

With a jet velocity of 680 ft/sec and with and without forward velocity, the OASPL's for the noisy flow system are higher than those for the quiet flow system at nearly all angles. Also, the attenuation of the OASPL's with forward velocity for the noisy flow system is a maximum near the peak lobe angle of 155° and decreases with increasingly smaller angles. In the range of 20° to 60° little attenuation due to forward velocity is obtained. The general lack of attenuation due to forward velocity and the high OASPL's at this low jet velocity are caused by the domination of the internal noise source over the jet noise sources (figs. 8 and 9).

Sound Power Level

Zero forward velocity. - The sound power level spectra with zero forward velocity are shown in figure 11. The solid curves represent the spectra obtained with a quiet flow system (ref. 3). The symbols are the data obtained with the flow system having a low frequency internal noise source. As was the case for the sound pressure level spectra, the sound power level data obtained with both flow systems are the same at high frequencies. The coincidence frequency varies inversely with the jet velocity. With a jet velocity of 940 ft/sec, the coincidence occurred at a frequency of about 1600 Hz while with a jet velocity of 680 ft/sec, the coincidence occurred at about 5000 Hz.

With decreasing jet velocity, the internal noise becomes increasingly dominant compared with the jet noise. At the lowest jet velocity used in the present tests, the peak sound power level internal noise was about 8 dB greater than the peak sound power level of the jet noise.

Effect of forward velocity. - The effects of forward velocity on the sound power level spectra obtained with the two flow systems are shown in figure 12. The data shown in figure 12 are again for jet velocities of 680 and 940 ft/sec and a forward velocity of 175 ft/sec. For comparison the data for zero forward velocity are repeated.

With forward velocity, the internal noise becomes more dominant, particularly as the jet velocity is decreased. The peak sound power level with a jet velocity of 680 ft/sec and a forward velocity of 175 ft/sec is about 15 dB greater than that of the jet noise. This difference of 15 dB compares with 8 dB at the same jet velocity but zero forward velocity. Also the coincidence of sound power level data for the two flow systems occurs at higher frequencies with increasing forward velocity.

Total Sound Power

A comparison of the total sound power at zero forward velocity as a function of jet velocity is shown in figure 13 for both the quiet flow system and that with internal noise. The acoustic data with the quiet flow system follow the usual 8-power law with jet velocity. The acoustic data with the noisy flow system is higher than and deviates progressively more from the 8-power law with decreasing jet velocity. Even at the highest jet velocity (940 ft/sec) the total sound power with the noisy flow system is greater (by about 3 dB) than that with the quiet flow system. This indicates grossly that the internal noise source in the test flow system at this jet velocity contributes as much sound power as does the jet noise. Because the acoustic differences become much larger with decreasing jet velocities, the internal noise soon overwhelms the jet noise and becomes the dominant noise source.

The total sound power emanating from the circular nozzle with forward velocity for a flow system dominated by the low frequency internal noise source is shown in figure 14 as a function of relative velocity, U_j-U_o. Also shown in the figure, by the solid curve, is the 8-power velocity law for cold-flow pure subsonic jet noise with zero forward velocity. With decreasing values of relative velocity (particularly with increasing forward velocities for a constant jet velocity), the variation of total sound power with relative velocity approaches a $(U_j-U_o)^2$ relationship.

A comparison between the measured total sound power attenuated by the effect of forward velocity (PWL_T - PWL_T') and that calculated empirically for a quiet flow system (ref. 3) is shown in figure 15 for both the quiet flow and noisy flow systems. The quiet flow system data (clear symbols), from which the empirical relationship was developed in reference 3, are included only to show the good agreement between the measured and the calculated values of total sound power attenuation with forward velocity for pure jet noise. With the noisy flow system (solid symbols), the measured sound power attenuation was less than that calculated for a quiet system. The differences between the calculated and measured sound power values increased with decreasing jet velocity. This is consistent with the data trends shown previously in figure 14 and is due to the increasing domination of the internal noise source with decreasing jet velocity, together with internal noise being nearly independent of forward velocity effects.

CONCLUDING REMARKS

This study has shown that internal noise generation by flow processes upstream of the nozzle exhaust plane is not substantially attenuated by forward velocity. Such upstream noise, being monopole or dipole in nature, could, however, affect the radiation pattern of the noise associated with the propulsion system. Such trends were not evident in the present work with a cold jet. However, with a hot jet such trends could become discernible. With a given internal noise source, decreasing the jet velocity can cause the internal noise source to become dominant over the jet noise. As the jet velocity is further lowered, the dominance of the internal noise over the jet noise will extend over an increasingly wider band of frequencies. Operating the jet at a fixed exhaust velocity with increasing values of forward velocity will cause similar acoustic trends.

These results imply that low-frequency flow-related (i.e., combustion) noise will not be substantially attenuated by forward velocity. This can create a problem for turbofan engines designed to operate with low exhaust velocities as in the case of future STOL aircraft. For such engines, internal noise can quickly provide a fixed noise floor with little relief from forward velocity.

For high velocity engine exhausts, current jet suppression devices, such as multi-element nozzles, are substantially ineffective when internal flow noise becomes dominant over jet exhaust noise. This is because such suppressors are usually effective only at the higher frequencies: i.e., out of the range of the low frequency combustion noise. Confirmation of this observation was obtained in an unpublished similar study to that reported herein for an 8-tube mixer suppressor nozzle.

While much of the internal noise can be attenuated by suitable acoustic lining techniques, either in the tailpipe or inside an ejector, their use causes weight and performance penalties. This, in turn, is reflected in engine cost and aircraft operation economics by an increase in direct operating costs (DOC) and a reduction in the return on investment (ROI) by the airlines. A need exists, therefore, for research on the reduction of internal source noise generation and the development of suitable liners to optimize the suppression of internal noise.

Much of the jet noise data in the literature taken with air rigs or actual engines include internal flow-related noise. Indeed, the latter dominates in many cases. The presence of internal noise, as distinct from other contributors to high jet noise values (stream turbulence, etc.), when not recognized, has led to questionable correlations and analyses in the past two decades. While jet noise investigators in recent years have become aware of the effect of internal noise sources on the measurements of jet noise, the need for further improvements in internal noise control for jet noise rigs cannot be over-emphasized when suppressors and/or forward velocity effects are investigated for aircraft noise control and noise level predictions.

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NOMENCLATURE

(English units, except as noted)

f	1/3 octave band spectrum frequency
OASPL	overall sound pressure level, dB re 20 N/m^2
PWL	sound power level, dB re 10^{-3} w
SPL	sound pressure level, dB re 0.0002 microbar
U_j	jet exhaust velocity
U_o	free stream velocity
PWL_T	total sound power, zero forward velocity, dB
PWL_T'	total sound power, with forward velocity, dB

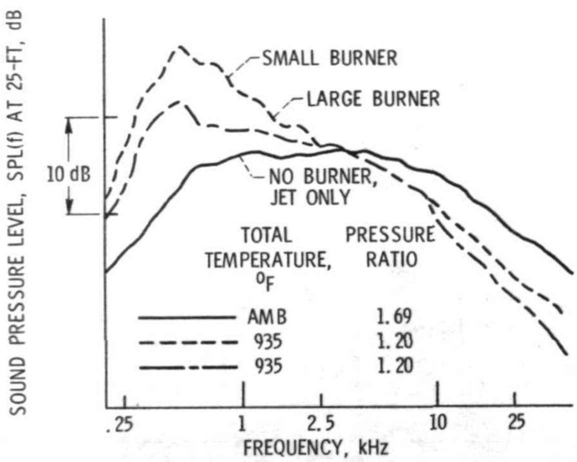

Figure 1. - Effect of combustion on sound pressure level spectra with circular nozzle. Nozzle diameter, 3.22-in.; jet velocity, 930 ft/sec; ref. 1.

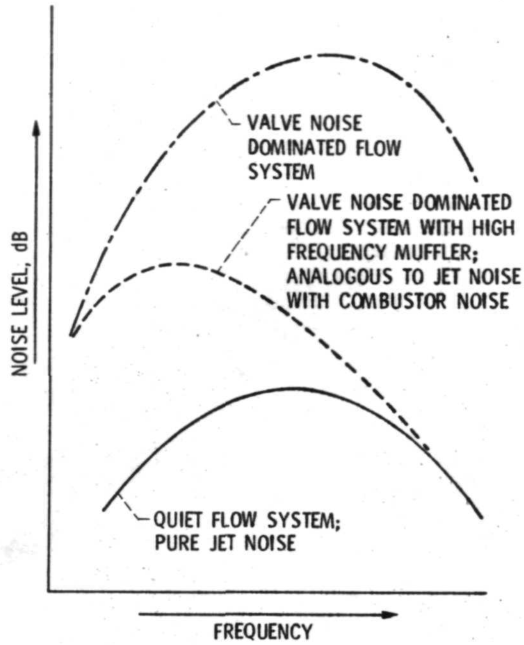

Figure 2. - Schematic showing effect of flow system characteristics on jet noise level and spectra.

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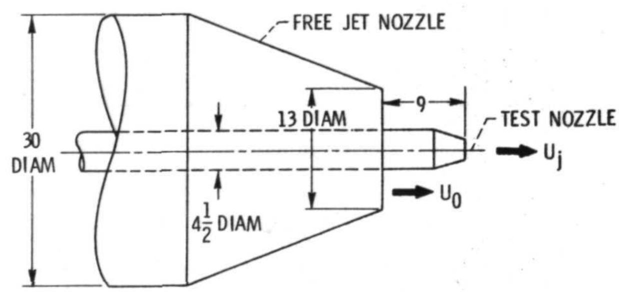

Figure 3. - Test nozzle installation in free jet for acoustic measurements. All dimensions in inches.

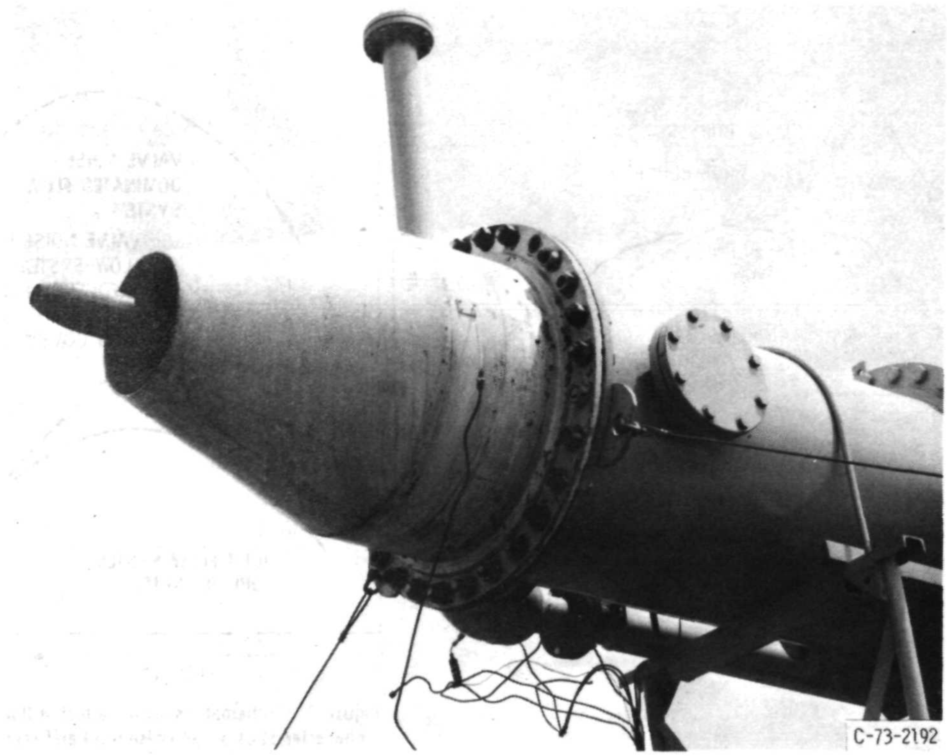

Figure 4. - Typical nozzle installed on centerline on free jet for acoustic tests with forward velocity.

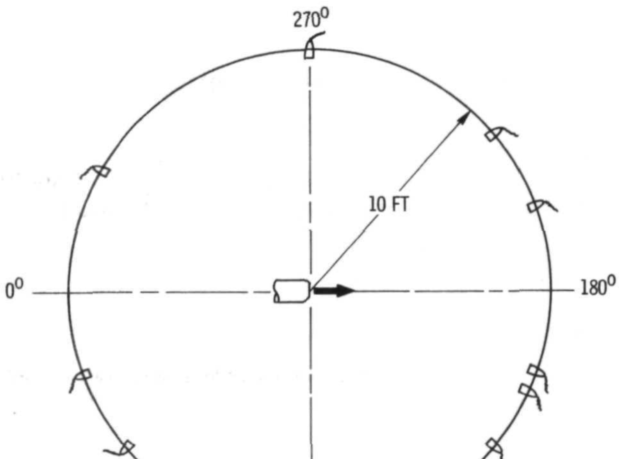

Figure 5. - Typical microphone layout for present tests.

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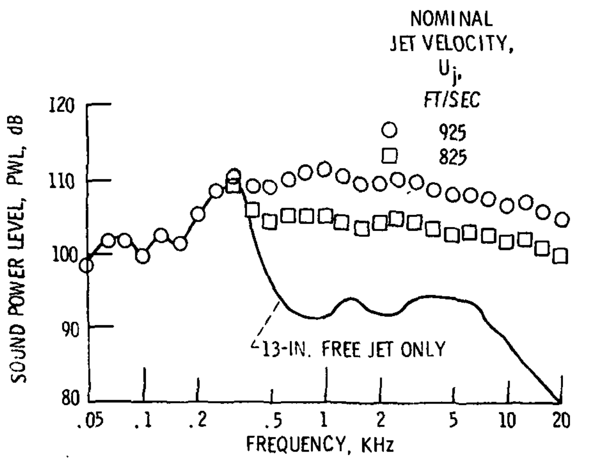

Figure 6. - Comparison of typical sound power level spectra for free jet with and without operation of circular nozzle. Quiet test nozzle flow system; free jet velocity, 260 ft/sec.

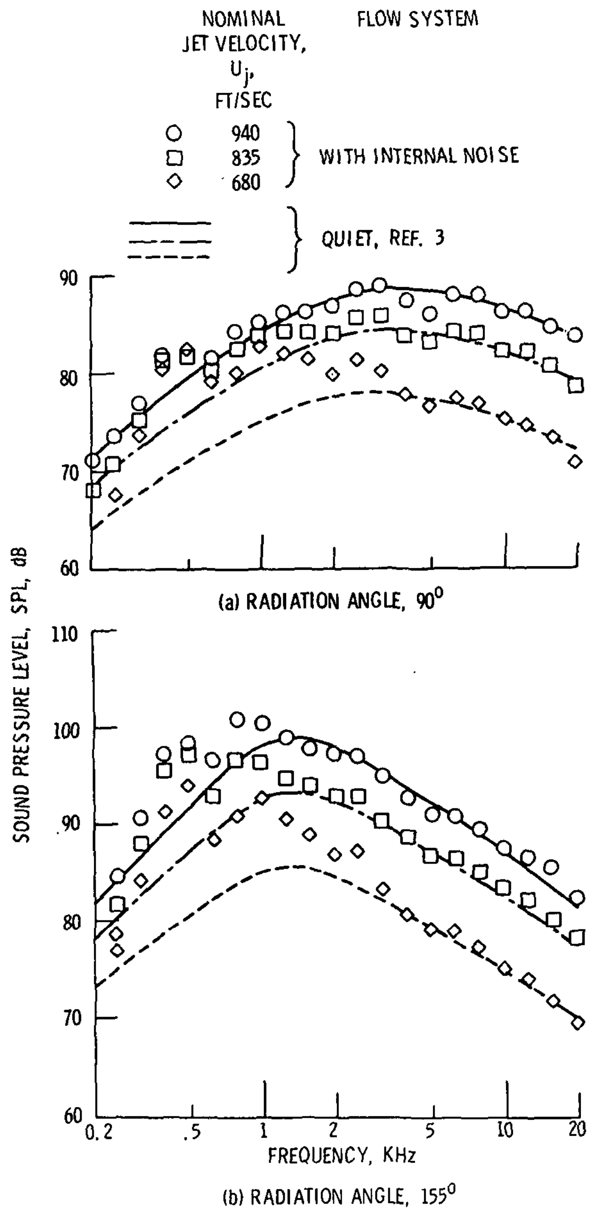

Figure 7. - Sound pressure level spectra for circular nozzle with and without internal noise. Zero forward velocity.

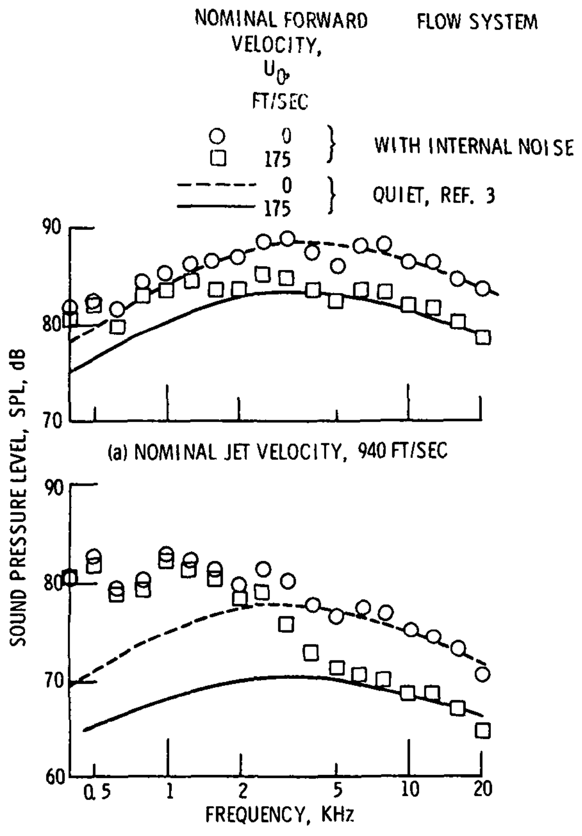

Figure 8. - Effect of forward velocity on sound pressure level spectra for circular nozzle with and without internal noise. Radiation angle, 90°.

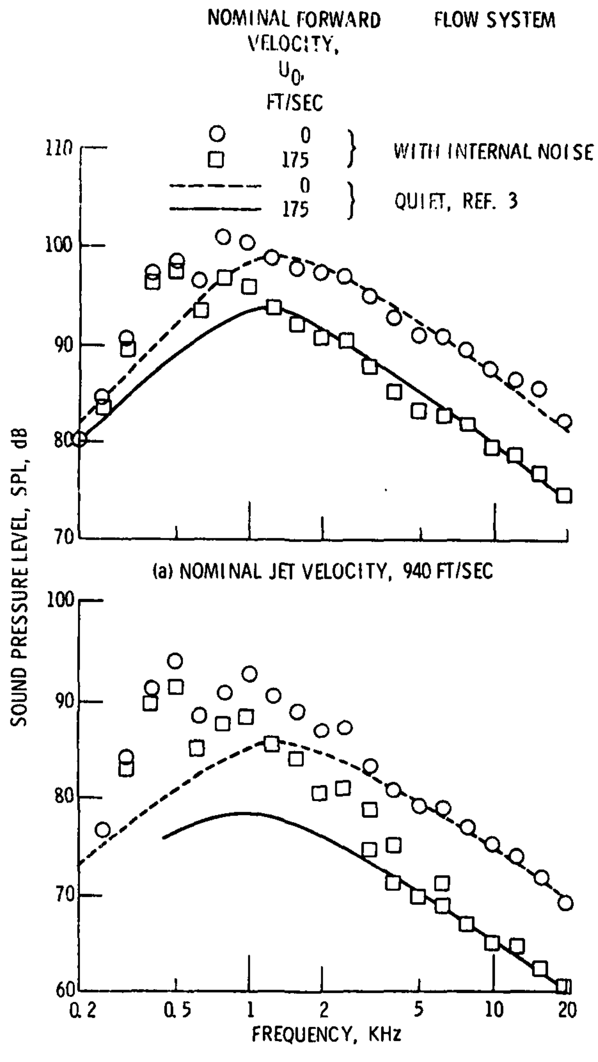

Figure 9. - Effect of forward velocity on sound pressure level spectra for circular nozzle with and without internal noise. Radiation angle, 155°.

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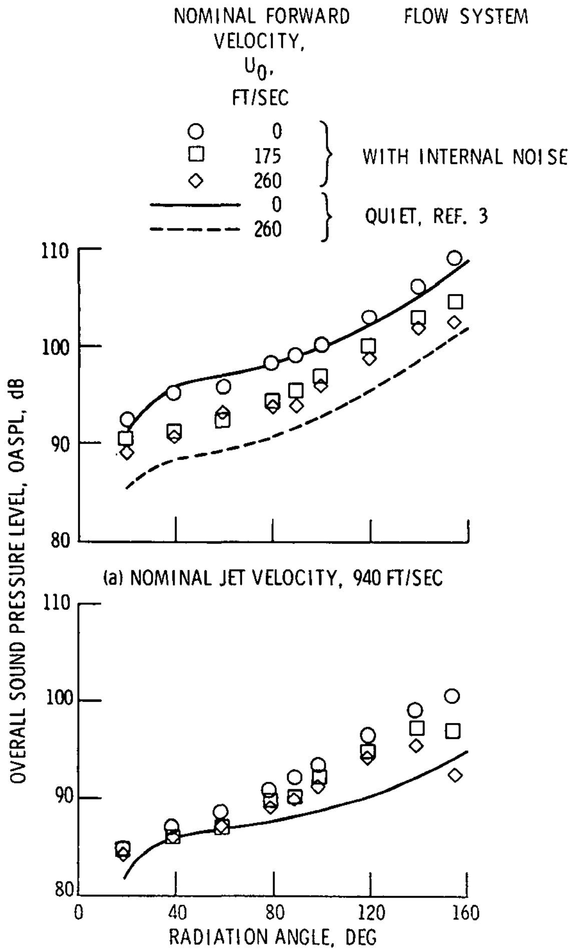

Figure 10. - Effect of forward velocity on OASPL for circular nozzle with internal noise.

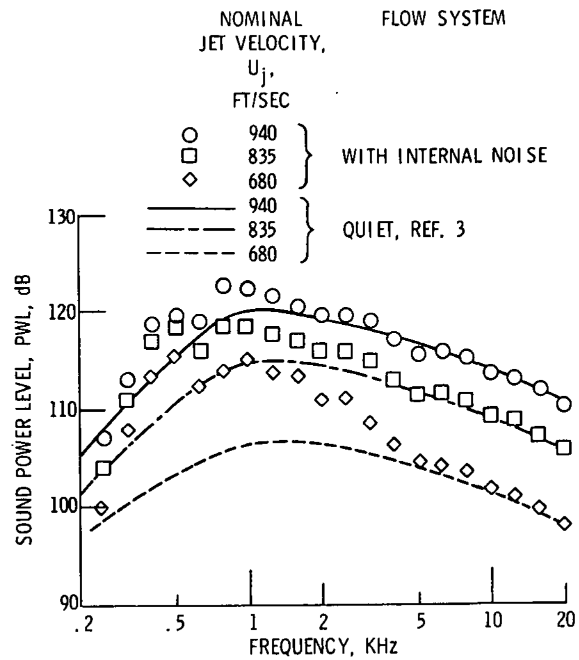

Figure 11. - Sound power level spectra for circular nozzle with internal noise. Zero forward velocity.

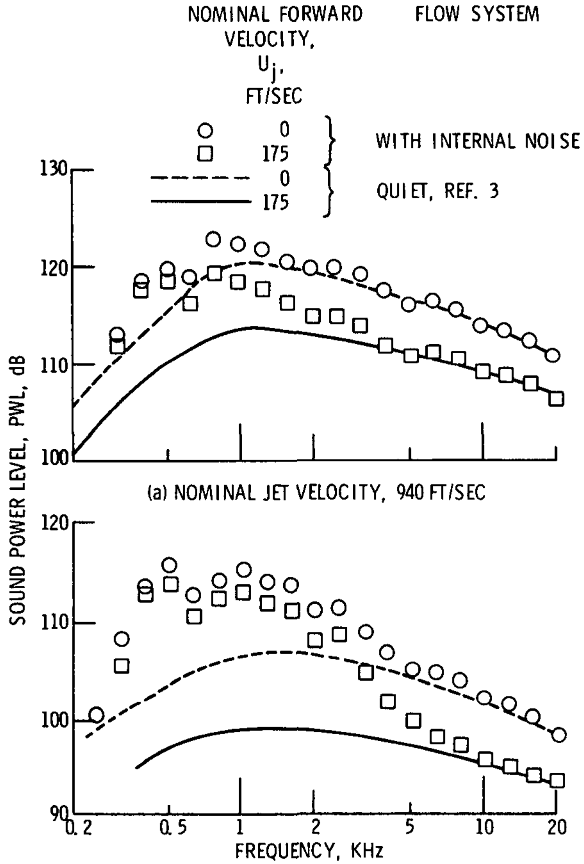

Figure 12. - Effect of forward velocity on sound power level spectra for circular nozzle with and without internal noise.

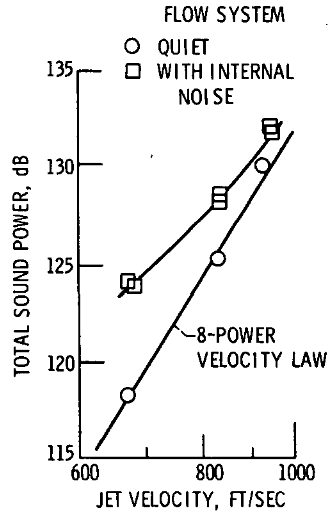

Figure 13. - Comparison of total sound power variation with jet velocity for circular nozzle with and without internal noise. Zero forward velocity.

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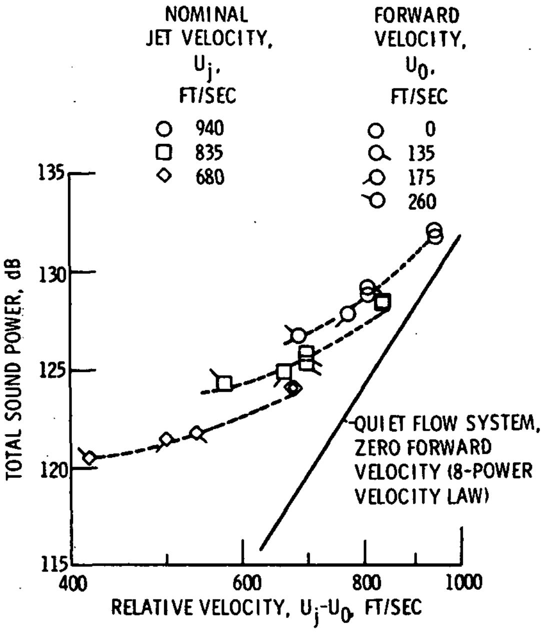

Figure 14. - Total sound power as function of relative velocity, U_j-U_0, for circular nozzle with internal noise.

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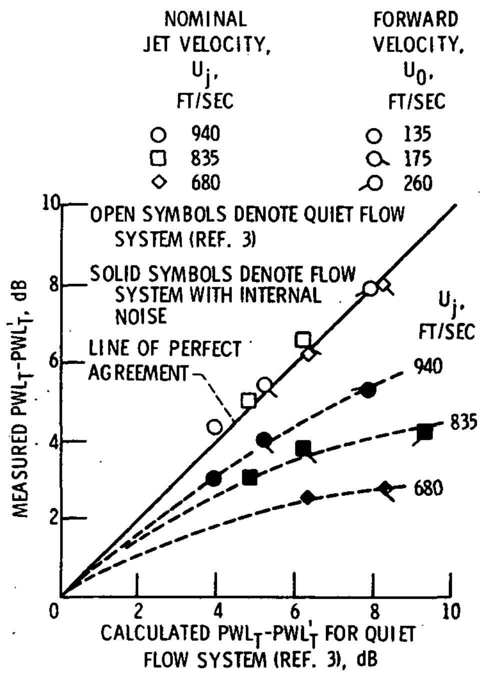

Figure 15. - Comparison of measured and calculated total sound power reduction due to forward velocity for circular nozzle with and without internal noise.