Design and Development of the United Aircraft Research Laboratories Acoustic Research Tunnel

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This new wind tunnel, designed specifically for aerodynamic noise research, has a variable area, open jet test section enclosed in an anechoic chamber. Speeds up to a Mach number of 0.65 are possible with a test section area of 5 ft^2. A separate, low noise level, high pressure air source is provided for jet noise studies. Design and construction considerations for the major tunnel sections (i.e., inlet, anechoic chamber, diffuser, muffler, driver) are described. Aerodynamic and acoustic calibration of the tunnel is discussed in relation to design criteria. Problems applicable to other acoustic tunnels such as background noise, edge tone suppression, deflected jet noise and distortion of noise directivity patterns by shear layer refraction are discussed. Initial testing demonstrated that a sufficiently low background noise level has been obtained to permit measurement of the noise radiated by the relatively weak noise source of an isolated airfoil placed in a uniform, low turbulence stream.

Introduction

THE recent emphasis on environmental aircraft noise and techniques for its reduction has resulted in an increased need for fundamental study of the generation, transmission and radiation of sound from noise sources such as jet engines, propellers and helicopter rotors. Both theoretical and experimental studies are necessary if understanding of these sources and significant reduction of radiated noise are to be achieved. The recently completed United Aircraft Research Laboratories Acoustic Research Tunnel was designed to provide the capability for experimental investigation of these sources. This paper describes the design and performance of the tunnel with attention being given to problems likely to occur in other acoustic tunnels. A more detailed description is given elsewhere.[1]

The characteristics which permit noise studies to be carried out impose a number of constraints which limit the usefulness of many existing wind-tunnel facilities for such work. In addition to the usual wind-tunnel design objectives of minimum tunnel circuit total pressure loss, low turbulence level, uniform test section flow and suitable Reynolds and Mach number ranges, an acoustic tunnel must provide both low background noise levels and a suitable acoustic field for noise measurement. For these reasons wind-tunnel facilities designed specifically for acoustic testing are required. In addition to the tunnel described in this paper, other acoustic tunnels (Table 2) have been completed or are in the process of being built. The UARL tunnel differs most significantly from these other open jet, anechoic chamber test facilities in that its design maximum speed is some three times higher than that of the other tunnels with the exception of one mode of operation of the proposed NASA tunnel. The provision for high tunnel speed was motivated by the nature of acoustic tests envisioned for the UARL tunnel as discussed in the section entitled Design Requirements.

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Index categories: Aerodynamic and Powerplant Noise; Aircraft and Component Wind Tunnel Testing; Research Facilities and Instrumentation.

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Design Requirements

The tunnel design requirements were determined by the desire to carry out experimental noise studies of the following nature: a) isolated airfoils and cascades at Reynolds and Mach numbers approaching full-scale values and with large enough model sizes to permit incorporation of unsteady surface pressure instrumentation; b) static and forward flight operation of model propellers, helicopter rotors and engines (powered nacelles) over a range of typical flight velocities; c) model engine inlets, exhausts, and components; d) single and coaxial jet streams, including the effect of simulated forward flight; and e) acoustic wave propagation through shear layers, turbulence and ducts.

Based on these requirements, a test section area of 5 ft^2 and maximum tunnel Mach number of 0.60 were selected as test section design criteria. Since the flat plate boundary layer turbulent transition Reynolds number is unaffected by turbulence levels of less than about 0.1%,[2] this value was selected as the design tunnel turbulence level. The capability to vary the intensity and scale of test section turbulence by use of grids in the inlet was included in the tunnel design since incident turbulence is a potentially important noise source. The test section velocity was specified to be uniform to within 0.25% as recommended by Pope and Harper.[3] The desired background noise level was specified to be less than that of the weakest of potential noise sources, the vortex shedding noise of an isolated airfoil placed in a low turbulence level, uniform stream. It was desired that the test chamber be anechoic at all frequencies above 250 Hz to permit measurements of noise directivity.

To assist in the design of the tunnel, a ⅕ scale model of the test section, anechoic chamber and diffuser was fabricated. Aerodynamic and acoustic testing of this model proved valuable in defining the pressure losses and acoustic characteristics of the full-scale tunnel.

Tunnel Circuit

As shown schematically in Fig. 1, the Acoustic Research Tunnel is an open circuit, open jet tunnel (Eiffel configuration) consisting of the following five major sections: inlet, anechoic chamber and test section, diffuser, fan muffler and tunnel drive system. In addition to the fan-driven open jet test section, a separate high pressure coaxial source of air is located at the anechoic chamber forward wall for tests which require a dual airstream or smaller but higher energy single airstream.

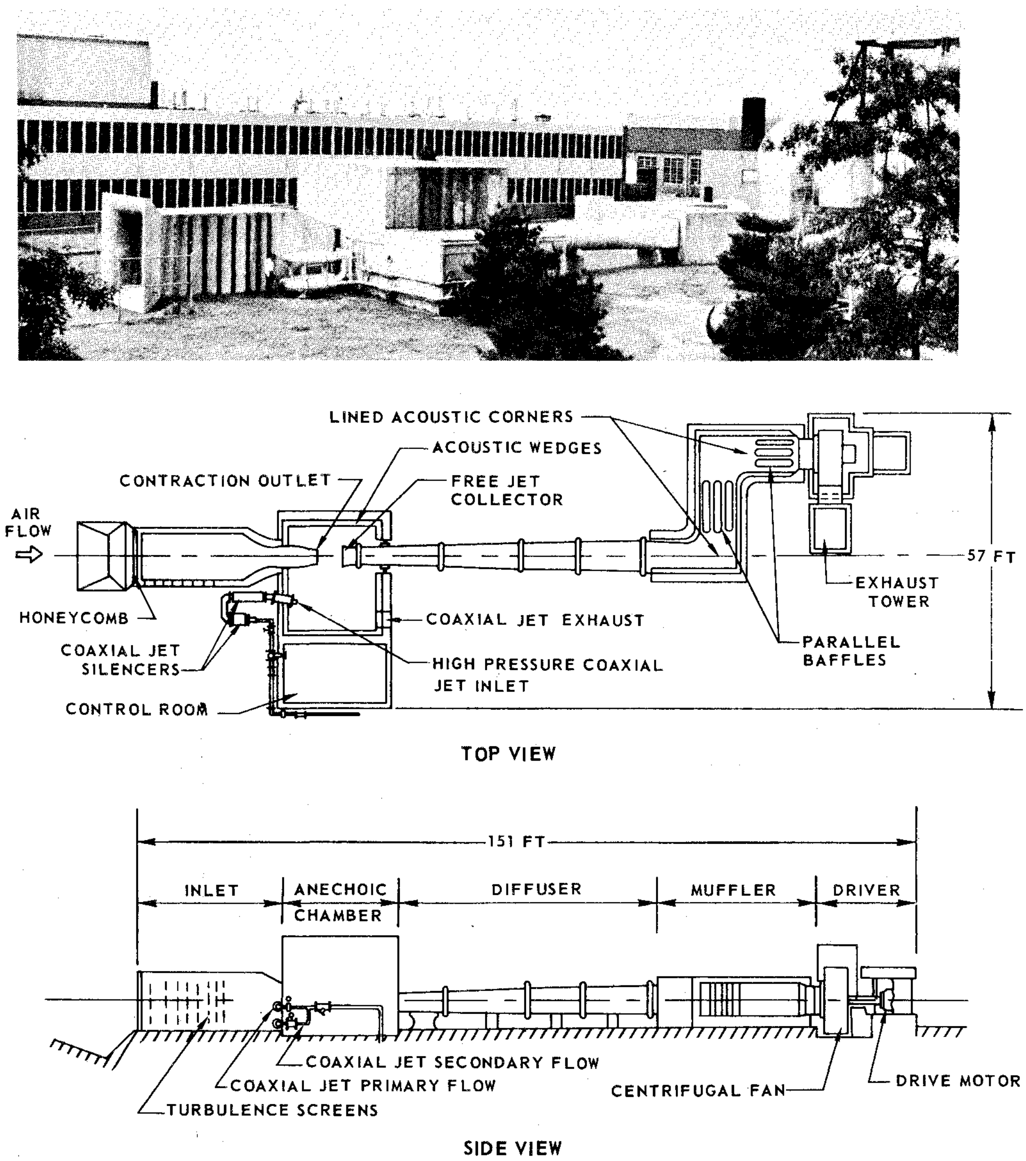

Fig. 1 UARL acoustic research tunnel.

Tunnel Inlet

This section provides for the intake of air from the atmosphere. The open-circuit tunnel configuration was selected to obviate the need for extensive fan exhaust acoustic treatment in the tunnel return leg. Few open-circuit tunnels have been constructed in recent years primarily because they are considered to possess a number of disadvantages,[3] the most serious of which is a reported sensitivity of test section flow to gusts, cross winds, and a ground vortex at the inlet. It was concluded that the provision of a long, small cell size inlet honeycomb would eliminate these problems since it removes the two velocity components normal to the cell axis. The honeycomb used was aluminum and contained 9-in. long, ⅛-in. hexagonal cells. It was estimated that the maximum turbulence intensity and scale at the honeycomb exit would be on the order of 10% and 1/16 in., respectively. Based on the combined effects of screens, stream contraction and turbulence decay, it was estimated that the design test section turbulence level and flow uniformity could be achieved with a contraction ratio of 16 and the use of four screens each possessing a loss coefficient of 1.6. Seamless screens of mesh size 28 and wire diameter of 0.009-in. were selected to yield this loss coefficient.[4] Since the screens and honeycomb were located in low velocity regions, no significant noise generation problems were encountered.

The portion of the tunnel contraction located in the inlet reduces the flow area from 9-ft square to a 44-in. diam circle via a 16-sided polygon in a distance of 10.7 ft. The length and rate of change of area with distance were chosen[1] to minimize adverse wall pressure gradients and prevent separation of the contraction boundary layer.

Test Section and Anechoic Chamber

The tunnel was designed with an open jet test section, rather than a closed jet, since in-duct acoustic measurements are severely complicated by tunnel wall reflections and wind noise on microphones. The resulting open jet shear layer, however, introduces measurement difficulties since it is a principal source of tunnel background noise and causes refraction of the radiated noise, as discussed below. The open jet is contained within a 16-ft-high, 18-ft-long (axial direction) and 22-ft-wide sealed, 1 ft thick reinforced concrete chamber. Since far-field noise directivity measurements were considered important, the chamber was made anechoic as the normal test configuration. Based on frequencies typical of model jet noise, bluff-body vortex shedding and blade passage of rotating models, an anechoic chamber cutoff frequency (frequency below which the normal incidence energy absorption coefficient decreases below 0.99) of 250 Hz was selected. To achieve this the chamber was lined with 1-ft depth, two-dimensional fiber-glass wedges which were determined to have this cutoff frequency in impedance tube tests.

The final section of the tunnel contraction, contained within the anechoic chamber, was designed as a removable piece of ducting to permit variations in test section cross section shape and in area from a minimum of about 4 ft^2 to a maximum of 9.6 ft^2. For operation with a 9.6 ft^2 test section, the maximum achievable Mach number is approximately 0.4. This larger test section would be required for model propeller and rotor tests where diameters of about 2 ft would have to be accommodated. To date, the tunnel has been operated primarily with a 31-in. × 21-in. rectangular (5 in. radius rounded corners) test section which yields a total tunnel contraction area ratio of 18.5, and a maximum tunnel Mach number of 0.65. The tunnel speed is limited to this Mach number for open jet test configurations by chamber structural load limits. Figure 2 shows the 31-in. × 21-in. test section with a model turbofan engine installed in the open jet. When two-dimensional flow is desired, sideplates are installed between the contraction outlet and downstream jet collector (Fig. 4). A three-component balance permits force measurements to be made concurrently with acoustic measurements.

For the Mach number range of the tunnel, it was estimated that isolated airfoil noise of a dipole nature (noise level porportional to the sixth power of velocity) would stand out approximately 20 db above background jet quadrupole noise (V^8 dependence). Since reliable estimates of the noise associated with impingement of the turbulent open jet shear layer on the downstream jet collector did not appear feasible, a one-fifth scale model of the open jet geometry and chamber was tested. These tests indicated that the shape and size of the jet collector lip were critical to the noise level and that this noise mechanism would dominate the background noise level in the full-scale tunnel. Based on these tests, a 4-in. radius collector lip was provided for the full-scale jet collector. The collector cross section was chosen to be rectangular and slightly larger (23 in. × 33 in.) than the inlet.

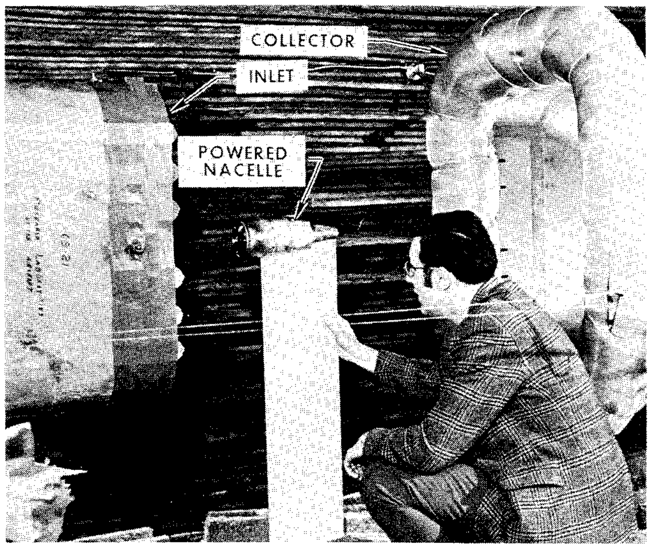

Fig. 2 Typical test section arrangement.

curred, the tunnel was provided with an absorptive and reactive Z-shaped muffling section consisting of two 8-ft sections of parallel baffles (1-ft thickness on 2-ft centers, 40% open area) and two 90° lined bends. The use of a sonic throat for fan quieting at the diffuser inlet is not feasible in tunnels such as this which have a wide variation in test section speeds. Turning vanes were not installed in the bends because of the possibility of discrete frequency noise, "singing," [5] and broadband noise generation due to incidence of turbulent flow originating in the diffuser. The measured effect of the Z-section attenuation and diffuser reflection was to attenuate over-all fan noise 34 db; for frequencies above which the chamber was anechoic, 50 to 70 db attenuation occurred.

Tunnel Diffuser

Avoidance of diffuser stall was considered critical to the achievement of design background noise levels, design speed and a temporally steady test section flow. The thick diffuser inlet boundary layer caused by the open jet test section shear layer enhances the possibility of stall relative to closed jet tunnels. While vortex generators can be employed to improve diffuser performance in conventional wind tunnels, their use in acoustic tunnels would be expected to contribute to increased background noise. Based upon model tests the tunnel was provided with an area ratio 5.5, three-stage diffuser as described in Ref. 1.

Fan Muffler

Since the tunnel fan was initially designed to operate at fixed rotational speed, diffuser propagated fan noise was expected to dominate background noise spectra at low tunnel speeds. To limit the speed range for which this oc-

Table 1 Measured total pressure loss of tunnel components

Tunnel section	Loss coefficients K_1	K_2	% of total circuit loss
Honeycomb	4	0.011	3.2
Screens (5)	9.1	0.025	7.1
Contraction	3.6	0.010	2.8
Open test section	0.16	0.16	45.2
Diffuser	0.10	0.085	24
Muffler	1.7	0.024	6.8
Fan exhaust	2.5	0.025	7
Kinetic energy dump loss	1	0.014	3.9

Tunnel Drive System

The tunnel drive system consists of a 1500 hp induction motor driving a single-stage, 10-bladed, backward-curved-vane centrifugal fan. Controllable-pitch radial vanes located at the inlet of the 1800 rpm fan provide continuously variable tunnel speed control. Measured fan inlet noise levels near design speed were predicted within 4 db by empirical methods.[6] Initially, the fan was provided with exit vanes for tunnel speed control; these proved unsatisfactory at low tunnel speeds due to a strong, low-frequency Helmholtz resonance in the tunnel circuit caused by operation at flow rates below the fan surge point. While eliminating this problem, the addition of radial inlet vanes for speed control gave rise to a strong 40 Hz tone at low tunnel speeds, which, while not evident in the anechoic chamber, caused disturbing noise in surrounding buildings. To eliminate this problem, a solid-state frequency converter was installed to provide continuously variable fan speed from 0 to 900 rpm for low-speed tunnel operation. Based on these results and the fact that the extent of fan muffling required is considerably less for a variable speed fan (sound power level proportional to speed raised to the fifth power) this type of installation is preferable to constant speed fans for acoustic test facilities.

Jet Noise Installation

For jet noise studies and high Mach number model tests, the anechoic chamber is also provided with a 400 psia air source. A series of mufflers were installed upstream of the anechoic chamber penetration to attenuate air supply background noise due to flow regulating values.

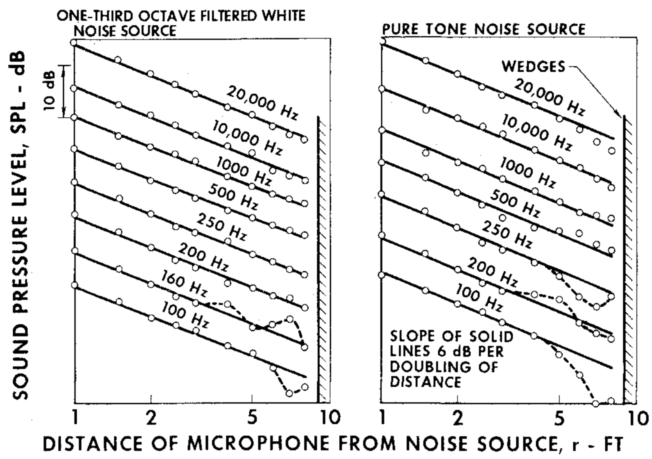

Fig. 3 Anechoic chamber acoustic calibration.

Single-jet or coaxial-jet noise studies simulating turbofan exhausts can be carried out. Provisions have been made for mounting rotating machinery in the plenum which supplies the inner jet for simulation of exhaust flow disturbances. Continuous operation at 10 lb/sec provides Mach one operation with a single 4.5-in.-diam nozzle. Maximum nozzle diameters which can be tested are 18 in. for the outer and 9 in. for the inner coaxial stream. Higher flow rates can be sustained by operating in a blowdown mode. A heater can be installed upstream of the mufflers to permit simulation of turbofan exhaust temperatures in the inner stream.

Aerodynamic Performance

The tunnel achieved a speed of Mach 0.65. The ratio of test section dynamic pressure to complete tunnel circuit total pressure loss (tunnel energy ratio) has been measured to be 2.8. This is higher than that for most of the open jet tunnels listed by Pope and Harper.[3] The loss of each tunnel circuit component is given in Table 1 based on measurements at a test section velocity of 300 fps and and test section length of 49 in. The losses for all components except the test section were obtained by direct measurement. The test section loss was determined by subtracting the sum of the measured component losses from the fan total pressure gain. The loss coefficient K_1 is defined as the measured component total pressure loss divided by the mean dynamic pressure (dynamic pressure based on mean velocity given by the ratio of mass flow rate to the product of local density and duct area) at the inlet to that component whereas K_2 is the same pressure loss referenced to test section dynamic pressure. Table 1 shows that the open jet loss dominates the tunnel component losses. This corresponds to an open jet loss coefficient of 0.092 times jet length to diameter ratio, a value some 15% higher than that given by Abramovich.[7] The second largest loss was in the diffuser and corresponded to a coefficient of performance (ratio of static pressure gain to mean inlet dynamic pressure) of 0.86. This relatively high value is indicative of unstalled diffuser flow.

Measurement of the contraction outlet boundary layer at a tunnel speed of 200 fps showed a $1/7$ power turbulent velocity profile with 0.07-in. displacement thickness indicating an unseparated contraction boundary layer flow and confirming the validity of the contraction design procedure. Measurement of the test section total turbulence level at 300 fps with a triaxial hot wire probe located 3 ft downstream from the contraction outlet yielded an over-all value of 0.12%, a value in close agreement with the design level. The test section velocity distribution was measured with a traversing pitot-static probe every 2 in. throughout the test section cross section and found to be uniform to within 0.25% for a tunnel speed of 300 fps and 0.5% for a speed of 65 fps. These data were obtained on relatively quiescent days (wind less than 10 knots). The test section distribution for severe wind conditions has not yet been evaluated. Operation of the tunnel during rain and light snow has not proved to be a problem. The variation of static pressure along the axis of the open jet test section due to the downstream collector was measured to be less than 1.5% of the velocity head for three-fourths of the test section length.

Acoustic Performance

Anechoic Chamber Calibration

To determine the acoustic characteristics of the tunnel chamber a measurement was made of the sound pressure level (SPL) falloff as a function of distance from a noise source. The frequency range over which SPL decreases 6 db with doubling of distance (corresponding to free space behavior) is taken as the range over which the chamber is anechoic. For this test, a 9-in.-diam Altec speaker was located between the side plates in the test section and directed vertically upward. A $\frac{1}{2}$-in.-diam condenser microphone was traversed on a wire located on the speaker axis vertically above the speaker. Both a one-third octave filtered white noise source and a pure tone noise source were used. The pure tone source results in a more severe test since room resonances can be more easily produced (with filtered white noise the averaging resulting from the presence of many wavelengths tends to minimize the effects of standing waves). Figure 3 shows that the chamber is anechoic for frequencies at and above 200 Hz for a white noise source. For a pure tone source, the chamber is anechoic above 250 Hz except in the vicinity of the wall. Thus, the experiment verifies the achievement of the design cutoff frequency.

Background Noise

During initial operation of the tunnel, an aerodynamic resonance between the inlet (contraction outlet) and col-

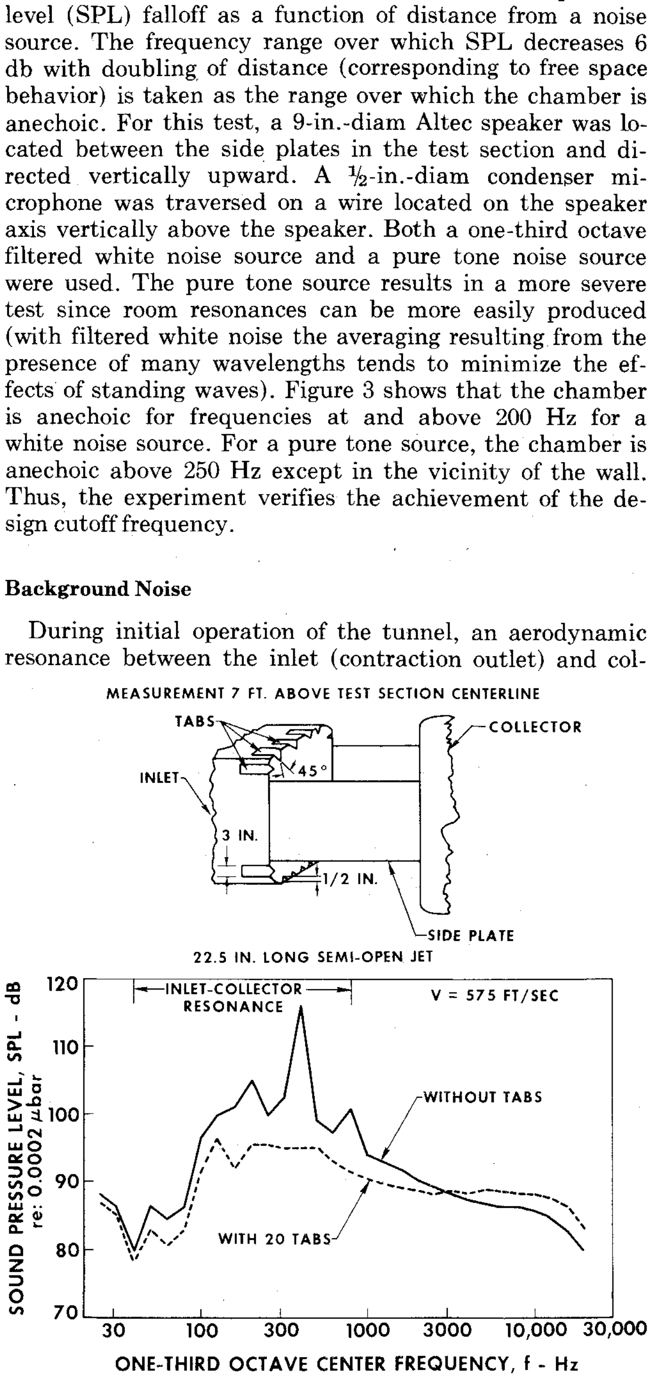

Fig. 4 Effect of inlet tabs on background noise spectra.

Table 2 Comparison of parameters for various acoustic tunnels

	UARL	BBN[10] Cambridge	MIT (AVL)[11] Cambridge	NASA Langley[12] (Planned)	NSRDC[13] Carderock	MIT (FTL)[14] Cambridge
Maximum velocity, (fps)	690	120	180	700/114	200	115
Test section area (ft^2)	4.37 (21 × 31 in.) Variable 4 to 9.6 ft^2	1.77 (16 × 16 in. or 18 in. diam)	1.56 (15 × 15 in.)	1.0/12.5	58.4 (8 × 8 ft)	35.5 (5 × 7.5 ft)
Contraction ratio	18.5 Variable	15	20	Varies	10	3.4
Open jet length	Variable 2 to 12 ft	12 ft	10 in.	20 ft	12 ft	11 ft
Anechoic chamber volume (ft^3)	6340 (16 × 18 × 22)	3000	850 (13.5 × 9 × 7)	18,000 (20 × 30 × 30)	11,600 (23.5 × 23.5 × 21)	3300 (10 × 11 × 30)
Chamber cutoff frequency (Hz)	250	180	200[a]	100	150	250[a]
Type	Anechoic or reverberant	Semi-reverberant	Anechoic or reverberant	Anechoic/ reverberant	Anechoic	Anechoic
Mode of operation	Suction	Suction	Suction	Blown or suction	Suction	Suction
Circuit	Open	Open	Open	Open	Closed	Closed
Turbulence Level	0.12% (total)		0.05 to 0.2% (axial)		0.1% (design value)	1.0% (total)

[a] Design value; not achieved with initial wall treatment.

lector lip of the tunnel produced sharp tones in the acoustic spectrum in the frequency range of 40 Hz to 800 Hz depending on tunnel speed. Resonances of this nature have been reported previously[5] but the phenomenon was not considered of importance for nonacoustic tunnels except where closed circuit tunnel resonant frequencies could be excited thereby endangering the tunnel structure. Tests in the 1/5-scale model tunnel showed that the source of this discrete noise was an edge tone interaction between the contraction outlet and jet collector, the intensity and frequency being a function of open jet length and tunnel speed. This phenomenon was not detected in initial model tunnel noise studies since the jet length exceeded the maximum length for edge tone production. By placing screens or other protrusions in the open jet shear layer, the tone intensity could be decreased. The most successful suppression method, and that employed in the full-scale tunnel, was to place an array of 20 small triangular tabs projecting 1/2-in. into the jet at the contraction outlet. The edge tone suppression achieved with these tabs is shown in Fig. 4. While the tabs reduced the edge tone level by some 20 db they increased the high frequency background level by some 3 db. Additional measurements of edge tone characteristics as a function of tunnel speed and test section length are given in Ref. 1.

Tunnel background noise spectra for a semiopen jet configuration with tabs are shown in Fig. 5 as a function of tunnel speed. Measurements with and without sideplates showed similar spectra. For reference purposes, the calculated noise spectra for a pure jet of the same area as the test section (i.e., 2.36 ft diam) are also shown. The difference between background level and calculated jet noise decreases with increasing velocity, but the background noise level generally is greater than the calculated jet noise level.

To determine the velocity dependence of the background noise, third-octave band levels should be compared on a constant Strouhal number basis (ratio of band center frequencies equal to the ratio of test section velocities). Such comparisons show that the high frequency end of the spectra above about 800 Hz follow most closely a V^6 power law. This fact in conjunction with the relative jet and background noise levels in Fig. 5 suggest that a dipole noise mechanism (such as would be associated with im-

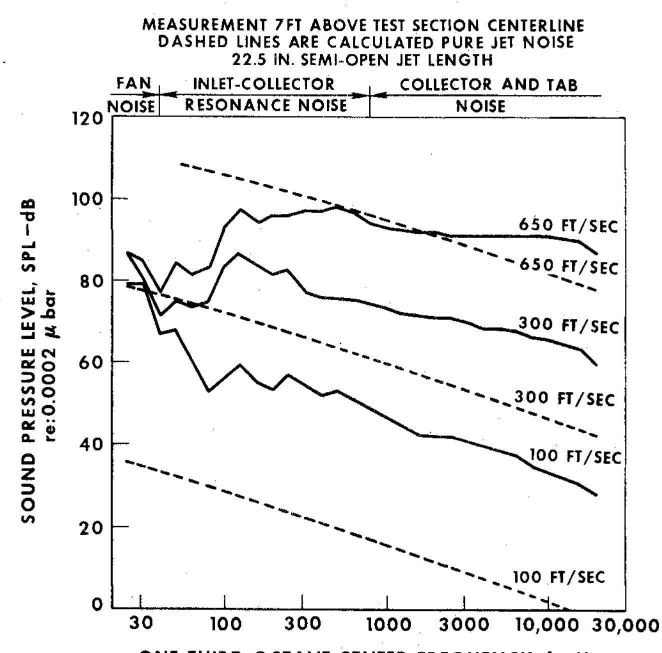

Fig. 5 Tunnel background noise spectra for various speeds.

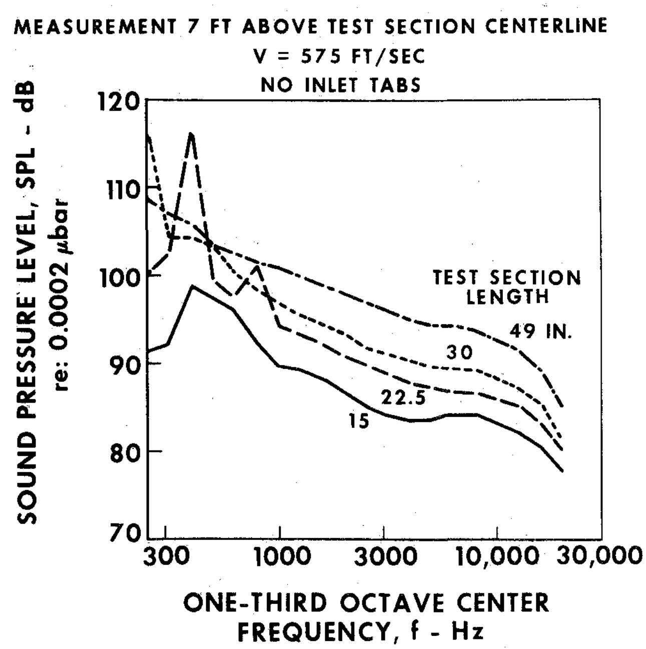

Fig. 6 Effect of test section length on background noise spectra.

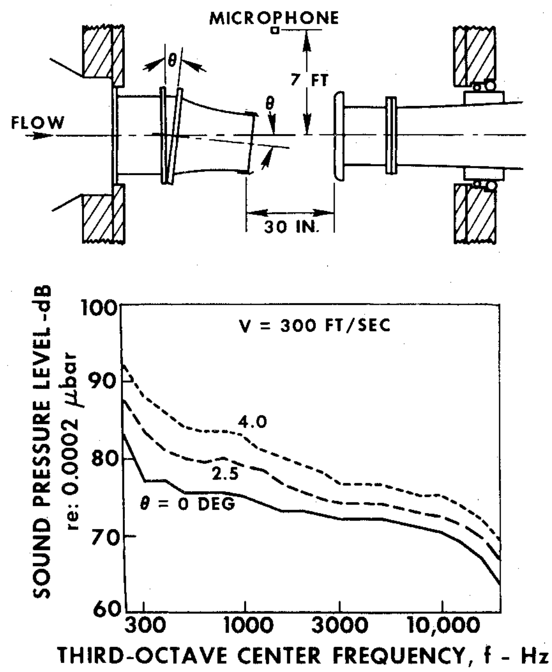

Fig. 7 Effect of jet deflection on background noise spectra.

pingement of the turbulent shear layer on the collector or caused by the tabs) rather than pure jet noise dominates the high frequency end of the tunnel spectra.

For frequencies less than about 40 Hz the background noise is relatively insensitive to both test section length and tunnel speed and is therefore attributed to the constant speed fan. In the intermediate frequency range from about 40 Hz to 800 Hz the background noise is strongly dependent on the size, number and placement of tabs. This frequency range, therefore, is apparently dominated by an edge tone noise mechanism.

The effect of test section length on tunnel background spectra is shown in Fig. 6. The tunnel background noise level increases with increased open jet length except at low frequencies where edge tones dominate. While decreasing open jet length will therefore improve the signal to noise ratio, a minimum length exists for a given experiment below which interference with the noise directivity pattern occurs.

Jet Deflection Noise

The open jet flow will be deflected when tests are made with a lifting body causing higher velocity portions of the shear layer to impinge on the collector lip. This collector impingement is a source of noise and an investigation of its magnitude was made. To simulate the deflected flow,

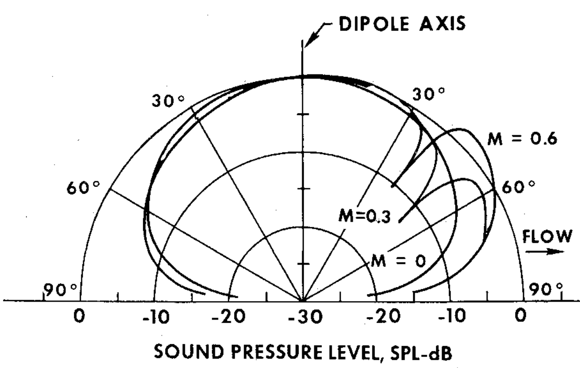

Fig. 8 Effect of Mach number of the directivity pattern of a dipole perpendicular to the shear layer.

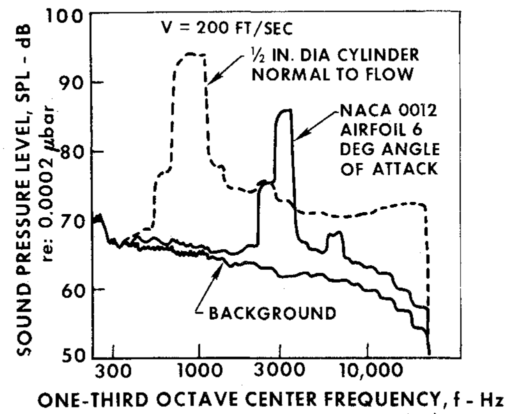

Fig. 9 Vortex shedding noise of airfoil and cylinder relative to tunnel background noise.

the inlet was positioned at various angles (θ), as shown in Fig. 7. At a tunnel speed of 300 fps Fig. 7 shows a significant increase in the background level obtained as the flow deflection angle was increased. Thus broadband noise increases above tunnel empty background noise levels measured during lifting body tests can be caused by jet deflection rather than the noise source under evaluation.

Shear Layer Refraction

Sound waves originating from a noise source in the tunnel test section must pass through the open jet shear layer which can reflect and refract the waves prior to detection by a microphone. Based on a zero thickness, plane shear layer model, an analytical study by Amiet[8] has shown that the shear layer transmission coefficient is a function of the tunnel Mach number, the type and orientation of noise source (e.g., monopole, dipole perpendicular or parallel to the shear layer) and the angle of the observer relative to the source. Figure 8 gives the predicted directivity pattern as a function of Mach number for a dipole with axis perpendicular to the shear layer. Measurements of the directivity pattern of the vortex shedding tone of a ½ in. diam cylinder (a good physical representation of the mathematical dipole) as a function of Mach number confirmed that distortions of the magnitude predicted are obtained at the angles predicted by theory.[8]

These preliminary results indicate that shear layer refraction effects are important in interpreting open jet acoustic data. The analytical method described above is currently being extended to provide corrections to the measured data that are independent of the type of noise source; this is required since the noise source in most practical experiments performed in the tunnel cannot be represented by a single mathematical singularity such as a monopole, dipole, quadrupole, etc.

Typical Acoustic Test Results

Figure 9 shows spectra obtained with a ½ in. diam cylinder (shown dashed) and a 9-in. chord, 21-in. span NACA 0012 airfoil (shown solid) measured 7 ft above the noise sources at a tunnel speed of 200 fps. The isolated airfoil noise, which has been identified as a vortex shedding noise,[9] stands out some 20 db above background, satisfying the design criterion set on tunnel background noise. The importance of a high Reynolds number test capability was confirmed in the study of this noise mechanism since the phenomenon was found to disappear at the high Reynolds numbers for which the trailing edge boundary layers on the suction and pressure surfaces of the airfoil were fully turbulent. When this occurred, the airfoil noise could not be detected above tunnel background noise.

Comparison With Other Facilities

Acoustic tunnels vary widely in capabilities due to a wide range of test requirements. A comparison of some of the more important parameters of existing and planned tunnels is shown in Table 2. The UARL tunnel and the NASA Langley Tunnel (now under construction) have the capability of high subsonic Mach numbers. The relative importance of edge tones, jet noise and shear layer-collector interaction noise would be expected, based on the present study, to vary amongst the tunnels because of the varying velocity ranges and test section lengths. The chamber cutoff frequencies vary somewhat from tunnel to tunnel depending upon the acoustic treatment and method of cutoff frequency determination.

Summary of Results

1) A sufficiently low background noise level has been obtained in a freejet acoustic wind tunnel to permit measurement of the relatively weak vortex shedding noise of an isolated airfoil placed in the uniform, low-turbulence airstream.

2) In this tunnel, shear layer-jet collector interaction background noise is dominant after readily suppressed sources such as edge tones and fan noise have been reduced. Jet deflection due to lifting bodies in the airstream causes a significant increase in this background noise level.

3) Tabs located on the lip at the upstream end of the freejet effectively reduce the edge tone noise which occurs under most freejet operating conditions.

4) Shear layer refraction of sound waves can be significant and should be taken into account when making directivity measurements in freejet acoustic tunnels.

References

[1]Paterson, R. W., Vogt, P. G., and Foley, W. M., "Design and Development of the UARL Acoustic Research Tunnel," AIAA Paper 72-1005, Palo Alto, Calif., 1972.

[2]Schlicting, H., *Boundary-Layer Theory*, McGraw-Hill, New York, 1968.

[3]Pope, A. and Harper, J. J., "*Low-Speed Wind Tunnel Testing*," Wiley, New York, 1966.

[4]Bradshaw, P. and Pankhurst, R. C., "The Design of Low-Speed Wind Tunnels," *Progress in Aeronautical Sciences*, Vol. 5, edited by D. Kuchemann and L. H. G. Sterne, MacMillan, New York, 1964, Chap. 1.

[5]Batchelor, G. K., "Sound in Wind Tunnels," Rept. ACA-18, Australian Council for Aeronautics, June 1945, Melbourne, Australia.

[6]Walters, T. A. and Wendover, W. E., "Predicting Forced Draft Fan Noise," presented at 26th Annual Meeting, American Power Conference, Illinois Inst. of Technology, Chicago, Ill. April 14–16, 1964.

[7]Abramovich, G. N., *The Theory of Turbulent Jets*, MIT Press, Cambridge, Mass., 1963.

[8]Amiet, R. K., "Propagation of Sound Through a Two-Dimensional Shear Layer with Application to Measurements in the Acoustic Research Tunnel," Rept. UAR-L40, March 1972, United Aircraft Research Lab., East Hartford, Conn.

[9]Paterson, R. W., Vogt, P. G., Fink, M. R., and Munch, C. L., "Vortex Noise of Isolated Airfoils," *Journal of Aircraft*, Vol. 10, No. 4, May 1973, pp. 296–302.

[10]Hersh, A. S. and Hayden, R. E., "Aerodynamic Sound Radiation From Lifting Surfaces With and Without Leading-Edge Serrations," CR-114370, June 1971, NASA.

[11]Hanson, C. E., "The Design and Construction of a Low-Noise, Low-Turbulence Wind Tunnel," TR 79611-1, Jan. 1969, Acoustics and Vibration Lab., MIT, Cambridge, Mass.

[12]Maynard, J. D., Barna, P. S., and Keever, K., "Investigation of the Aerodynamic Characteristics of a One-Tenth Scale Model of the Air Supply System for the Aircraft Noise Reduction Laboratory," Working Paper LWP-1046, April 1972, NASA.

[13]Brownell, W. F., "An Anechoic Test Facility Design for the Naval Ship Research and Development Center," Carderock Rept. 2924, Sept. 1968, Hydromechanics Lab., Naval Ship Research and Development Center, Washington, D.C.

[14]Bauer, P. and Widnall, S., "The Development of a Wind Tunnel Facility for the Study of V/STOL Noise," Flight Transportation Lab. Rept. R-72-6, Aug. 1972, MIT, Cambridge, Mass.