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USB NOISE REDUCTION BY NOZZLE AND FLAP MODIFICATIONS

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SUMMARY

Upper surface blown (USB) system configuration parameters are chosen with both takeoff and cruise performance in mind. Indications are that configuration requirements for cruise may compromise the ability to derive low takeoff and landing noise from USB designs by selection of nozzle/flap locations and designs which are inherently quiet. Thus, additional noise reduction at the source will be required.

This paper reviews the development of concepts for reducing USB flap noise at the source through flap modifications and special nozzles. In particular, recent results obtained on the aerodynamic and acoustic performance of flaps with porous surfaces near the trailing edge and so-called multi-slotted nozzles are reviewed. Considerable reduction (6-10 dB) of the characteristic low frequency peak has been shown. The aerodynamic performance is compared with conventional systems, and prospects for future improvements are discussed.

INTRODUCTION

Upper surface blown powered lift aircraft appear to be attractive from an aerodynamic point of view. However, these aircraft incur noise problems associated with the basic physical phenomena responsible for the powered lift attachment of the engine exhaust flow to a single flap, or series of flaps. Because of the stringent community noise goals set for propulsive lift aircraft, much attention is being focussed on the flap noise problem in the aircraft concept development stage. The problem peculiar to USB aircraft is a pronounced low frequency peak in the radiated noise spectrum. This peak contributes to, but does not dominate the commonly accepted measure of community noise from aircraft - the perceived noise level (PNL or PNdB). However, the low frequency peak is expected to produce a community noise impact due to secondary effects such as transmission into and excitation of building structures. Thus, significant reduction of the low frequency peak is desired. The high frequency sound levels produced by typical USB systems appear to be within a few dB of the desired goal and, thus, will require a lesser degree of reduction.

Cabin interior noise is an important area for both commercial and military aircraft applications. The USB powered lift system produces significantly higher source levels of low frequency noise than conventional jet aircraft, with a resultant increase in noise levels inside the cabin. Thus, due to the relatively poor noise-attenuating capabilities of conventional airframe structures at low frequencies, considerable attention must be given to reducing the levels of the source in the low frequency range.

TYPICAL USB NOISE CHARACTERISTICS

Figure 1 illustrates typical flyover noise spectra for a USB system under static conditions. The levels and frequencies are scaled from model data (Ref. 1) to a "full scale" (26,800 N (6000 lb) thrust) engine/flap configuration at a 152 m (500 ft) flyover distance. The nozzle pressure ratio (1.38) is representative of the upper part of the range currently being considered for powered lift aircraft. The single 26,800 N (6000 lb) engine/flap noise levels scale to about 95 PNdB at the 152 m (500 ft) distance. Four such engines and flaps would add 6 dB to these levels. [Note that a single 88,960 N (20,000 lb) thrust engine, identically mounted on a flap system whose dimensions were scaled to the nozzle diameter, would produce a noise spectrum 5 dB higher in level, and one octave lower in frequency than the single 26,800 N (6000 lb) engine.]

The pronounced low frequency peak is evident in Fig. 1. Levels in both the low and high frequency range are typically within a 5 dB range at all azimuths in the flyover plane, except in the immediate area of the deflected exhaust. Nozzle and flap details will affect the details of the far field sound spectra, so the data in Fig. 1 should only be regarded as typical examples.

Figure 2 compares predicted cabin internal noise levels with those actually measured on a range of CTOL jet aircraft (including all positions in the aircraft). The estimates for the USB system were made from fuselage sidewall fluctuating pressure data measured on an actual USB configuration (Ref. 1) combined with analytical and empirical estimates for acoustic and aerodynamic transmission loss of actual aircraft fuselage structures (Ref. 2).

For the USB model tested, the jet exhaust noise alone (as measured with flaps removed) shows a significantly lower level and compares favorably with levels inside current CTOL passenger jets. From these comparisons, it is clearly evident that both flap source noise reductions at low frequencies and fuselage structural design changes will be needed to reduce USB cabin noise levels to an acceptable range.

Figure 3 shows measured continuous-traverse directivity of an unmodified USB flap system (60° flap setting) in the flyover plane. The evidence is that the flap sources are not strongly directional. Other measurements have shown that the directivity is even weaker (i.e., more uniform), except at those azimuths in the vicinity of the deflected flow axis. The directivity pattern has been observed to rotate with the flap deflection which clearly implicates the flaps as a major source of noise. From these and extensive similar data, it is concluded that one cannot rely on utilizing directivity effects in developing low noise design strategies.

NOISE REDUCTION AT THE SOURCE

Identification of Physical Parameters

Noise reduction of flap sources involves first identifying the physical parameters responsible for sound generation and then developing concepts which modify the most important parameters. Figure 4 shows schematically how USB fluid mechanical parameters combine to radiate sound. The problem can be summarized by stating that the far field sound intensity $[I(r,\theta)]$ is related to the spanwise sum of individual source intensities whose strength is a function of the fluctuating fluid forces F, frequency ω of the fluctuating forces, and the directivity $D(\theta)$ of the local source.

$$I(r,\theta) \propto \sum_{W} \left(\overline{F^2} \ \omega^{2\pm} \ D(\theta) \right)$$

Examination of each element of Fig. 4 will lead to identification of the physical parameters which can be modified by nozzle and flap design changes. The fluctuating forces can be viewed as a product of fluctuating pressures and the respective correlation area of various pressures. The fluctuating pressures on a USB flap are intense, often being as high as .03 - .1 of the local dynamic pressure q_o, and may vary significantly with location on the flap. The characteristic side shear layers of a USB flap system produce intense low frequency pressures, while the attached flow along the nozzle centerline has greater high frequency content. The frequency ω of the fluctuating forces with respect to a stationary observation point on the flap is a ratio of the local convection velocity of turbulent eddies U_c, to the eddy length scale in the streamwise direction ℓ_x (i.e., $\omega \propto U_c/\ell_x$). The correlation areas are simply the product of the local streamwise and spanwise length scales, which are in turn proportional to the local shear layer thickness, δ. Both the fluctuating pressures and correlation areas can be reduced by flap and nozzle modifications. Diagnostic cross-correlation studies have shown that the acoustically important flap pressures on a USB system occur between the knee of the flap and the trailing edge, with the high frequency components being concentrated at the trailing edge.

The fluctuating hydrodynamic forces must accelerate the acoustic medium to cause far field sound. The efficiency of conversion of fluctuating hydrodynamic forces to far field sound increases with frequency, usually as the square of the frequency, except at values greater than unity of the ratio of flap or wing chord (C) to acoustic wavelength λ ($\lambda = c_o/\omega$). This acoustic "transfer function" can be influenced by flap modifications through varying the rate of change of surface flow resistance in the vicinity of the trailing edge or by producing a reactive component of unsteady surface pressure in the noise producing regions near the trailing edge.

The directivity of the flap sources (Fig. 4) is maximum at a direction ≈90° from the plane of the flap surface near the trailing edge and minimal in the downstream direction aligned with the flap surface. In the upstream direction, the pressure of the wing surface leads to significant sound radiated forward. Little can be done to affect the basic directivity characteristics of the flap sources. However, the flap and wing may be used effectively to shield sound from sources located above the flap surface, as is also shown in Fig. 4. Such sources include the free shear layer near the nozzle, the nozzle lip and deflector, blowing slots, and engine internal noise.

To arrive at the total far field noise spectrum, one must add up the contribution of all individual sources, including source strength, radiation efficiency, directivity, and shielding. The effective number of sources, m, on a USB system increases with frequency, approximately linearly. In developing noise reduction concepts, it must be kept in mind that devices for reducing source strength at a given frequency may lead to increasing the number of sources contributing to the far field, thus leading to a lesser amount of noise reduction than expected from source strength reduction.

Source Noise Reduction Strategy

The above discussion may be summarized in the form of a "strategy" for developing noise reduction techniques as follows:

- Reduce forcing function
  - fluctuating pressures
  - turbulence length scales
- Reduce transfer function between hydrodynamic forces and radiated sound
  - make surface discontinuity more gradual at trailing edge
  - add reactive interference with sources
- Take advantage of shielding benefits
  - move sources away from trailing edge or substitute high frequency sources away from edge for low frequency sources

The latter point may be implemented with a penalty in the number of effective sources contributing to the far field.

NOISE REDUCTION CONCEPTS

Several noise reduction concepts have been developed from the above-described source reduction strategy. In this section, the applications of flap surface modifications and nozzle modifications to USB source reduction are discussed.

Porous Flap Surface Concept

The basic idea of the porous surface (or variable impedance surface) concept is to replace the acoustically rigid flap surface with a porous surface with appropriate backing air cavities, over *all* areas of significant sound generation on the flap. Figure 5 illustrates the application of this concept to a simplified USB flap.

The effects of a porous surface are both hydrodynamic (source reduction) and acoustic (modification of transfer function), although the relative effects of each have not been conclusively determined.

Variations on the basic porous edge design are also shown in Fig. 5. These are:

(1) Fully porous tapered edge with a constant flow resistance per unit thickness; the tapering gives a decreasing flow resistance toward the trailing edge

(2) Constant impedance porous surfaces only, on upper and lower flap surfaces

(3) Porous upper surface with a simple cavity formed by the rigid lower surface

(4) Porous upper surface with individual compartments formed by flap lower surface and flap internal structure; such compartments can be tailored to acoustic and aerodynamic details, if they are known for a given configuration

Noise reduction has been achieved on a wide range of configurations ranging from a simple airfoil to an aerodynamically optimized USB flap at high turning angle setting (Fig. 6). Figure 7 summarizes these results. The airfoil shown was operated in the cone of a free jet and had a simple tapered porous edge. Noise reduction of the low frequency noise arising from free jet shear layer interaction with the trailing edge and of the airfoil's discrete frequency wake noise was achieved. A simple wall jet has been tested by both BBN and Bohn of Boeing (Ref. 3). The noise reduction shown is a typical reduction which was maximum at the Strouhal peak and less at high frequencies. Peak reductions of at least 10 dB were commonly achieved. Early tests on the potential applicability of porous edges to USB systems were conducted by BBN (Ref. 4) on a small scale (·1/20) USB turning flap with a 10:1 AR nozzle kicked down at about 15°. As shown in Fig. 7, the flyover noise reduction at the Strouhal peak was substantial for both a simple porous edge and one with a simple cavity backing. However, the cavity reduced the flyover noise levels in the high frequency regime and was qualitatively found to improve turning.

Recently-completed exploratory tests on an aerodynamically optimized USB configuration (Fig. 6) were conducted by BBN under NASA Langley contract (Ref. 1). The objective of the study was to show that significant noise reduction could be achieved without impairing the aerodynamic performance of the USB system. It was also desired to develop a data base to improve the understanding of the important parameters influencing noise reduction.

A sampling of key results from the Aero Commander USB tests are shown in Fig. 7. Noise reduction was achieved over a wide range of frequencies at all observation points under the wing and along the sideline. Curves are shown for a simple porous flap with the entire flap surface treated with a 0.9 ρc flow resistance* material, the same surface treatment with a solid lower flap surface in place, and a cavity-backed configuration where only the last 20% of the flap chord was treated. The latter configuration had superior aerodynamic performance as is discussed below. The peak noise reduction was about the same for all flap configurations, while high frequency noise reduction was better for the fully porous treatments than for those with the last 20% only treated. In cases where a large area was treated, the flow failed to stay attached at high exhaust velocities. This led to an apparent increase in high frequency noise, such as is shown at the 110° position. In fact, the high frequency noise was merely the free jet from the nozzle, being almost identical in level and frequency to the spectra with the flaps removed.

From these tests, it may be concluded that porous surface treatment may be successfully applied to an aerodynamically satisfactory USB configuration to achieve around 6 dB of reduction of the low frequency peak and 3-6 dB reduction of high frequency levels. Further optimization studies could improve the noise reduction through spatial variation in surface impedance and better matching of cavity geometry to local pressure field details.

USB NOZZLE MODIFICATIONS

The detailed flow parameters previously shown to influence flap-radiated noise are a function of the USB configuration details, namely:

- Nozzle shape, aspect ratio, kickdown angle
- Nozzle axial location
- Flap radius and length.

These details affect the intensity of turbulent pressure fluctuations and the scale at the trailing edge. The side shear layers are primarily responsible for the characteristic low frequency peak in both community noise and interior noise. Thus, if the intensity and scale of turbulence can be reduced, the source strength will be reduced, and the characteristic frequency will increase, thus taking advantage of shielding benefits for community

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*ρc = density × sound speed of ambient medium
 = acoustic impedance of air

noise, and improved transmission loss of the fuselage for high frequency noise.

Several baseline variations on USB nozzles (such as deflectors) can produce up to 5 dB reduction of the low frequency peak, but cause a comparable increase in high frequency levels (Ref. 1). This section describes a class of multi-segment nozzles which when integrated with turning flaps have shown considerable potential. Figure 8 shows the basic concept which combines ideas derived from concentric cylinder low noise free jet nozzles (Ref. 5), and flap trailing edge blowing (Ref. 6).

The expected benefits of multi-segment, or multi-slot nozzles, are both hydrodynamic (reduce intensity and scale of turbulence) and acoustic (replace low frequencies with high frequency sources above the wing to take advantage of shielding). Aerodynamically, high turning angles can be achieved with a short flap chord. All configurations involve using a small flap with three or more tangential blowing slots at the knee and trailing edge blowing slots. The fixed nozzle is either a single low aspect ratio nozzle with deflector ("split flow") or a series of fixed slots deployed during the powered lift mode of flight ("7-slot" nozzle or "14-slot" nozzle). The principal objectives of these integrated nozzle/flap designs were to reduce the low frequency noise peak and achieve high turning angles with a short flap. The results of several test programs (Refs. 7-9) are summarized below.

All three multi-segment nozzles were compared with a 6:1 AR Coanda nozzle and flap. The baseline nozzle/flap system had a 10° kickdown but no deflector and thus cannot be considered the most advanced design. Figure 9 shows typical reductions of community noise with various multi-slot nozzles. The low frequency peak was reduced by 10 - 15 dB, while high frequency levels increased by up to 5 dB in the important frequency range. Above the wing, high frequency levels increased by up to 15 dB, but sound radiation to the hemisphere above the wing is inconsequential. The seven slot nozzle was the quietest overall at the sideline position. Also shown in Fig. 9 is a significant reduction of cabin noise in the low frequency regime. The interior noise curves were based upon analytical estimates of the sound in the nearfield of the nozzles and not upon actual sidewall pressure measurements as was the case for the curves presented in Fig. 2. Due to shielding effects of the flow, the actual high frequency levels might be lower than shown in Fig. 9.

From the tests summarized above, it is concluded that the integrated multi-segment nozzle/slotted flap system offers potential noise reduction of over 10 dB for both low frequency community noise and interior noise. Since the noise reduction with the 14-slot nozzle was not significantly greater than the simpler split flow nozzle, it may be concluded that the tangential multi-slot blowing at the high curvature region of the flap is the most important aspect of the noise reduction concept. It is also noted that porous edge treatment described earlier would provide additive noise reduction of edge sources producing the high frequency noise.

AERODYNAMICS

The practical feasibility of flap and nozzle modifications proposed for noise control purposes depends upon the ability of the system to produce acceptable aerodynamic performance without excessive weight penalties. The porous flap and multi-slot nozzle concepts have been studied with aerodynamic performance and noise reduction treated simultaneously. In both cases, the aerodynamic performance of many configurations is comparable with baseline USB systems. A sample of the findings is given below.

Porous Flaps

The porous flap configurations were tested for aerodynamic performance by measuring axial (A) and normal (N) forces as a function of nozzle pressure ratio. The baseline solid flap produce a linear variation of both axial and normal force components as a function of nozzle pressure ratio. All porous flap configurations followed the linear variation of A and N forces with pressure ratio at low pressure ratios, and many were linear through the lateral range of nozzle pressure ratio. However, some of the highly porous configurations underwent flap separation prematurely; an example of the raw data curves obtained in Ref. 1 is shown in Fig. 10. For those configurations for which flow separated, noise was evaluated at pressure ratios on both sides of the stall point. Those configurations treated on the last 20% of the flap did not stall and, as described above, produced 4 - 8 dB of noise reduction over a wide frequency range.

The static turning of porous flap configurations tested is summarized in Fig. 11. It can be seen that the turning efficiency and turning angle performance are acceptable for most configurations except the simple porous flap with no backing. No forward speed tests have been conducted to date.

Multi-Slot Nozzles

The integrated multi-slot nozzle/flap configurations were generally characterized by excellent turning performance at all flap settings, including 90°, for both static and forward speed tests. Tests were conducted by the Los Angeles Aircraft Division (LAAD) of Rockwell International Corp. (Ref. 9) on the same models tested acoustically by BBN in the low noise acoustic wind tunnel.

The static turning characteristics of the three nozzle/flap configurations described earlier are shown in Fig. 12. The split flow nozzle with slotted turning flap performed the best at high flap settings.

Figure 13 summarizes some of the forward speed performance of the multi-slot nozzles on a low aspect ratio swept wing. Again, the split flow nozzle appears to have excellent performance. Comparable data for the simple Coanda flap are not available, but these data may serve as a useful baseline for comparison with other flap systems.

Conclusions

The limited aerodynamic studies conducted to date on the porous flap and multi-slot nozzle have shown that these noise reduction concepts can have aerodynamic performance which is comparable to unmodified USB nozzle/flap systems. Further aerodynamic diagnosis and optimization could enhance the performance of USB systems using these concepts.

CONCLUDING REMARKS

This paper has presented data which show that significant noise reduction of USB flap sources can be achieved with flap and nozzle modifications, without serious compromise of aerodynamic performance. The porous flap concept can be used to reduce noise from any baseline level achieved through primary configuration variables. The porous flap and multi-segment nozzles can undoubtedly be optimized further to improve both noise reduction and aerodynamic performance.

APPENDIX

SYMBOLS AND ABBREVIATIONS

A	area
AR	aspect ratio
A/C	aircraft
BB	Bolt Beranek and Newman
C	flap or wing chord
C_D	drag coefficient
C_L	lift coefficient
$C_{L_{max}}$	maximum lift coefficient
C_{L_0}	lift coefficient at $\alpha = 0$
C_T	thrust coefficient
c	sound speed of ambient medium
c_0	speed of sound
F	fluctuating fluid force
f	frequency
I	intensity
ℓ_x	eddy length scale in streamwise direction
m	effective number of sources
N,A	normal and axial force, respectively
N_2	14-slot nozzle
N_3	7-slot nozzle
N_4	split flow partially slotted nozzle

p_R	pressure ratio
p_s	surface pressure
p_T	total pressure
q	dynamic pressure
q_{max}	maximum dynamic pressure
q_o	local dynamic pressure
r	radial distance
T	thrust
USB	upper surface blown
U	velocity
U_c	local convection velocity of turbulent eddies
U_e	exit velocity
w	span
α	angle of attack
δ	local shear layer thickness
δ_F	outboard flap angle
δ_N	turning flap angle
θ	angle between flow direction and observer direction
λ	acoustic wavelength
ρ	density of ambient medium
ρ_c	acoustic impedance of air
ω	frequency of fluctuating forces

REFERENCES

1. Hayden, R.E.: "Exploratory Investigation of Aeroacoustic Optimization of the Variable Impedance Edge Concept Applied to Upper Surface Blown Configurations," BBN Report No. 3245, Feb. 1976.

2. Wilby, J.F., and Scharton, T.D.: "Acoustic Transmission Through a Fuselage Sidewall," BBN Report No. 2742, July 1974.

3. Bohn, A.J.: "Edge Noise Attenuation by Porous Edge Extensions," AIAA Paper 76-80, Jan. 1976.

4. Hayden, R.E., Scharton, T.D., Kadman, Y., Wilby, J., and Rudd, M.J.: "A Preliminary Evaluation of Noise Reduction Potential for the Upper Surface Blown Flap," BBN Report No. 2478, Nov. 1972 (NASA CR-112246).

5. Scharton, T.D., White, P.H.: "Simple Pressure Source Model of Jet Noise," J. Acous. Soc. Amer., vol 52, Nov 1972.

6. Scharton, T.D., Pinkel, B., and Wilby, J.F., "A Study of Trailing Edge Blowing as a Means of Reducing Noise Generated by the Interaction of Flow with a Surface," BBN Report No. 2593, Sept. 1973 (NASA CR-132270).

7. Kadman, Y., Hayden, R.E., and Scharton, T.D.: "Noise Characteristics of Conventional and Multislotted Upper Surface Blowing-Nozzle Concepts With and Without Forward Speed," BBN Report No. 2889, Sept. 1974.

8. Kadman, Y.: "Small Scale Noise and Wind Tunnel Tests of Upper Surface Blowing Nozzle Flap Concepts; NASA CR-137748, 1976.

9. Renselaer, D.J., Nishida, R.S., and Wilkin, C.A.: "Small Scale Noise and Wind Tunnel Test of Upper Surface Blowing Nozzle Flap Concepts," Volume I. "Aerodynamic Test Results." NASA CR-137747, Dec. 1975.

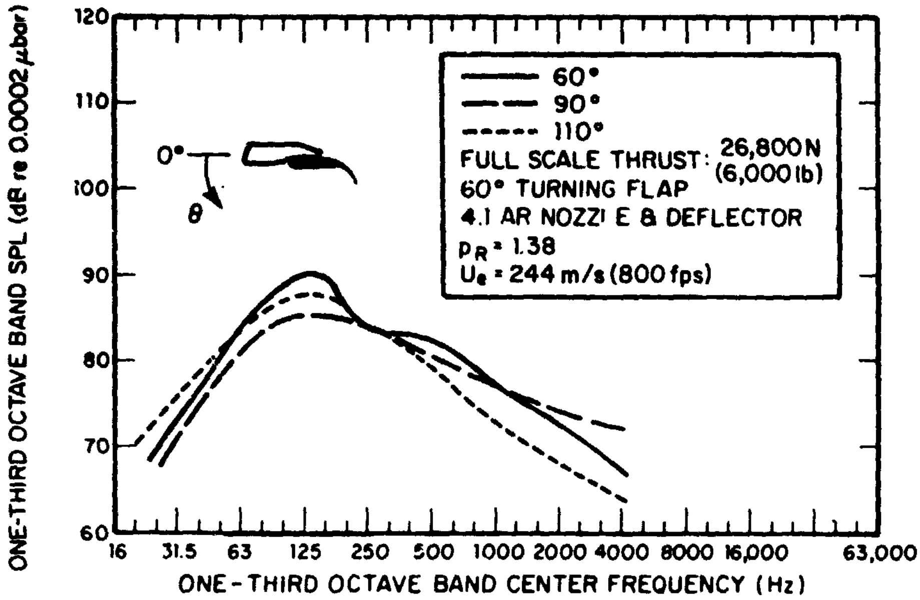


Figure 1.- Typical farfield USB sound spectra.

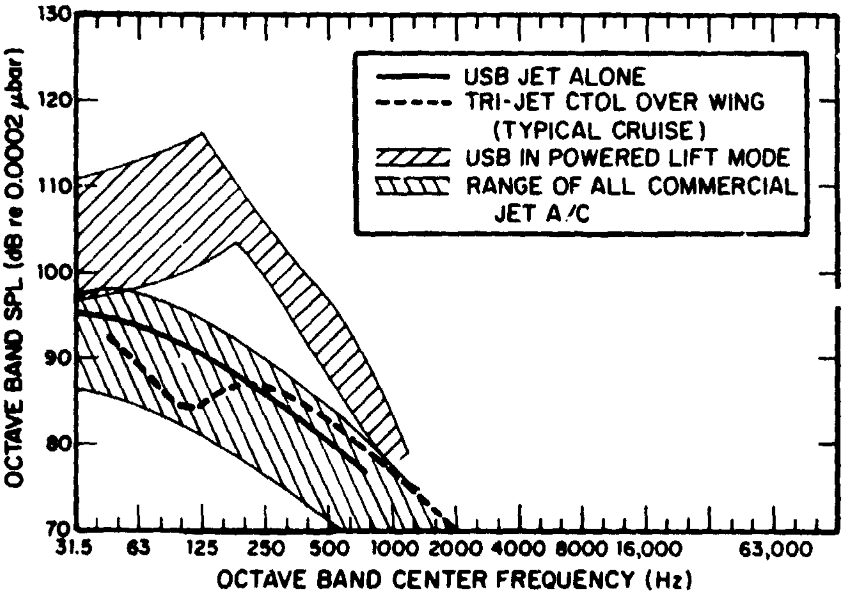


Figure 2.- Typical cabin noise levels.

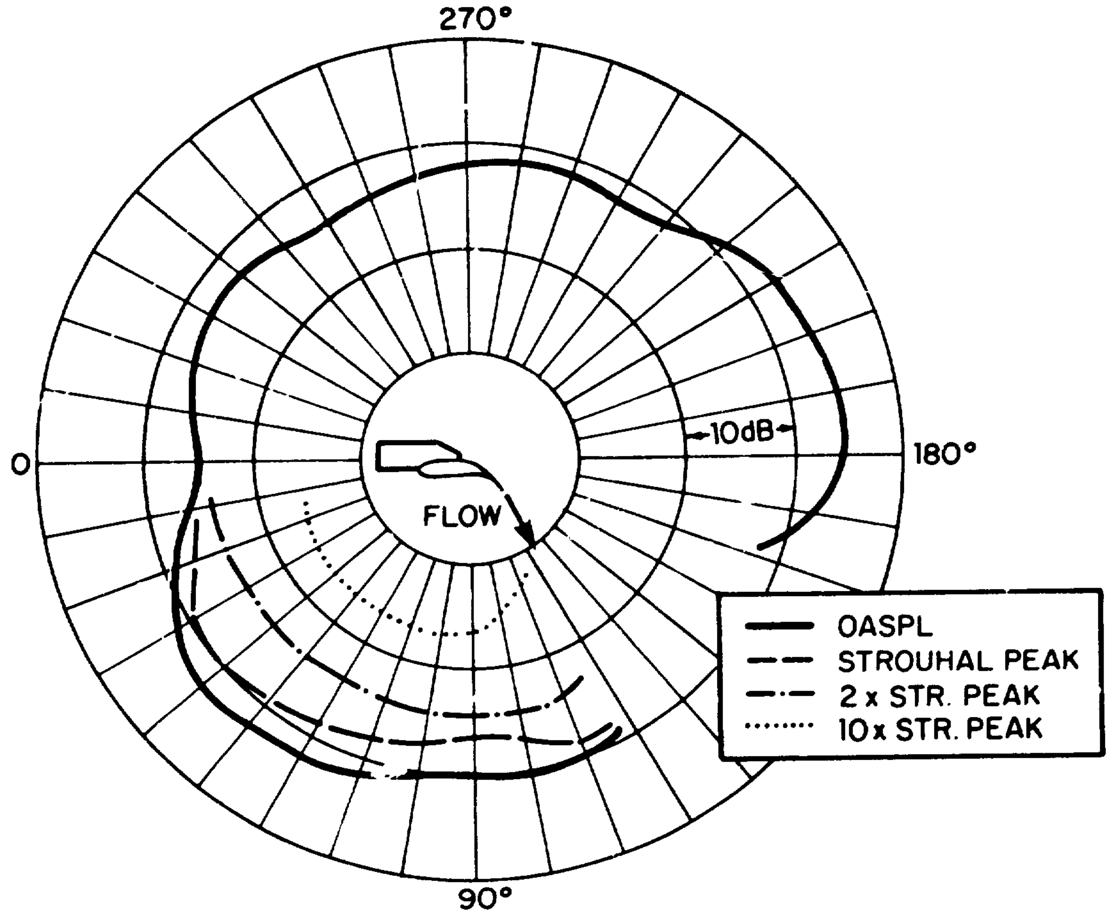


Figure 3.- Typical directivity in flyover plane.

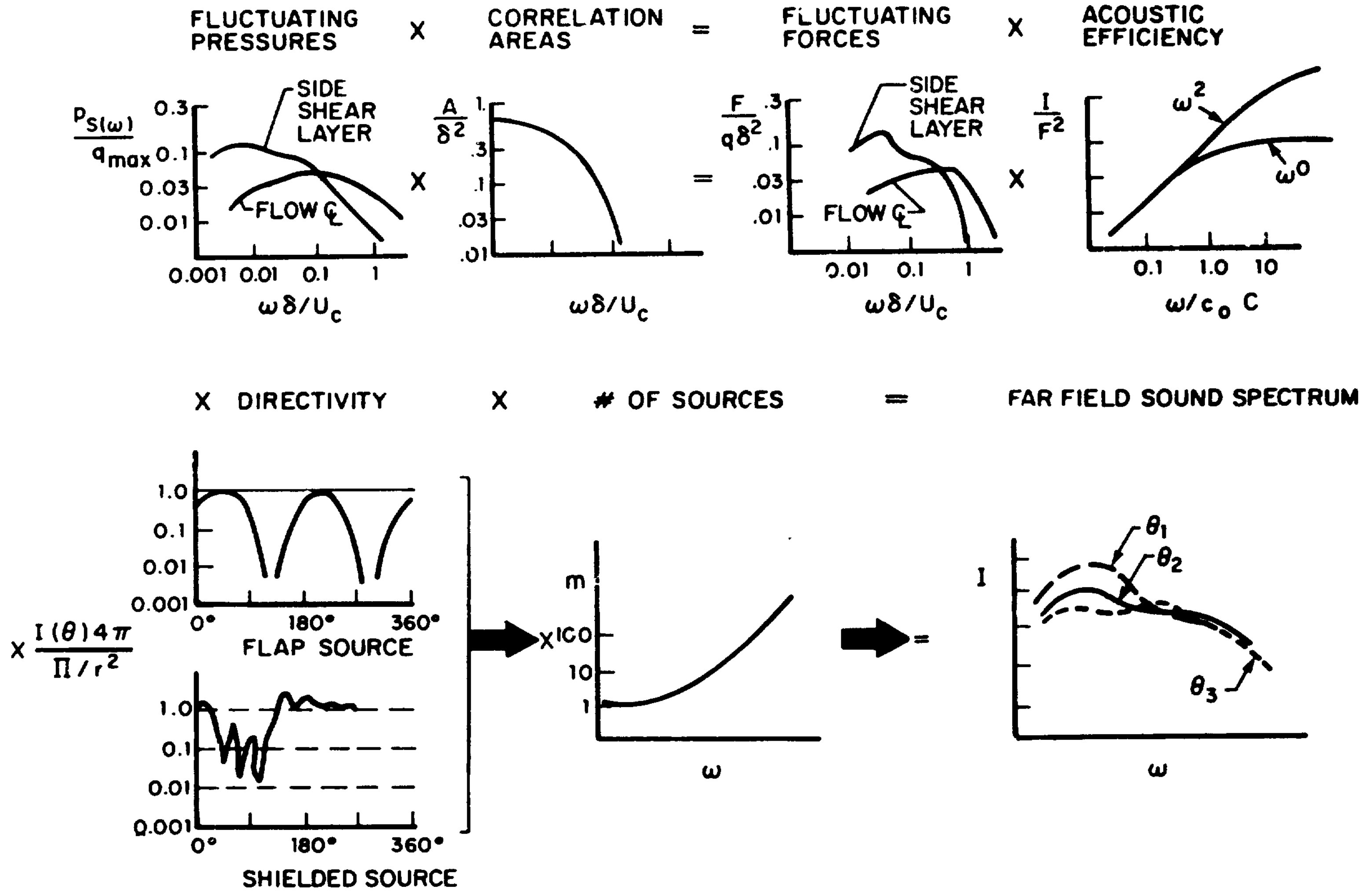
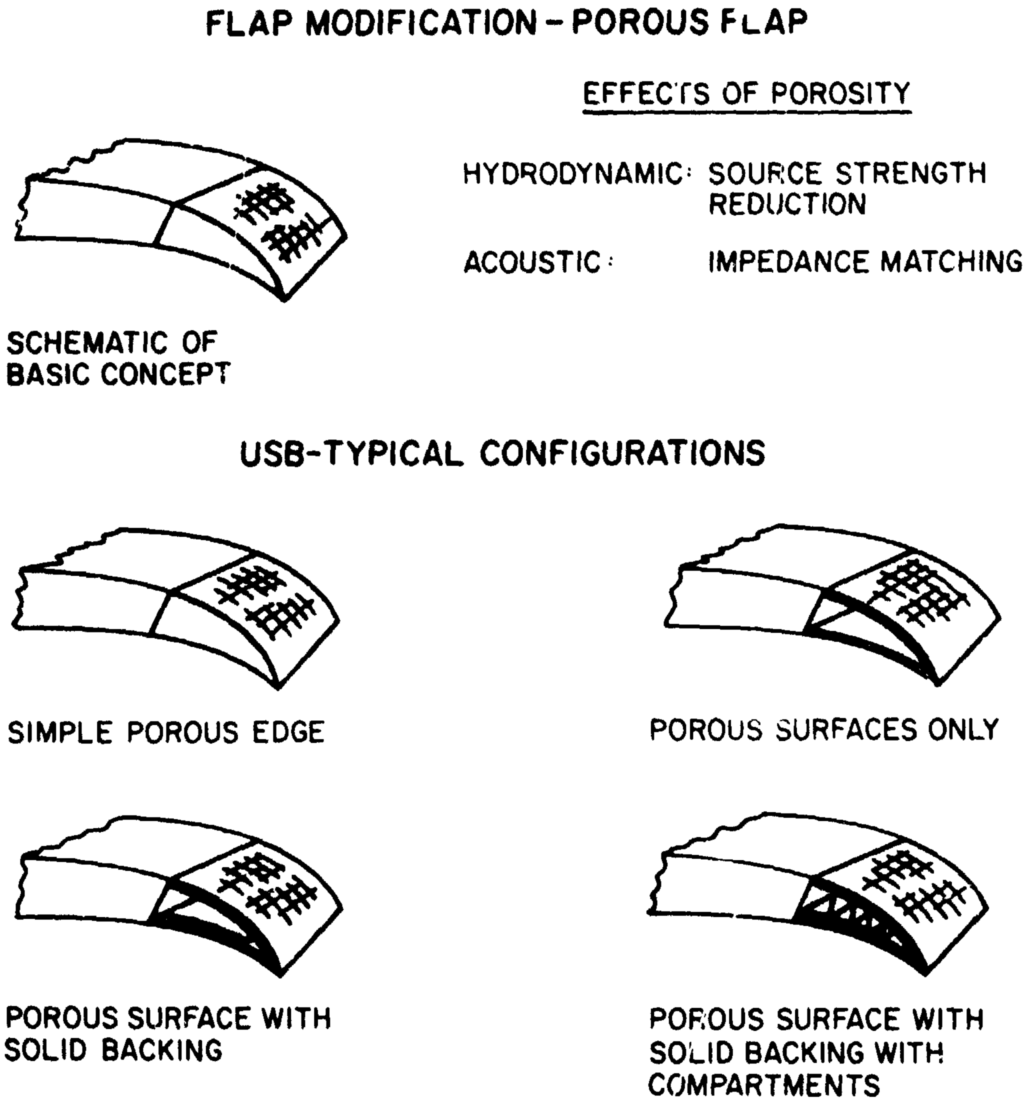


Figure 4.- Noise-producing parameters to be reduced.



FLAP MODIFICATION – POROUS FLAP

EFFECTS OF POROSITY

HYDRODYNAMIC: SOURCE STRENGTH REDUCTION

ACOUSTIC: IMPEDANCE MATCHING

SCHEMATIC OF BASIC CONCEPT

USB-TYPICAL CONFIGURATIONS

SIMPLE POROUS EDGE

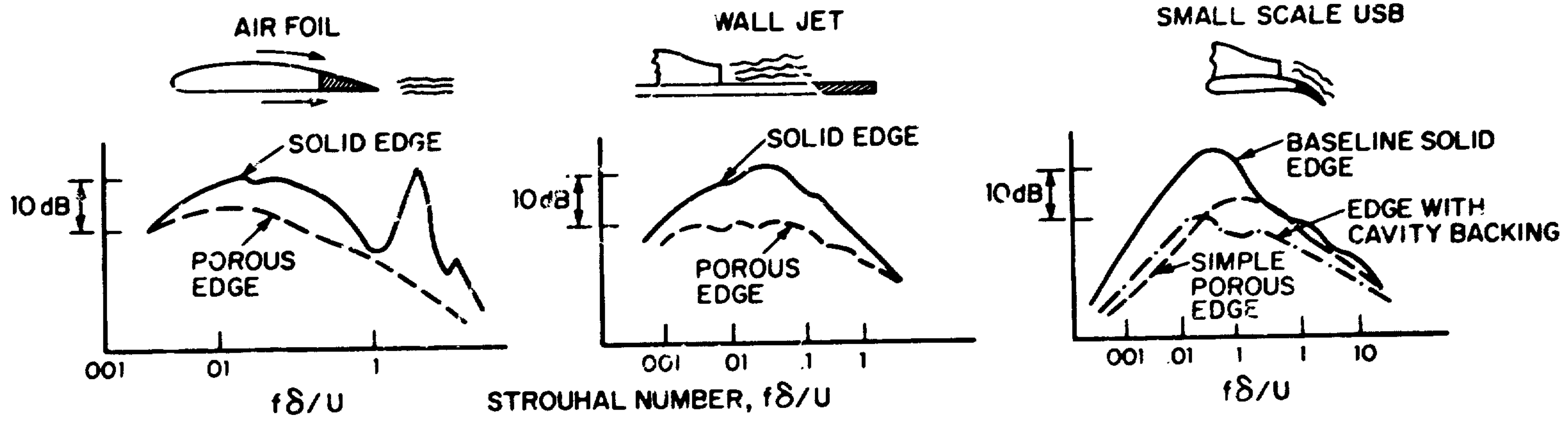
POROUS SURFACES ONLY

POROUS SURFACE WITH SOLID BACKING

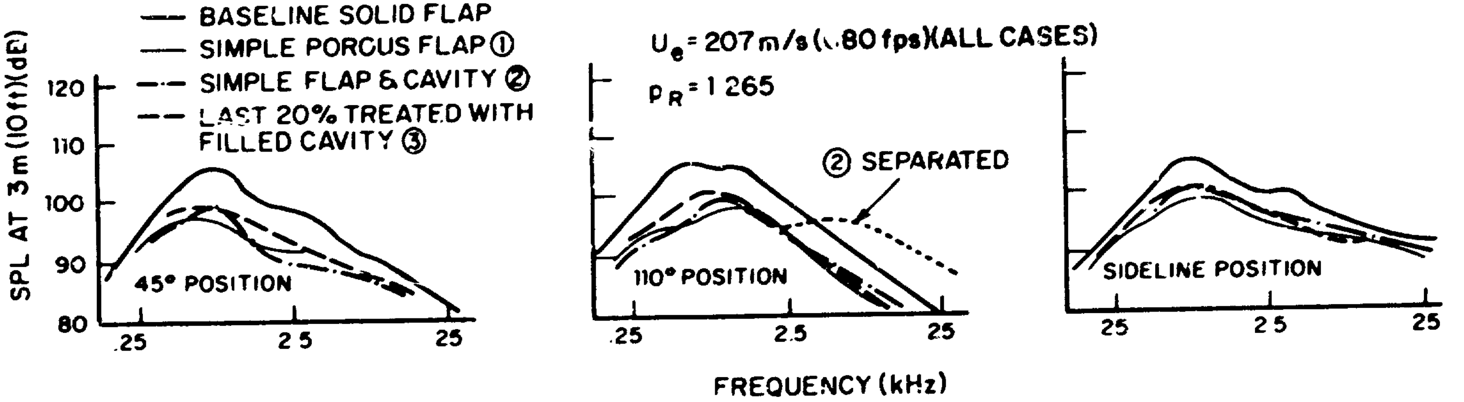
POROUS SURFACE WITH SOLID BACKING WITH COMPARTMENTS

Figure 5.- Noise reduction concepts.

Figure 6.- Aero Commander USB model.

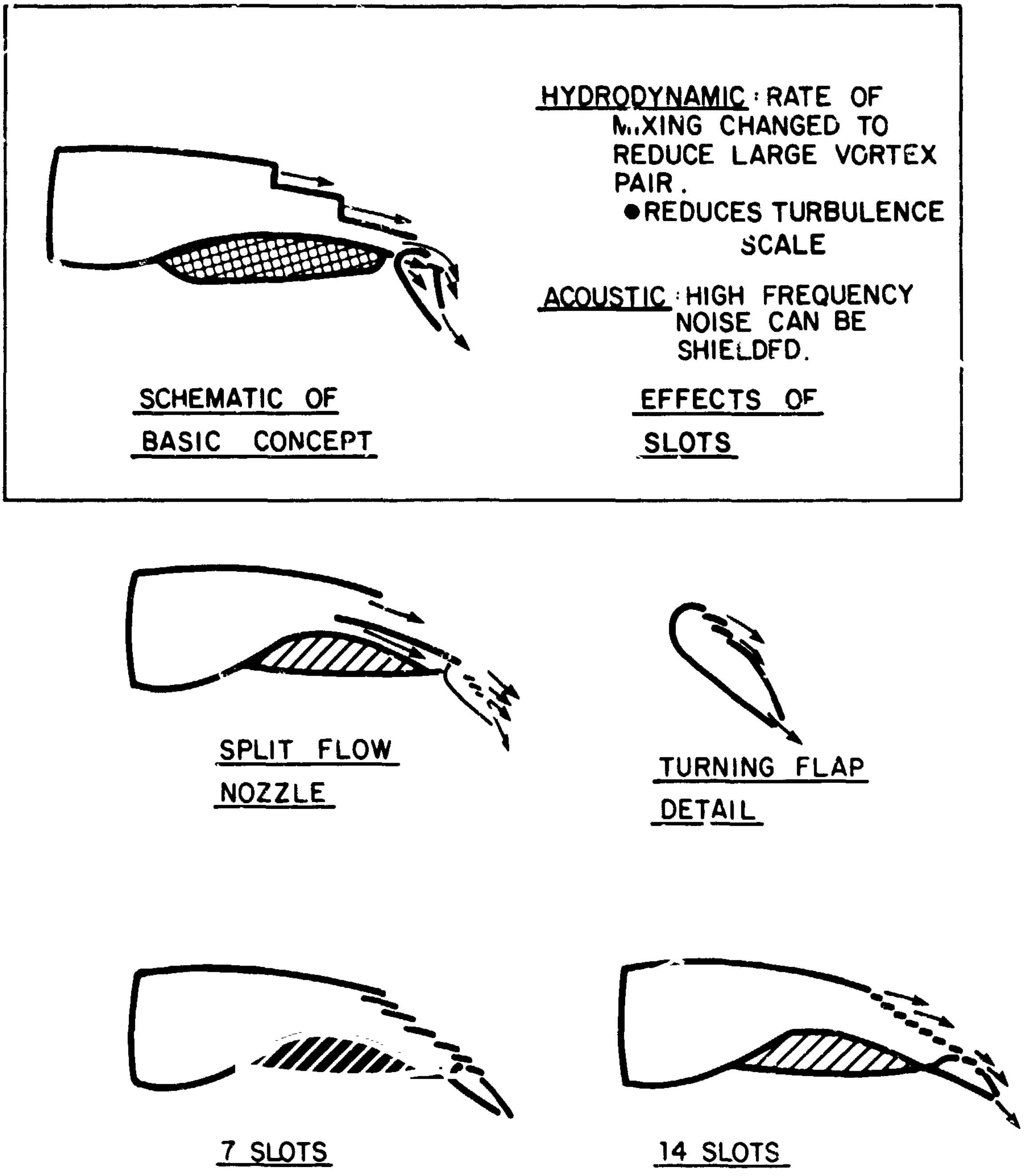


SIMPLE CONFIGURATIONS



1/5 SCALE USB (AERO COMMANDER) WIT AP

Figure 7.- Summary of noise reduction with porous edges.



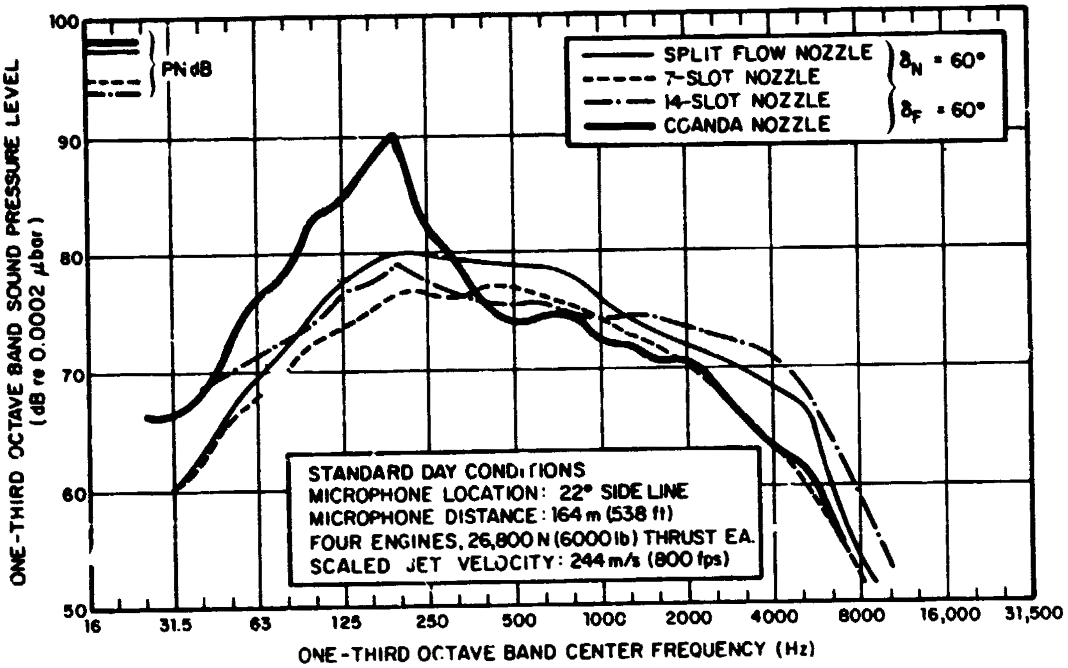
HYDRODYNAMIC: RATE OF MIXING CHANGED TO REDUCE LARGE VORTEX PAIR.

- REDUCES TURBULENCE SCALE

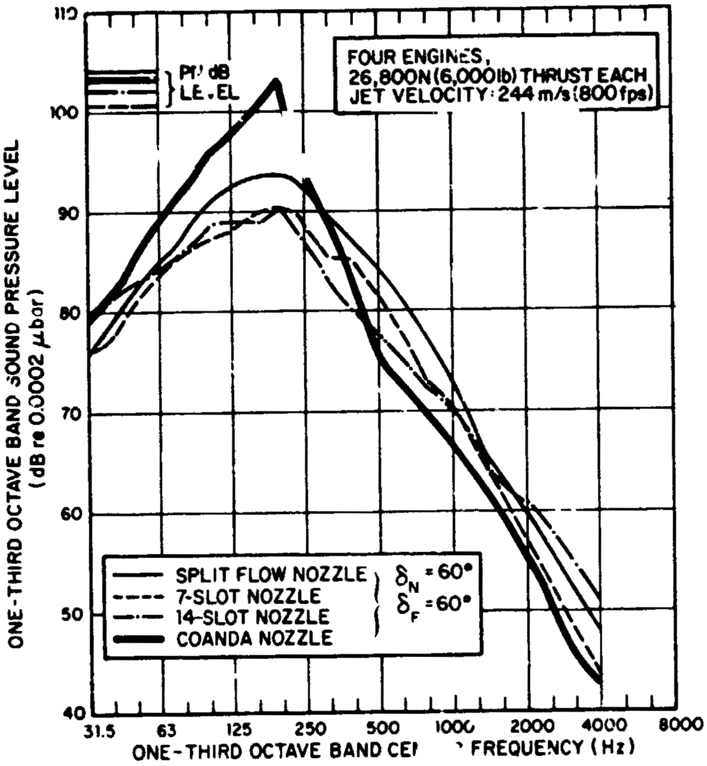
ACOUSTIC: HIGH FREQUENCY NOISE CAN BE SHIELDED.

MULTI-SLOT NOZZLES

Figure 8.- Nozzle modifications.



(a) Community noise.



(b) Cabin interior noise.

Figure 9.- Noise reduction with multi-slot nozzles.

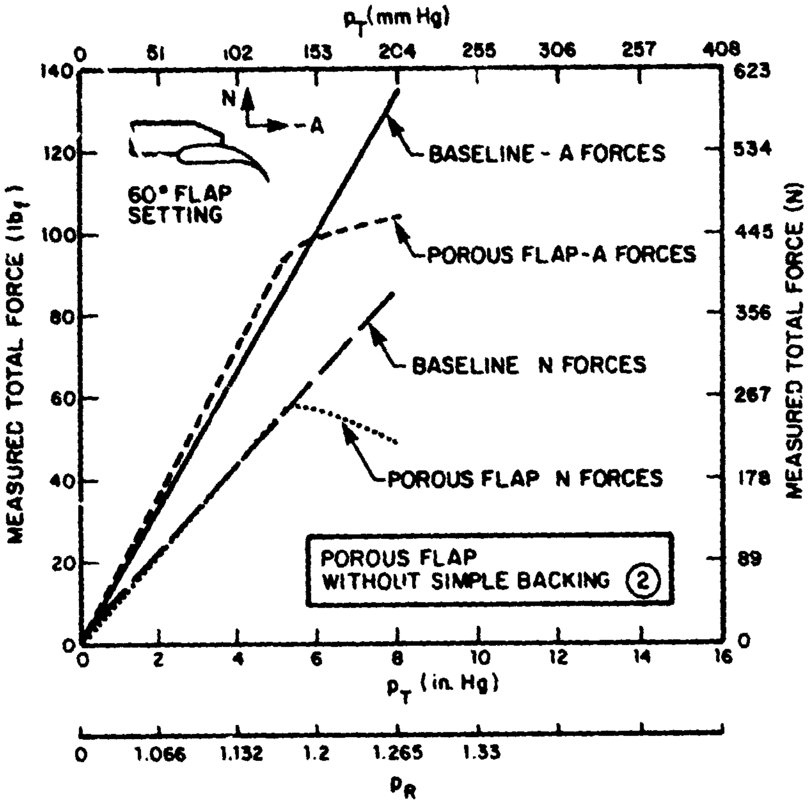


Figure 10.- Velocity dependence on porous flap forces.

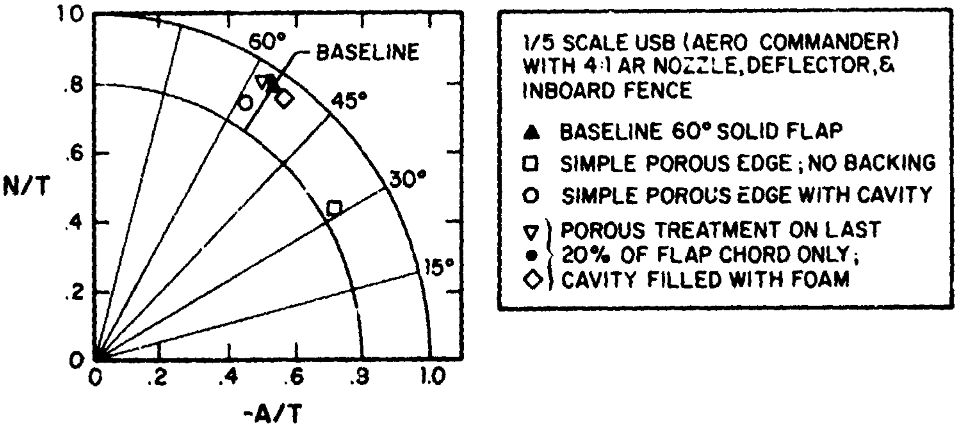


Figure 11.- Static turning of porous flap configuration.

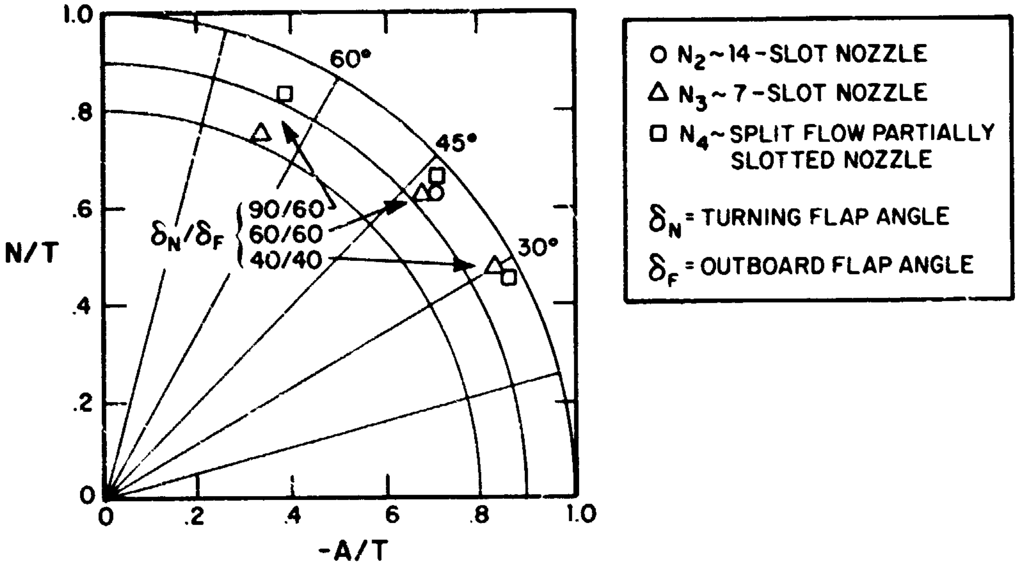
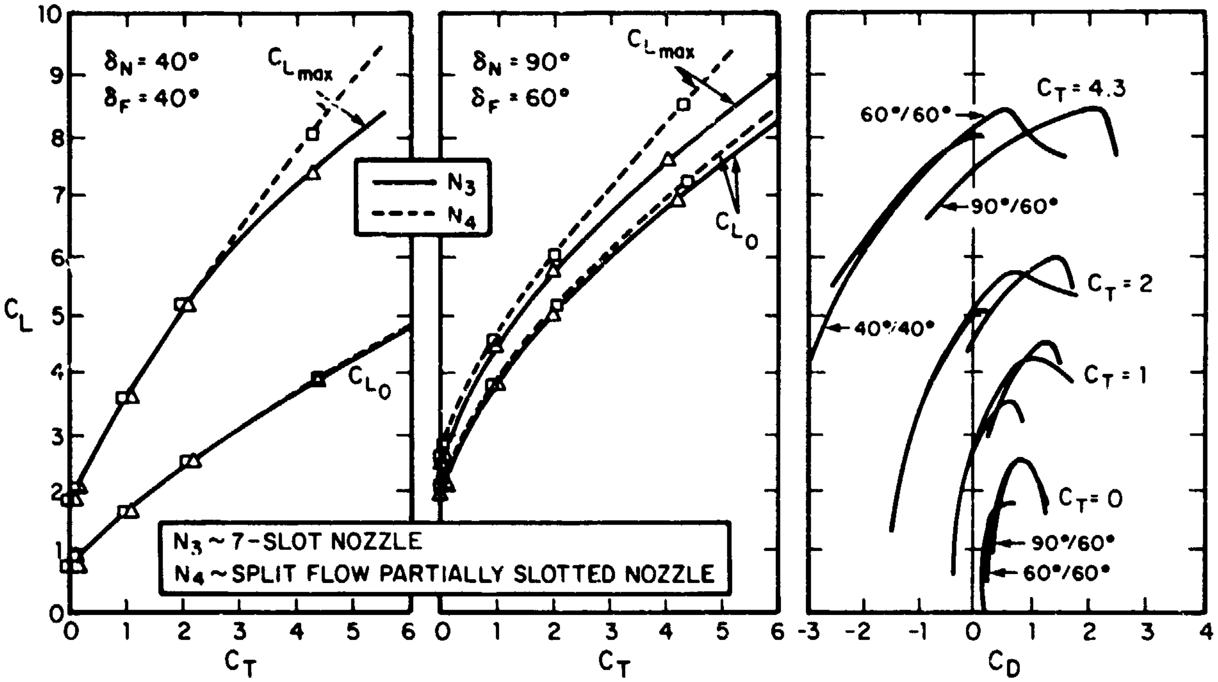


Figure 12.- Static turning of multi-segment nozzles on USB configuration.



LIFT AT ZERO ALPHA & MAX. LIFT CORRELATION WITH C_T, δ_N/δ_F = 40°/40°

LIFT AT ZERO ALPHA & MAX. LIFT CORRELATION WITH C_T, δ_N/δ_F = 90°/60°

DRAG POLARS - SPLIT FLOW PARTIALLY SLOTTED NOZZLE

Figure 13.- Aerodynamic performance of multi-segment nozzle on USB configuration.