Comparison of the Acoustic Characteristics of Large-Scale Models of Several Propulsive-Lift Concepts

Michael D. Falarski,* Thomas N. Aiken,† Kiyoshi Aoyagi,† and David G. Koenig†
NASA Ames Research Center, Moffett Field, Calif.

Wind-tunnel acoustic investigations were performed to determine the acoustic characteristics and the effect of forward speed on these characteristics of four propulsive lift concepts: the over-the-wing externally-blown jet flap (OTW), the under-the-wing externally-blown jet flap (UTW), the internally-blown jet flap (IBF), and the augmentor wing (AW). The data in this paper represent the basic noise generated by the powered-lift system without acoustic treatment, assuming all other noise sources, such as the turbofan compressor noise, have been suppressed. Under these conditions, when scaled to a 45,500 kg (100,000 lb) aircraft, the OTW concept exhibited the lowest perceived noise levels because of dominant low-frequency noise and wing shielding of the high-frequency noise. The AW was the loudest configuration because of dominant high-frequency noise created by the high jet velocities and small nozzle dimensions. All four configurations emitted noise 10 to 15 PNdb higher than the noise goal of 95 PNdb at 153 m (500 ft). The AW is the only powered-lift concept which has shown the capability of acoustic suppression to this level. The effect of forward speed did not approach that expected from the relative velocity increments investigated. The dominant low-frequency noise of the OTW and UTW was reduced 2 db by an 80 knot free-stream velocity. The dominant high-frequency noise of the IBF and AW was unaffected by forward speed.

Nomenclature

$OASPL$	= overall sound pressure level, db
PNL	= perceived noise level, PNdb
SPL	= sound pressure level, db referred to 2×10^{-5} N/m^2 (0.0002 microbar)
V_{J_I}	= average isentropic jet exhaust velocity, m/sec (fps)
V_∞	= freestream velocity, knots (fps)
α	= angle of attack with respect to wing chord plane, deg
δ_f	= flap deflection with respect to wing chord plane, deg
θ	= polar angle to observer position, deg (see Fig. 6)

Introduction

SEVERAL propulsive-lift concepts are being investigated as a means of attaining short takeoff and landing (STOL) performance in turbofan-powered aircraft. For commercial applications, STOL aircraft may be operating out of airports in densely populated urban or suburban areas. Acceptable noise levels around these airports will be substantially less than for airports used by today's commercial aircraft. The use of existing noise reduction technology and careful cycle selection can reduce the noise of new turbofan engines to levels where the propulsive-lift system will become the dominant noise source. It is thus necessary to conduct research on the acoustic characteristics of powered-lift concepts. The results of several investigations using part-span, small-scale models under static conditions have been reported in Refs. 1 and 2.

This paper presents the results of wind-tunnel acoustic investigations of large-scale, 3-dimensional models of four powered-lift concepts: over-the-wing externally-blown jet flap (OTW); under-the-wing externally-blown jet flap (UTW); internally-blown jet flap (IBF); and augmentor wing (AW). The OTW concept takes advantage of wing shielding by mounting the turbofan engines on the wing's upper surface and deflecting the exhaust with a coanda flap. The UTW has the engines mounted in the conventional manner under the wing with the exhaust deflected by a multi-element flap system. The IBF and AW have fan-bypass air ducted into the wing and expelled along the wing trailing edge. For the IBF, the compressed air is blown out along the trailing edge of a simple flap, while for the AW, the air is blown from a lobed nozzle into a trailing-edge ejector system.

The results presented herein represent the basic noise generated by the powered-lift system without acoustic treatment, assuming all other noise sources, such as turbofan compressor noise, have been suppressed. The investigations were performed in the NASA Ames 40- by 80-ft Wind Tunnel. The aerodynamic characteristics were also documented.[3-6]

Model Description

Figure 1 shows a typical propulsive-lift model installed in the wind tunnel. Figure 2 shows the model geometric details.

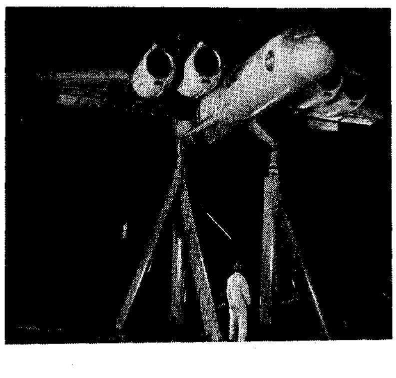


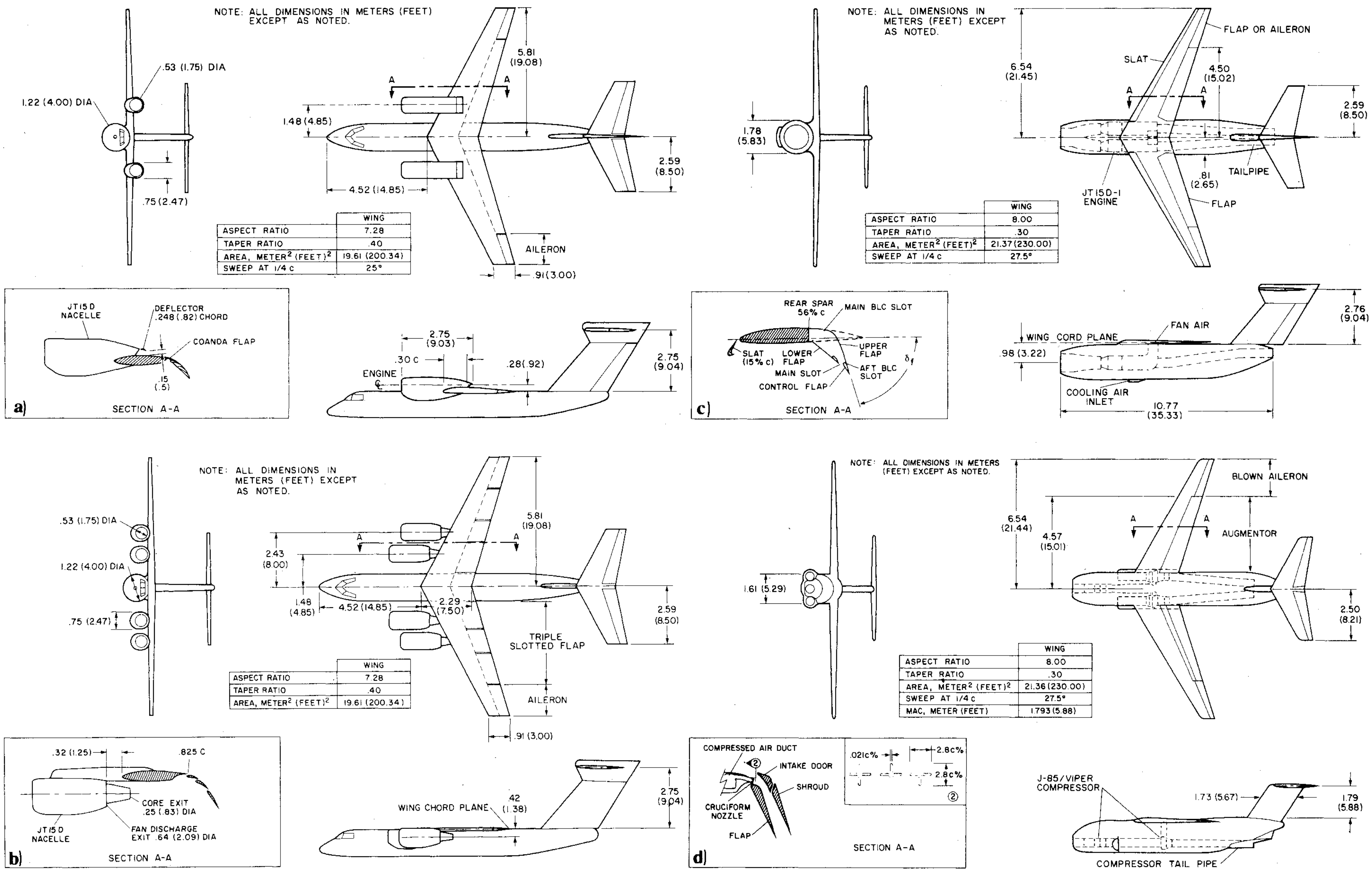
Fig. 1 UTW model installed in the wind tunnel.

Received October 17, 1974; presented as Paper 74-1094 at AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974; revision received December 18, 1974. The authors wish to acknowledge the contributions made in support of the NASA Ames, Air Force Flight Dynamics Laboratory and Lockheed-Georgia joint research by the staff and management of these organizations during the internally-blown jet flap program. The augmentor wing program was performed under a joint research program with NASA Ames, Canadian Department of National Defense, and DeHavilland Aircraft of Canada, Ltd. The authors wish to thank these organizations for their support.

Index categories: Aircraft Noise, Aerodynamics (including Sonic Booms).

*Aerospace Engineer, U.S. Army Air Mobility R&D Laboratory.

†Aerospace Engineer.



a)	WING
ASPECT RATIO	7.28
TAPER RATIO	.40
AREA, METER^2 (FEET)^2	19.61 (200.34)
SWEEP AT 1/4 c	25°

c)	WING
ASPECT RATIO	8.00
TAPER RATIO	.30
AREA, METER^2 (FEET)^2	21.37 (230.00)
SWEEP AT 1/4 c	27.5°

b)	WING
ASPECT RATIO	7.28
TAPER RATIO	.40
AREA, METER^2 (FEET)^2	19.61 (200.34)

d)	WING
ASPECT RATIO	8.00
TAPER RATIO	.30
AREA, METER^2 (FEET)^2	21.36 (230.00)
SWEEP AT 1/4 c	27.5°
MAC, METER (FEET)	1.793 (5.88)

Fig. 2 Geometric details of propulsive-life models: a) OTW; b) UTW, c) IBF; d) AW.

The models are representative of typical STOL transports with high wings and T-tails. The four models were similar in wing sweep, taper ratio, aspect ratio, and span. When mounted in the wind tunnel, the wing chord plane was approximately 6.1 m (20 ft) above the tunnel floor.

Over-The-Wing Externally-Blown Jet Flap (OTW)

The exhaust from two JT15D-1 turbofan engines was blown over the wing upper surface of the OTW model and deflected by a curved coanda surface at the wing trailing edge (Fig. 2a). The coanda surface extended from 11%—48% span. The JT15D-1 nacelles were equipped with rectangular exhaust nozzles whose aspect ratio was 5 and an exhaust deflector to induce flow turning over the small coanda radius. The engines had a bypass ratio of 3, a maximum fan pressure ratio of 1.5 and a maximum thrust of 8900 N (2000 lb).

Under-The-Wing Externally-Blown Jet Flap (UTW)

To induce high lift, the exhaust of four JT15D-1 turbofan engines was blown over the lower surface of a triple-slotted flap system of the UTW model (Fig. 2b). The nacelles were equipped with circular, concentric exhaust nozzles that had an increased fan-bypass exhaust area to properly simulate the ratio of exhaust diameter to flap chord. Each nacelle generated a maximum thrust of approximately 8900 N (2000 lb). The flap system extended over 75% of the wingspan and, when deflected, was 57% of the local wing chord.

Internally-Blown Jet Flap (IBF)

This configuration was a derivative of the basic jet flap and had the principle jet located at the trailing edge of a simple flap (Fig. 2c). The internal ducting was formed by a cavity between the lower flap surface, the wing's rear spar, and the upper flap surface. The blowing system comprises the main jet at the trailing edge and a boundary-layer control (BLC) slot at the flap knee. The model was equipped with separate blowing systems for each semispan. The compressed air to each semispan was the fan-bypass air of a JT15D-1 turbofan engine. The JT15D-1 hot primary air was ducted through tail pipes out the fuselage aft end. The jet flap extended to 70% of the wing semispan; the outer 30% semispan was a blown aileron that received 5% of the fan air. The ailerons were symmetrically dropped to 30°.

Augmentor Wing (AW)

The augmentor wing employs an ejector system that comprises a trailing-edge primary nozzle (through which high-pressure air is delivered), a lower flap, an upper shroud, and an intake door (Fig. 2d). Secondary air was entrained from the wing's upper surface, a slot between the intake door and shroud, and a lower slot between the wing's lower surface and flap. The augmentor extended over 70% of the wing semispan; the outer 30% was a blown aileron drooped to 30°. The compressed air for the augmentor and aileron was provided by a fuselage-mounted turbocompressor which comprised a J-85 turbojet that was pneumatically coupled to two modified Viper engines. The exhaust gas of the J-85 was split and ducted into the turbine section of the Vipers. The output of the Viper compressors was piped into the wing. The residual J-85 exhaust was ducted out the aft end of the fuselage. The turbocompressor provided compressed air at pressure ratios of 1.3 to 1.85.

Acoustic Data Acquisition and Reduction

Acoustic measurements were made using an array of eight microphones located under the left model wing tip. B&K 1.27-cm (1/2-in.) condenser microphones equipped with nose cones were mounted on 1.83-m (6-ft) stands. The microphone output was recorded on Ampex F1300A multichannel tape recorders. The recorded acoustic data was reduced to 1/3-octave band-frequency spectra by integration, for a period of at least 30 sec on a real-time analyzer.

An investigation of the acoustic environment in the wind-tunnel test section has shown it to be semireverberant. Several techniques have been developed which allow the prediction of free-field noise levels from wind-tunnel measurements. These techniques and comparison with flight data are reported.[7,8] The technique developed for large, distributed sources such as powered-lift models involves the comparison of wind-tunnel and outdoor-static test spectra for identical model configurations and microphone arrays. The reverberation corrections consist of the average difference between wind-tunnel and static test spectra for several power settings. Figure 3 shows typical reverberation corrections for the powered-lift models.

To evaluate the noise of only the powered-lift system, extraneous noise sources were removed from the acoustic spectra. For the OTW and UTW models, the removal of the JT15D fan noise from the high-frequency portion of the spectra was required. The fuselage exhaust tail pipes of the IBF and AW models created a low-frequency noise which was removed from their spectra. The powered-lift spectra in these regions,were estimated from small-scale model data. Both the IBF and AW models were equipped with inlet suppressors to eliminate noise emitted by their fuselage compressors.

Assuming appropriate thrust-to-weight ratios for each configuration, the acoustic spectra were then scaled to a 45,500 kg (100,000 lb) aircraft. The scaling was based on the ratio of full-scale to model scale mass flow rates. The takeoff and approach characteristics of each model are presented in Table 1. Using accepted procedures, the scaled spectra were projected to a 153 m (500 ft) radius in a plane 36° below the wing chord plane as illustrated in Fig. 4.

Results and Discussion

For powered-lift concepts, the dominant noise source is the acoustic dipole that is created by flow turbulence which interacts with a surface to produce pressure fluctuations that propagate at the speed of sound away from the surface. Theory has shown the dipole to be a more efficient acoustic generation mechanism than the quadrapole sources of simple jet-mixing noise and to be characterized by a sixth power variation in acoustic power with flow velocity. The exact flow mechanism by which the dipoles are created is not known, but it is believed to be some combination of: 1) edge noise caused by turbulent eddies as they pass the leading and trailing edges of the flap elements; 2) scrubbing noise generated in the turbulent boundary layer; and 3) in some cases, noise from separated flow on the flaps.

Comparison of Powered-Lift Configurations

The STOL aircraft powered-lift system will operate in either a takeoff mode with a high power setting and low flap deflection or an approach mode with a lower power setting and high flap deflection. The primary consequence on acoustics of these modes is the change affected by velocity differences due to power setting variations and a redirection due to flap deflection. This is true if the noise-generating flow mechanisms are the same for both modes. The perceived noise level (PNL) directivity for the takeoff and approach modes for the models scaled to a 45,500 kg (100,000 lb) aircraft are compared in Fig. 5. This is a comparison of the basic powered-lift system noise without benefit of acoustic treatment. For takeoff, the OTW, UTW, and IBF have generally the same directivity, with peak PNL of approximately 105 PNdb. The AW is much more directional, with a peak of 111 PNdb. For approach, the noise levels are lower, as would be expected from the reduced power levels. The AW is still the loudest, with a peak PNL of 107 PNdb, while the OTW is the quietest, with a peak level of 97 PNdb. In all cases, the levels

Table 1 Powered-lift propulsion characteristics

Powered-lift concept	Operation mode	δ_f, deg	V_{J_I} m/sec (fps)	Pressure ratio	Thrust/weight	Scale factor
OTW	Takeoff	30	241 (790)	...	0.6	4.2
	Approach	75	204 (670)	...	0.35	3.9
UTW	Takeoff	40	...	~1.5	0.6	3.5
	Approach	55	...	~1.3	0.35	3.1
IBF	Takeoff	30	227 (720)	...	0.4	4.0
	Approach	60	201 (660)	...	0.2	2.9
AW	Takeoff	30	335 (1100)	1.85	0.4	4.7
	Approach	70	296 (970)	1.64	0.2	3.8

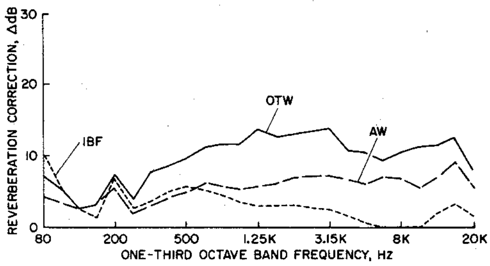


Fig. 3 Typical reverberation corrections for wind tunnel acoustic measurements.

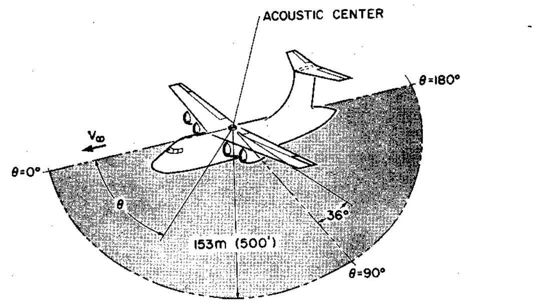


Fig. 4 Illustration of scaled acoustic data plane.

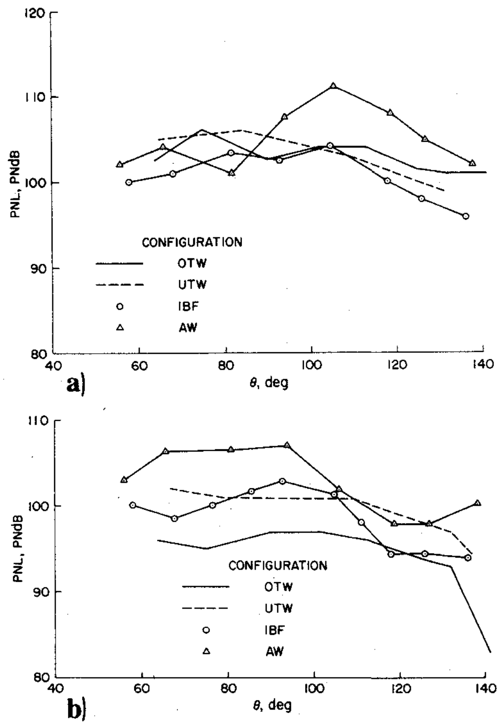


Fig. 5 Comparison of the perceived noise level directivity patterns of the powered-lift concepts: a) Takeoff configuration; b) Approach configuration.

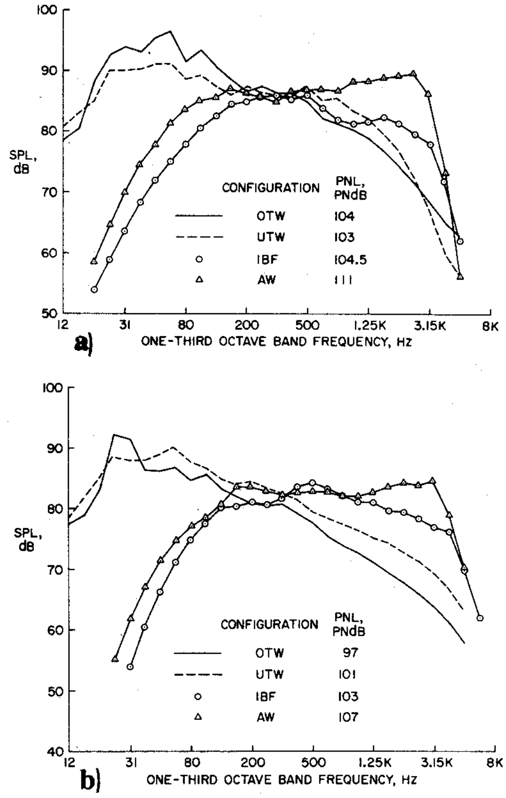


Fig. 6 Comparison of peak noise frequency spectra; a) Takeoff configurations; b) Approach configurations.

exceed the generally accepted noise goal of 95 PNdb at 153 m (500 ft).

To understand the directivity variation between concepts, an examination of their frequency spectra is required. The 1/3-octave band-frequency spectra for the peak levels of the scaled models is presented in Fig. 6. The OTW and UTW spectra have generally the same spectral content, which is dominated by low-frequency energy characteristic of the large exhaust nozzle dimension and low jet velocity. With their small characteristic jet height and higher velocities, the IBF and AW spectra are dominated by high-frequency noise. This is especially true of the AW, thus creating the high PNL shown for this configuration.

It must be remembered these results are for configurations which have not been acoustically treated. The same high-frequency sound which produces high PNL in the AW has shown itself to be amenable to absorption by acoustic lining. Research[9] has shown that noise levels below 95 PNdb can be achieved. A summary of these results is presented in Fig. 7. The low noise levels were obtained through a reduction of low-frequency noise and jet velocity with the corrugated lobe nozzles and attenuation of high-frequency sound with tuned linings inside the augmentor. With respect to the untreated augmentor blown by a slot nozzle, the lined augmentor blown

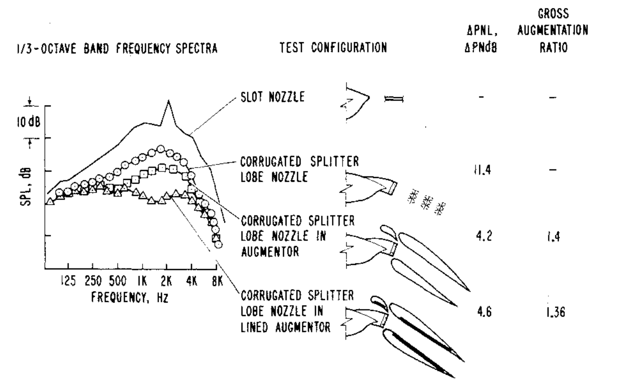


Fig. 7 Acoustic suppression of AW powered-lift noise for 91,000 kg (200,000 lb) aircraft and nozzle pressure ratio = 2.6.

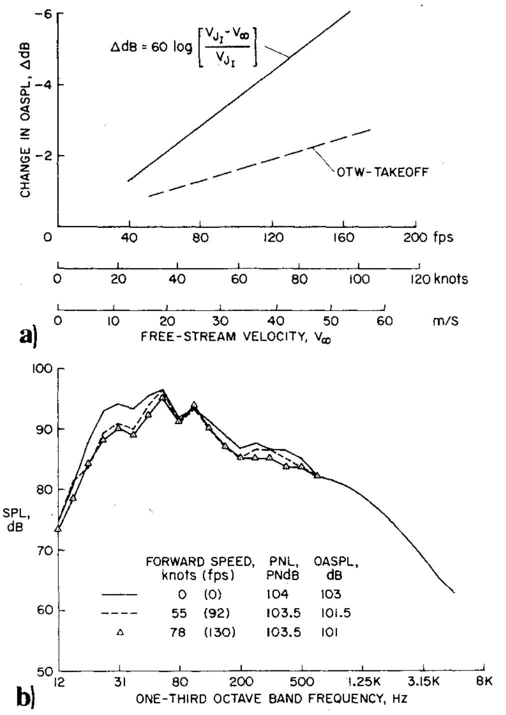


Fig. 8 Effect of foward speed on powered-lift noise: a) Variation in OASPL of OTW with forward speed; b) OTW configuration, takeoff, $\theta = 102°$.

by the corrugated nozzle improved the static augmentation ratio by 10%. This is opposite to what generally occurs with noise suppression.

The dominance of low-frequency sound in the OTW and UTW configurations, while not obvious in the PNL, will create difficulties unique to these configurations. Excessive passenger-cabin noise levels may result, because existing aircraft structures have little absorption capability at these low frequencies. This may also create acoustic fatigue problems in the aircraft structures, while propagating to the surrounding community with little or no atmospheric absorption. Devices such as porous leading and trailing edges, trailing-edge blowing, and multi-element nozzles are being investigated to reduce the low-frequency intensity. The limited data available show some acoustic benefit generally accompanied by a significant loss in aerodynamic performance and/or mechanical simplicity.[10] Much research is still required to define an acceptable solution.

Based on the acoustic results of this investigation of propulsive-lift systems without acoustic treatment, the OTW has the least objectionable community noise characteristics, because of the wing shielding of the high-frequency noise (assuming the powered-lift noise was the dominant aircraft acoustic source). The IBF, although it has higher approach noise levels, does not have to contend with the low-frequency noise of the OTW, and thus may be an alternative if the low frequence noise of the OTW cannot be reduced within acceptable performance levels. The AW is the only concept which has shown the potential for acoustically treating to acceptable levels without unacceptable performance penalties.

Flight Effects of Forward Speed and Angle of Attack

The primary reason for the investigation of these wind-tunnel models was to determine the effect of forward speed (V_∞) and angle of attack (α) on their acoustic characteristics. If the noise levels were a function of the relative velocity between the jet exhaust and freestream, as is the case with jet-mixing noise, the effect should be significant (Fig. 8a). This was found, however, not to be the case. Over the ranges of forward speed ($V_\infty = 0$ to 80 knots) and angle of attack ($\alpha = 0$ to 20°) for which acoustic measurements were made, their was no significant effect on the acoustics of either the IBF or AW. Forward speed did, however, reduce the low-frequency noise of the OTW and UTW without having an effect on PNL. The reduction was approximately 2 db for $V_\infty = 80$ knots (Fig. 8b).

The only effect of α was to increase the low-frequency noise of the UTW model by 2 db for an angle-of-attack change of 20°. In general, the effects of flight were smaller than would be expected from the relative velocity effect. Therefore, freestream velocity and angle of attack did not substantially alter the flow turbulence or its interaction with the surfaces.

Conclusions

The dominant acoustic mechanism of powered-lift noise is the acoustic dipole as exemplified by the sixth power variation of the noise with jet velocity. The spectral content of the noise can be related to the jet dimensions and velocity. The OTW and UTW are characterized by low-frequency noise, while the AW and IBF are high-frequency acoustic sources. The OTW concept has the lowest PNL because of the shielding afforded by the wing, but may have high cabin noise levels caused by the intense low-frequency sound. The AW had the highest PNL but can be acoustically treated. The noise levels of all the configurations without acoustic treatment are 10 to 15 PNdb higher than the noise goal of 95 PNdb.

The flight effects of forward speed and angle of attack were much smaller than would be expected from the relative velocity effect. V_∞ and α had no effect on the noise of the AW or IBF. Forward speed reduced the low-frequency noise of the UTW and OTW configurations by approximately 2 db.

References

[1] Dorsch, R. G., "Externally Blown Flap Noise Research," SAE Paper 740468, May 1974, Dallas, Texas.

[2] Dorsch, R. G., Goodykoontz, J. H., and Sargent, N. B., "Effect of Configuration Variation on Externally Blown Flap Noise," AIAA Paper 74-190, Washington, D. C., 1974.

[3] Aiken, T. N., Aoyagi, K., and Falarski, M. D., "Aerodynamic Characteristics of a Large-Scale Model with a Swept Wing and a Jet Flap with Expandable Duct," TM X-62, 281, Dec. 1973, NASA.

[4] Aoyagi, K., Falarski, M. D., and Koenig, D. G., "Wind-Tunnel Investigation of a Large-Scale Upper-Surface Blown-Flap Transport Having Two Engines," TM X-62, 296, 1973, NASA.

[5] Aoyagi, K., Falarski, M. D., and Koenig, D. G., "Wind-Tunnel Investigation of a Large-Scale 25° Swept-Wing Jet Transport Model with an External Blowing Triple-Slotted Flap," TM X-62, 197, Nov. 1973, NASA.

[6] Falarski, M. D. and Koenig, D. G., "Longitudinal and Lateral Stability and Control Characteristics of a Large-Scale Model with a Swept Wing and Augmented Jet Flap," TM X-62,145, April 1972, NASA.

[7] Atencio, S. and Soderman, P. T., "Comparison of Aircraft Noise Characteristics Measured in Flight Tests and in the NASA Ames 40- by 80-Foot Wind Tunnel," AIAA *Progress in Astronautics and Aeronautics*, to be published.

[8] Falarski, M. D., Koenig, D. G., and Soderman, P. T., "Aspects of Investigating STOL Noise Using Large-Scale Wind Tunnel Models," TM X-62,164, June 1972, NASA.

[9] Campbell, J. M., Harkonen, D. L., Lawrence, R. L., and O'Keefe, J. V., "Noise Suppression of Improved Augmentators for Jet STOL Aircraft," CR-114, 534, Jan. 1973, NASA.

[10] Hayden, R. E., "Fundamental Aspects of Noise Reduction from Powered-Lift Devices," SAE Paper 730376, April 1973, Miami, Florida.