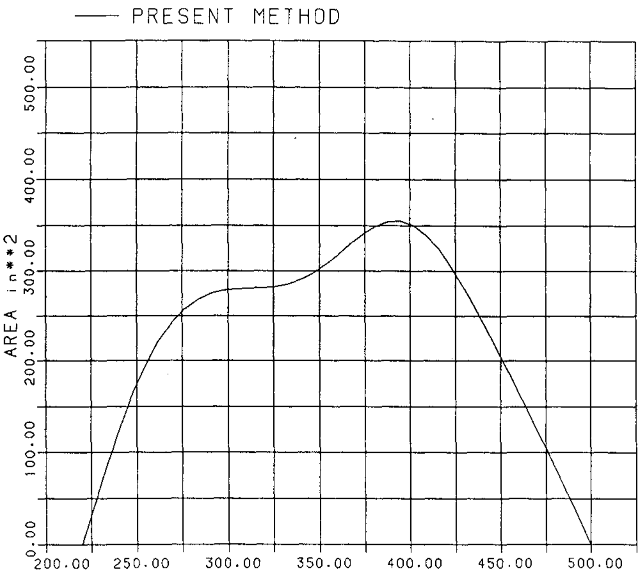

Fig. 3 Designed conformal tank area distribution.

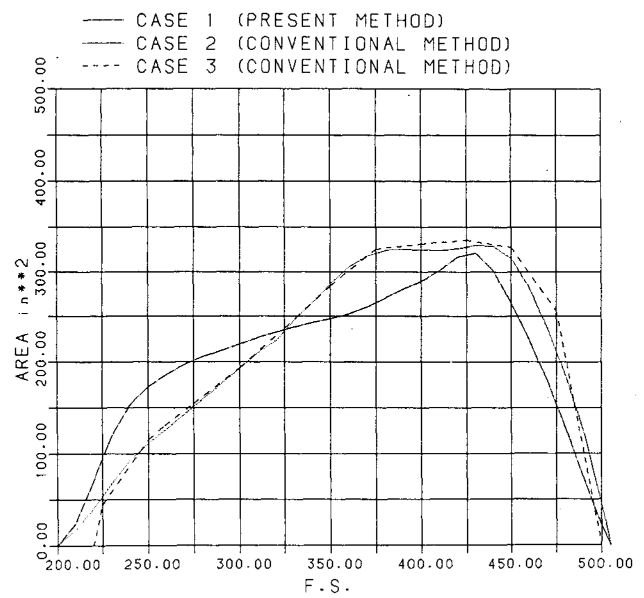

Fig. 4 Comparison of conformal tank area distributions designed by conventional method and present method.

Table 1 Comparison of drag increments for cases 1, 2, and 3. (Unit: counts)

Mach number	Design	Off-1	Off-2
Case 1	12.0	14.0	16.0
Case 2	19.0	19.0	20.0
Case 3	27.0	28.0	27.0

slightly modified by the lofting people to meet other design requirements such as structural constraints and subsystem arrangements. The modified area distribution is designated as case 1 in Fig. 4. Two other designs designated as cases 2 and 3 were obtained by modifying the results from Sheppard's design procedure based on designer's experiences.

All of these three cases were tested in the 4 × 4 ft high-speed wind tunnel (HSWT) of ARL at design Mach number and two off-design Mach numbers. The incremental drag coefficients obtained from the test are presented in Table 1. The wind tunnel data show that case 1 gives the lowest drag increment throughout the Mach numbers of interest. Note also, that case 1 gives least drag increment at design Mach number.

Conclusion

A computer program is developed for the design of optimum aircraft area distribution for minimum supersonic wave drag with physical constraints. This program can outperform the Harris code by its fully automated design process and its capability of dealing many physical constraints and balanced consideration of Mach numbers of interest. Wind tunnel test results of a conformal tank design shows that this method not only gives the lowest wave drag throughout the Mach numbers of interest, but also meets the objective of least drag increment at design Mach number.

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Suppression of Fatigue-Inducing Cavity Acoustic Modes in Turbofan Engines

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Introduction

MODERN turbofan engines use ducting systems to transport freestream air, bypass fan-air, and engine core primary air to pumps, generators, and heat exchangers. Typical ducting systems have upstream openings exposed to a flowing air field and are regulated by downstream valves (Fig. 1). Such ducting systems are cavities having acoustic modes that are often excited to high sound pressure levels (SPL) by the cavity shear layer when the downstream valve is closed. This can induce dynamic loads capable of causing fatigue failures in the ducting system and neighboring structures. Weight, cost, and design restrictions often force one to extend the fatigue life of such ducting systems by reducing the excitation of its acoustic modes rather than by raising its load-bearing capability. Three concepts of reducing shear-layer excitation of a cavity's acoustic mode are evaluated in this study using a full-scale turbofan engine test.

Shear-Layer Excitation of Cavity Acoustic Modes

When fluid passes over an open cavity, a shear layer of vortices may be generated at its upstream edge that roll across

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its opening (Fig. 1). The collision of a vortex on the downstream cavity opening edge can generate an acoustic pressure pulse that travels back to the upstream edge. This can create a feedback mechanism that organizes and triggers the formation of new vortices.[1-3] The frequency at which vortex collisions occur is called the primary shear-layer frequency, and is dependent upon the cavity impingement length. Depending on the cavity geometry and flow conditions, subharmonic frequencies may also be generated at factors of 0.2, 0.4, 0.5, 0.6, and 0.8 times the primary shear-layer frequency.[4] When the shear-layer primary frequency or a subharmonic is coincident with a cavity acoustic frequency, resonance is likely to occur.

There are several methods of reducing shear-layer excitation of a cavity's acoustic mode. Most involve changing the cavity's acoustic characteristics, changing its shear-layer frequencies, or by disrupting the shear-layer feedback system. A cavity's acoustic characteristics can be changed by connecting a side-branch Helmholtz resonator to it. A cavity's shear-layer frequencies can be increased by reducing the cavity impingement length by installing vanes in the cavity's mouth. The cavity's shear-layer feedback system can be disrupted by drawing the shear layer into the cavity via minimal continuous flow through the cavity.

Turbofan Test Description

Full-scale turbofan engine tests were performed on a ducting system experiencing fatigue failures due to shear-layer excitation of its acoustic modes. Dynamic pressure transducers were installed within the ducting system, and accelerometers and strain gauges were mounted on various ducting system components to measure dynamic excitation and response levels (Fig. 1). Each test sequence consisted of running the engine from ground idle to maximum power with the ducting system downstream valve open, and then closed. Steady-state runs were performed at engine power settings that induced high acoustic and/or structural response.

Baseline Ducting System

Turbofan engine runs were performed on the baseline ducting system to quantify the severity of its acoustic resonance. Dynamic pressure transducer data obtained with the valve closed show that the overall SPL in the ducting system exceeded 181 dB for a nominal local air velocity above 600 ft/s (Fig. 2). The ducting system's structural response was dominated by a 60 Hz component that was virtually unaffected by engine speed. At maximum engine power, the majority of the acoustic energy (181 dB) was concentrated at 60 Hz. When the valve was opened, the maximum overall SPL was attenuated to about 163 dB. At maximum engine power, the cavity SPL at 60 Hz was reduced to about 161 dB. Similarly, the ducting system's structural response was no longer dominated by a 60 Hz component. Such behavior is characteristic of structures excited by cavity acoustic modes.

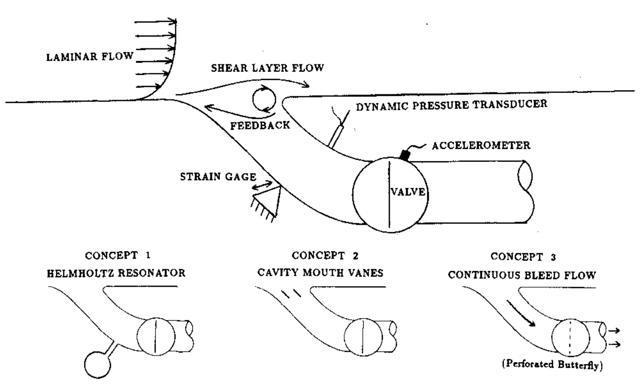

Fig. 1 Turbofan ducting system and concepts to suppress cavity acoustic modes.

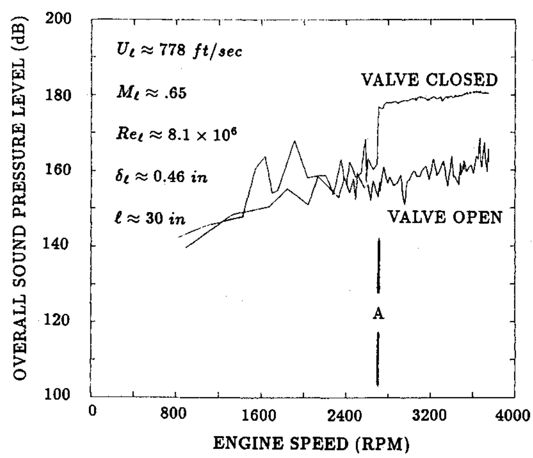

Fig. 2 Cavity overall SPL vs engine speed.

The ducting system's acoustic natural frequencies were calculated using a closed-form solution for the acoustic natural frequencies of a long slender tube.[5] Using a bounded range of air temperatures and duct lengths, the first acoustic mode frequency range of the ducting system was estimated to be 55–75 Hz. The duct's primary acoustic mode frequency (60 Hz) measured during baseline system testing is consistent with analytic predictions.

The cavity shear-layer frequencies were calculated at maximum engine power. Using Sarohia's data[2] with bounded mean-stream velocities and cavity impingement lengths, the primary shear-layer frequency range was estimated to be 210–420 Hz. Assuming the presence of a subharmonic frequency at 0.2 times the fundamental shear-layer frequency, the predicted subharmonic frequency range (42–84 Hz) is nearly centered on the baseline configuration's measured 60 Hz acoustic mode.

Helmholtz Resonator

A Helmholtz resonator was designed with the largest volume that could reasonably fit into the available engine compartment space (Fig. 1). Knowing the acoustic frequency to be absorbed (60 Hz), and the tube length required to connect the Helmholtz resonator to the ducting system, a tube diameter was calculated using an idealized closed form solution.[5] Once built, its acoustic frequency must be tuned to account for inaccuracies in the Helmholtz resonator's dimensions and its deviations from the idealized acoustic model used for sizing. This was done by exciting the resonator's primary acoustic mode with a hammer impact, and adjusting its duct-connecting tube length.

With the Helmholtz resonator installed and the valve closed, dynamic pressure transducer data show the SPL at 60 Hz in the ducting system to be reduced from 181–163 dB. The maximum SPL in the Helmholtz resonator was 167 dB at 60 Hz. Ducting system strain and acceleration levels were also reduced by nearly one order of magnitude. The length of the Helmholtz resonator tube was extended by about 7% to determine the resonator's attenuation sensitivity to inaccuracies of tube installation. Dynamic pressure transducer data show the Helmholtz resonator to reduce further the SPL in the ducting system (161 dB at 60 Hz).

Cavity Mouth Vanes

The primary shear-layer frequency and its subharmonics are inversely proportional to the cavity impingement length. If the cavity impingement length is sufficiently reduced, the shear-layer frequencies may be increased above the cavity acoustic frequency such that the acoustic resonant condition becomes detuned. Installing vanes in the cavity mouth can reduce the cavity impingement length effectively. If the vanes are properly positioned relative to the shear layer, extend deep enough into the cavity, and are stiff enough, they effectively create subcavity openings. Each subcavity opening

Table 1 Measured acoustic mode suppressions in a turbofan engine

Configuration	Duct SPL, 60 Hz
Baseline[a]	181 dB
Baseline[b]	161 dB
Helmholtz resonator[a]	163 dB
Helm. res. (tube + 7%)[a]	161 dB
Vanes[a]	162 dB
Vanes[b]	158 dB
Bleed air (4.5% area)[a]	174 dB
Bleed air (5.5% area)[a]	169 dB

[a]Valve closed.
[b]Valve open.

may be treated as single cavity openings having its own associated impingement length.

Two equally spaced vanes were installed in the baseline configuration ducting system opening to nominally triple the ducting system shear-layer frequency (Fig. 1). Shear-layer frequency calculations predict an increase in the primary shear-layer frequency range to 630–1260 Hz. This, in turn, increased the minimum subharmonic shear-layer frequency range to 126–252 Hz. These predicted subcavity opening shear-layer frequency ranges are well outside of the cavity primary acoustic mode frequency range of 55–75 Hz.

With vanes installed in the mouth of the ducting system, and its valve closed, the SPL in the ducting system at 60 Hz was reduced from 181–161.5 dB. With the valve open, the ducting system SPL at 60 Hz was further reduced to 158 dB, and no new acoustic resonances were observed. Similarly, ducting system strain and acceleration levels were reduced by an order of magnitude.

Continuous Bleed Flow

The shear layer can be drawn into the cavity by continually bleeding fluid through the cavity (Fig. 1). Only the minimum required amount of fluid should be allowed through the cavity to minimize the effects on system performance. Minimal flow through the duct may be achieved by drilling holes in the downstream valve's butterfly, or in the cavity wall. (Note that the effectiveness of these holes to draw the shear layer into the cavity is dependent upon their location within the cavity, and their geometry.)

Calculations to determine the minimum flow required to draw the shear layer into the duct are possible. The required ducting system pressure and flow data were not available for this investigation. The minimum flow required to suppress the acoustic mode was established by sequentially increasing the area of a bleed hole in the duct.

Engine test results show that no significant reduction of the ducting system acoustic mode SPL was realized until a hole area equal to 4.5% of the duct area was achieved. The ducting system SPL at 60 Hz was reduced from 181–174 dB for this bleed hole area. When the bleed hole was increased to 5.5%, the SPL was further reduced to 169 dB at 60 Hz. All strain gauges and accelerometers responded consistent with the dynamic pressure transducers.

Conclusions

Full-scale engine test results show that installing a Helmholtz resonator side branch in the cavity, installing vanes in the cavity mouth, and drawing the shear layer into the cavity via continuous minimum bleed flow through the duct, will significantly reduce the SPL of cavity acoustic modes resonantly excited by its shear layer. Table 1 lists full-scale turbofan engine test results that quantify the effectiveness of each method. These results demonstrate that there are several options for extending the structural fatigue life of cavity systems in lieu of potentially expensive structural redesign efforts aimed at increasing the load-bearing capacity of the cavity and its neighboring structures.

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Pitch Rate/Sideslip Effects on Leading-Edge Extension Vortices of an F/A-18 Aircraft Model

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Introduction

THE continuing demands for enhanced maneuverability of present and future fighter aircraft require a better understanding of the vortical flows generated during flight at high angles of attack (AOA). The vortex-bursting phenomenon is of particular importance and has been investigated extensively on stationary wings,[1] but experimental data for wings in unsteady motion are still rather scarce.[2,3] Data for complete aircraft configurations are even scarcer.[4,5] The investigation reported here is a continuation of work done by Hebbar, et al.[6] and focuses on the effect of pitch rate on the development and bursting of vortices generated from the leading-edge extensions (LEXs) of an F/A-18 aircraft model in the 0–50 deg AOA range, at sideslip angles of 0, 5, 10, and 20 deg. Additional details of the experimental investigations appear in Refs. 7 and 8.

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