Compact Combustion Noise Suppressor

R. P. Gerend* and B. N. Shivashankara†
Boeing Commercial Airplane Company, Seattle, Wash.

A concept for reducing combustion noise generated in gas turbine engines is presented. The suppressor concept involves perforating the engine casing either over or immediately downstream of the combustor (or both locations) and enclosing this area with resonator cavities. Experimental results were obtained for a number of flow and geometric variations using a 20-cm (8-in.)-diam single can-type research combustor. Several configurations, including the 10-cm (4-in.)-deep suppressor, gave 5- to 10-dB noise reduction in the 100- to 1000-Hz frequency range when located immediately downstream of the combustor. The test results indicate that it may be possible to reduce low-frequency combustion noise by liners considerably less deep than the conventional theories would predict. Applicability of the test results to full-scale engines is reviewed briefly.

Introduction

ADVANCES in gas turbine engine technology have resulted in a family of high-bypass-ratio engines that have reduced jet noise levels greatly. Consequently, other components, such as the low-frequency core engine noise, are becoming more important. Recent Boeing tests on a high-bypass-ratio engine have shown that for some power settings there is a good correlation between the combustor and primary tail-pipe pressure fluctuations. It is, therefore, apparent that the combustion noise could be a major source of aircraft engine noise for future high-bypass-ratio engines with reduced turbomachinery and jet noise components.

Extensive combustion noise research work has been done in the past few years following two distinct approaches. On one hand, there have been both experimental and analytical efforts to understand the noise generation by burners. Noise from various combustion sources, ranging from simple laboratory-type burners[1,2] to full-scale engine combustors,[3-5] has been measured. The scaling behaviors of the radiated sound power, spectral content, and directionality have been deduced from these experiments. On the other hand, data from tests on full-scale engines have been employed to develop empirical prediction equations[4-7] for the core engine noise. Through these research efforts, substantial understanding of the combustion noise generation and radiation mechanisms has been achieved. However, no systematic efforts to reduce combustion noise in realistic engine configurations have been made yet.

An exploratory attempt to suppress combustion noise from an annular combustor was reported by Kazin and Emmerling,[5] who tested a 30.48-cm-deep liner about 61 cm long around the duct downstream of an annular combustor. They found that such a suppressor would reduce combustion noise by about 10 dB in the 100- to 1000-Hz frequency range. Similar core noise reductions have been obtained by large exhaust duct mufflers by Gerend et al.[6] and Woodward and Minner.[8]

In this paper, a concept to reduce combustion noise close to the combustor is described. The concept required perforating the combustor outer wall and covering it with a compartmented cavity. The combination of cavity volume and perforated combustor wall can be designed to form an acoustically tuned liner. The motivation for the suppressor concept stems from the fact that, in some modern high-bypass-ratio engines, there may be room for such a suppressor between the combustor outer walls and the fan duct.

Although the concept could be applied to any combustor type (can, can-annular, or annular), a can-type laboratory test combustor was chosen to evaluate the concept. This can-combustor was of a simple design, having an appreciably higher pressure drop than full-scale engine combustors. However, for the purpose of providing a stable noise source for suppressor concept evaluation, it was considered satisfactory.

Experimental Details

Apparatus

The experimental setup is shown in Fig. 1. A can-type combustor was placed inside a 20.3-cm (8-in.)-diam flow duct. The flow duct was terminated by a round convergent nozzle [12.7-cm (5-in.) diam] outside the laboratory. Air entering the test section was metered using an ASME flow nozzle, and the velocity and temperature profiles of air upstream of the combustor were measured by a pitot tube/thermocouple rake at station 1. The fuel (JP4) for the combustor was metered using a turbine flow meter and sprayed using a conical spray nozzle at the centerline of the combustor. The flow properties of the combustion products were measured by a stationary pitot tube/thermocouple rake at station 2. Using wall pressure taps, the static pressures at both stations 1 and 2 also were measured. The flow rate of air through the burner ($\dot{m}_a$) was varied between 0.68 to 1.36 kg/sec (1.5 to 3.0 lb/sec). The burner exit temperature (T_2) was varied from ambient to 1088°K (1500°F). The nozzle pressure ratios for these flow conditions were in the range of 1.06 to 1.3.

Acoustic Instrumentation

The noise radiated from the exit nozzle was measured by an array of ½ in. condenser microphones, mounted at 10° intervals, between 70° and 160° (re: inlet axis), on a 7.6-m (25-ft)-radius vertical boom, as shown in Fig. 1. The microphone signals were recorded on magnetic tape during the experiment. The acoustic data were reduced to ⅓-octave band spectra and overall sound pressure levels (OASPL). A few constant-bandwidth narrow-band spectra also were obtained. The radiated sound powers were calculated from measured sound pressure levels.

The most important experimental result is the noise attenuation due to the suppressor. This was calculated as the measured noise difference between the hard-wall and soft-wall cases for OASPL (Σ50 to 10,000 Hz), ⅓-octave band SPL, and power level. The reduction in radiated sound power is called the power insertion loss. The power insertion loss can be considered to be a true indicator of the suppressor performance.

Presented as Paper 76-42 at the AIAA 14th Aerospace Sciences Meeting, Washington, D. C., Jan. 26-28, 1976; submitted Feb. 20, 1976; revision received Aug. 4, 1976.

Index categories: Aircraft Noise, Aerodynamics (including Sonic Boom); Aircraft Noise, Powerplant.

*Chief of Noise Research.

†Senior Engineer.

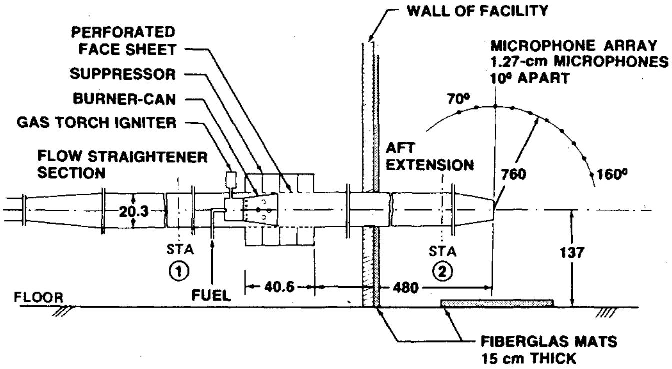


Fig. 1 Experimental setup (all linear dimensions in centimeters).

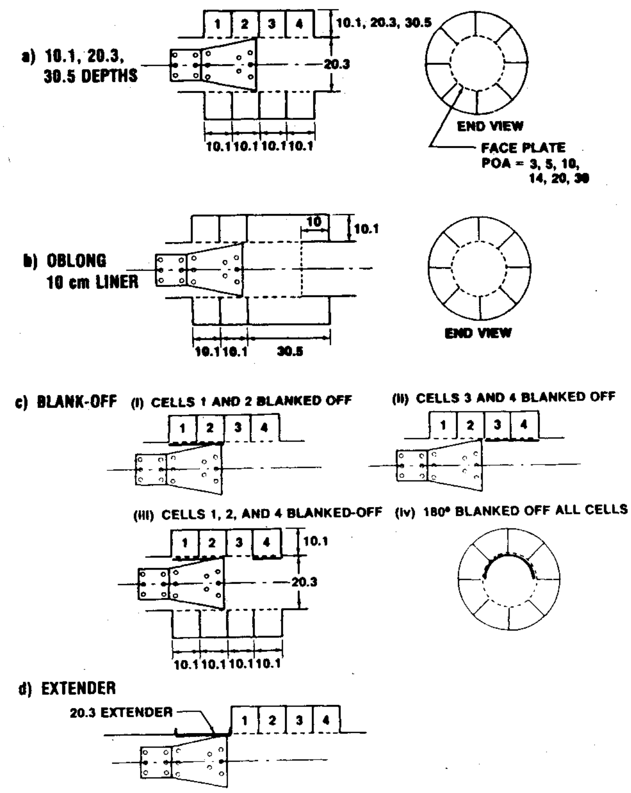


Fig. 2 Configurations (all linear dimensions in centimeters).

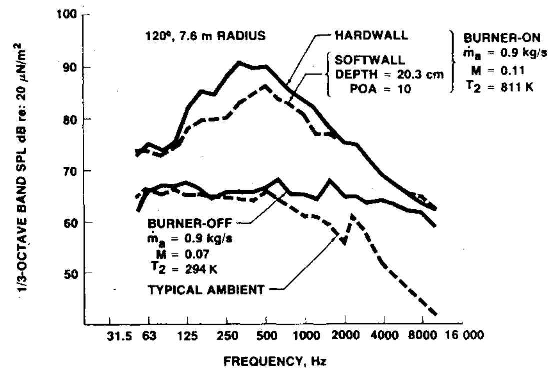


Fig. 3 Typical combustion noise and ambient noise.

Suppressor

The addition of the suppressor around the combustor was accomplished by replacing the duct wall in the vicinity of the combustor with a perforated duct. This perforated duct was surrounded by an annular cavity. The annular cavity was broken down further into smaller volumes by longitudinal spacers 10.1 cm (4 in.) apart and radial baffles at 45° intervals. Such compartmentation is necessary to avoid wave propagation in the cavity itself. The suppressor was designed to have one-half of its effective area over the combustor, with the remaining one-half immediately downstream of the burner-can, as shown in Fig. 1.

Preliminary calculations showed that a tuning frequency of 250 Hz‡ would be achieved by using a 30-cm (12-in.)-deep liner with a 7% open face plate. To determine if appreciable noise reduction could be obtained using shallower suppressors, liners of 20.3-cm (8-in.) and 10.1-cm (4-in.) depth were tested, along with the 30.5-cm (12-in.)-deep liner. It will be seen later that the smallest depth tested was quite efficient in attenuating the low-frequency noise. Although the original intent was to test only 3, 5, and 10% open areas, initial tests showed that the attenuation increased with percent of open area. Thus additional open areas of 14, 20, and 30% were added to the test program.

Several configurations that were tested are shown in Fig. 2. To get baseline data, a hard-wall facing was used. The combustor also was operated with no facing plate at all [percent of open area (POA) = 100]. For some tests, portions of the perforated face plate were covered. These tests were designed to determine the most effective location for the suppressor and also to determine the relation between the attentuation obtained and the liner exposed area. Effects on the suppression characteristics using 1) fiberglass bulk absorber, and 2) "exponential horns" also were examined.

Results

Combustor Noise and Ambient Noise

Typical combustion noise far-field measured spectra, with and without suppressor, are shown in Fig. 3. It can be seen that the unsuppressed noise output spectrum with the burner on is typical of combustion noise and has a broadband maximum in the 250-to 500-Hz frequency range. The burner-off noise levels at equivalent flow conditions are appreciably lower. The ambient noise levels are acceptable for burner-on noise measurements.

Effect of Suppressor Location and Exposed Area

Earlier in this paper, it is noted that the suppressor was designed to have one-half of its liner area over the combustor itself, with the other half immediately downstream of the combustor (see Fig. 2). Since in many high-bypass-ratio engine nacelles there may be room for a suppressor around the combustor itself, but virtually no room downstream of the combustor, it was of interest to determine if suppression were possible by perforating only the combustor outer walls and enclosing this section with a compartmented cavity. The configurations shown in Fig. 2c were tested for this purpose. The results of these tests are presented in Fig. 4, where it is seen that almost all noise reduction is due to the portion of the suppressor downstream of the burner-can.

Poor noise transmission across the burner-can walls is assumed to be the reason why the portion of the suppressor over the burner-can is ineffective. Noise due to the combustion process is generated within the burner-can. The suppressor over the combustor can provide attenuation only if the generated noise can pass through the burner-can and reach the suppressor. The burner-can appears to be a poor transmitter of noise for two reasons. First, only a small percent (≈3.3%) of its surface is open. Second, these openings are designed to bring air into the can for combustion, dilution, and cooling. The air flow§ through these holes reduces the noise transmission out of the burner-can. The net result is that, for noise transmission, the surface of the burner-can appears to behave like a hard wall. It may be entirely possible,

‡Peak noise for this combustor occurs around this frequency.

§Mean velocity through holes is approximately 76 m/sec.

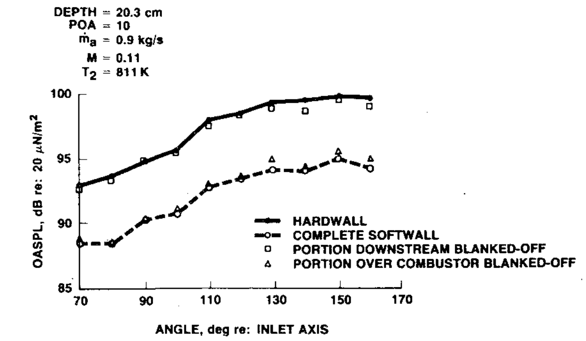


Fig. 4 Effect of suppressor location.

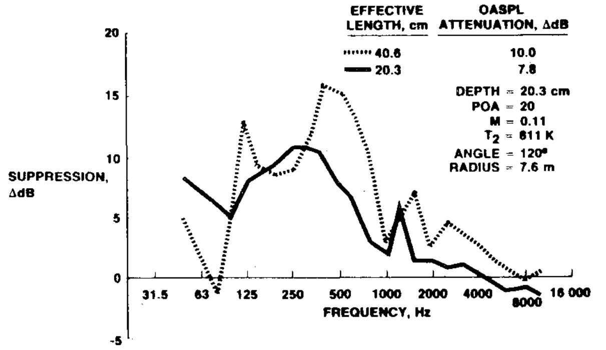


Fig. 5 Effect of increasing suppressor effective length.

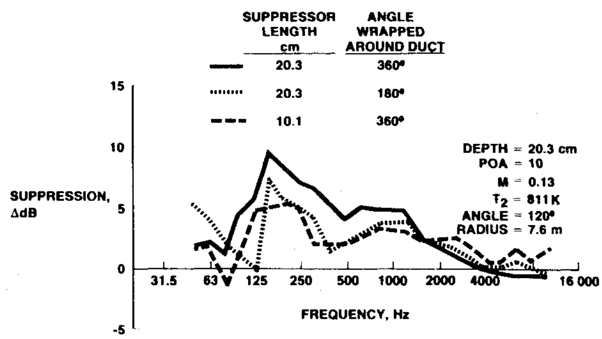


Fig. 6 Effect of reducing liner exposed area downstream of the burner can.

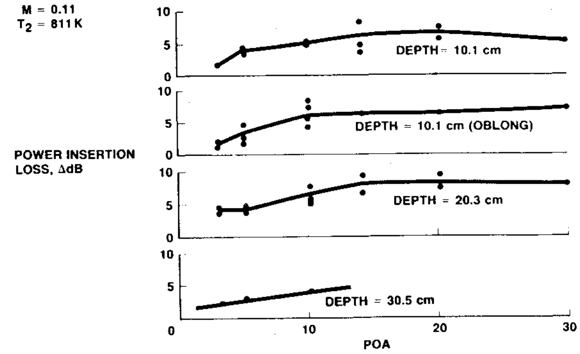


Fig. 7 Power insertion loss as a function of liner depth and POA.

however, to design an effective "over the combustor" suppressor if noise transmission across the burner-can could be improved while still retaining acceptable combustor performance and structural characteristics.

In another test an extender was used (see Fig. 2d) to locate the entire 41-cm length of the liner downstream of the burner-can. A substantial increase in noise suppression was obtained, as shown in Fig. 5. It is important to note that, with the increased suppressor length, the attenuation spectra also change. Surprisingly, however all POA's tested, 10, 14, and 20, gave identical attenuation spectra within experimental errors.

The effect of reducing the suppressor exposed area is shown in Fig. 6. The configurations for Fig. 6 are shown in Fig. 2c (i, iii, and iv). It can be seen in Fig. 6, that, when the effective area is reduced by one-half, an appreciable loss in attenuation results. In Fig. 2c (iii), the liner is symmetric about the duct centerline, whereas in Fig. 2c (iv), all of the liner area is on the top 180° of the duct surface. However, the exposed liner areas are the same for these two configurations. Both configurations were found to have similar attentuations, which gives the interesting result that symmetry of liner location was relatively unimportant for this particular case.

A comment regarding the effective suppressor length to be associated with the various test results is in order. Since it has been shown previously that only the downstream half of the suppressor is effective in reducing combustor exhaust noise, all of the attenuation data presented in this paper should be considered as being produced by a 20.3-cm (8-in.)-long and not a 40.6-cm (16-in.)-long liner. The few exceptions that exist are identified as such.

Directionality

The directionality of noise due to the combustor in the far-field, for both hard wall and suppressor cases, also can be seen in Fig. 4. It can be seen that the attenuation in OASPL is independent of the angular location. Furthermore the reduction in ⅓-octave band SPL at various ⅓-octave band center frequencies was examined. Again, the attentuation was found to be independent of the angular location. Based upon this finding, the 120° far-field microphone data were used as the basis in analyzing most of the test results.

Effects of Liner Depth and Percent Open Area

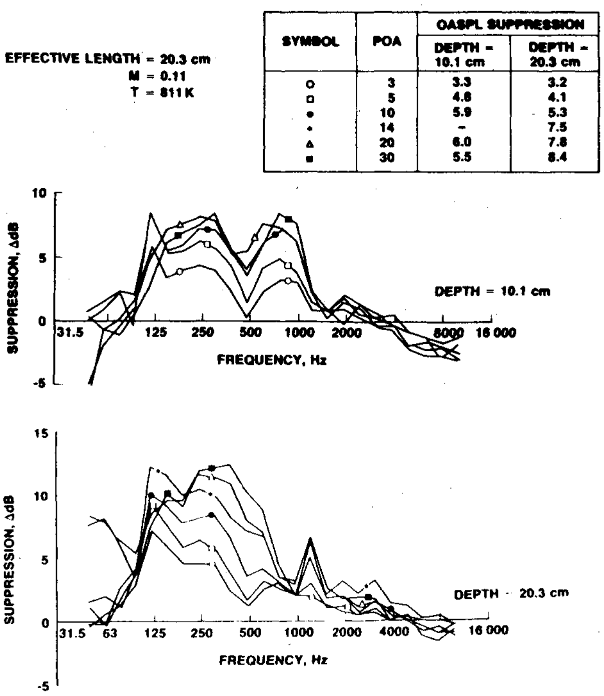
The power insertion loss for various liner depths and percent open areas is presented in Fig. 7. Contrary to the usual findings that deep suppressors of conventional design are needed for low-frequency application, it was found that a liner as small as 10 cm (4 in.) deep by 20.3 cm (8 in.) long wrapped around a 20.3-cm (8-in.)-diam duct was quite effective. Also, tests on a 30.5-cm (12.-in.)-deep liner showed that it was inferior to other shallower liners. Thus a very limited number of tests were conducted on the 30.5-cm liner.

Some indications regarding data scatter also can be obtained in Fig. 7. Although the data scatter is somewhat high (± 2.5 dB), it is within reasonable limits to enable the determination of the suppressor characteristics. Additional discussion regarding data repeatabilitiy is presented later in the paper.

Effects of POA on suppression at various frequencies are shown in Fig. 8 for 10.1-cm (4-in.) and 20.3-cm (8-in.)-deep liners. It can be seen that the attentuation increases with an increase in POA up to about 14 to 20 POA. Furthermore, the suppression is fairly broadband and extends over the entire 100- to 1000-Hz frequency range. This is a strong point in the favor of the suppressor, since it can be seen that the suppressor will not get "out of tune" if the source frequency distribution changes over a reasonable range of values.

Effect of Flow Conditions and Cavity Temperature

Over the range of flow conditions tested, the suppressor attentuation was not very sensitive to flow temperature and Mach number. The combustor discharge temperature was varied from 533° to 1080°K, and the flow Mach numbers ranged from 0.08 to 0.16. Furthermore, the temperatures within the suppressor cavities were found to vary from ambient to 478°K, depending upon the test duration. The suppressor performance was insensitive to these cavity temperature variations.



SYMBOL	POA	OASPL SUPPRESSION DEPTH = 10.1 cm	DEPTH = 20.3 cm
○	3	3.3	3.2
□	5	4.8	4.1
●	10	5.9	5.3
◆	14	-	7.5
▲	20	6.0	7.8
■	30	5.5	8.4

Fig. 8 Effects of liner depth and percent open area.

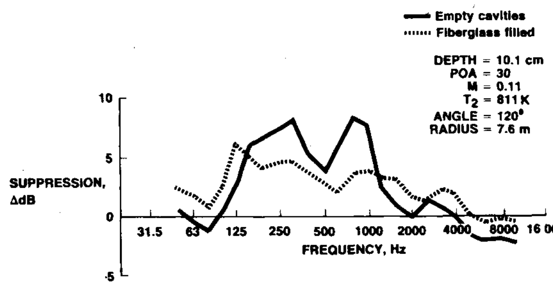


Fig. 9 Effect of fiberglass bulk absorber filling.

Effect of Fiberglass Bulk Absorber

In one test series, the cavities of the 10.1-cm-deep suppressor were filled with fiberglass (density: 181 kg/m^3; temperature rating: 920°K). Empty cavities were found to be more efficient than fiberglass-filled cavities (see Fig. 9), a result that cannot be generalized, since only one type of fiberglass was tested. Furthermore, the suppression of fiberglass-filled cavities was independent of POA for all POA's greater than 10, since fiberglass determines the liner resistance in this case. At the conclusion of a 20-min-long test, there was no deterioration of the fiberglass upon visual examination.

Effect of "Horns"

The liner, which is nothing but an empty volume in communication with the main duct through a perforated sheet, can be looked upon as a Helmholtz or a side-branch resonator. A simple Helmholtz resonator is a closed cavity that is connected to the main duct by a tube (or an aperture). This tube commonly is known as the "neck" of the Helmholtz resonator. The tuning frequency of the resonator is dependent upon the effective length and area of cross section of the neck. By increasing the effective length of the neck, it is possible to lower the tuning frequency.[9,10] To determine if the tuning frequency of the 10.1-cm (4-in.)-deep liner could be lowered, the configuration shown in Fig. 10 was tested. The suppression obtained with horns, as compared with that for a conventional liner, is shown in Fig. 10. It can be seen that some lowering of tuning frequency, as well as an improvement in suppression, is obtained. No conclusions regarding the superiority of the horn-type suppressors can be drawn from this test, since only one particular design was tested. The results do, however, suggest further testing of horn-type suppressors.

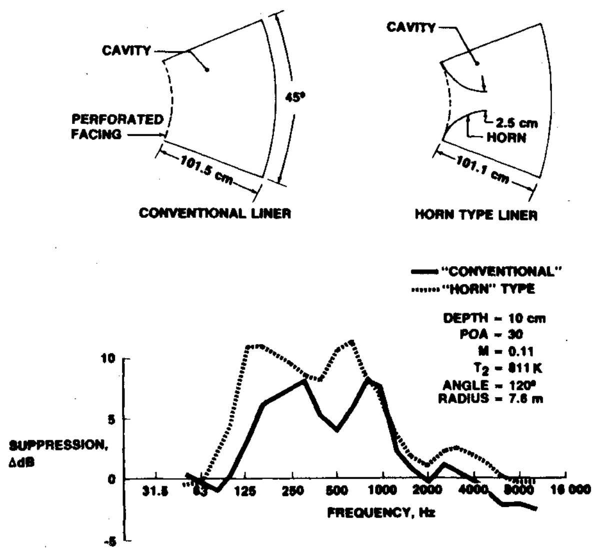


Fig. 10 Effect of "horns" on suppression.

Repeatability

The burner system was found to have a reasonably good repeatability if the hardware was not disturbed except for changing the percent open area. A comparison of spectra taken without any model change showed a repeatability within ± 2 dB on the ⅓-octave band spectra. However, with a change in the model to vary the cavity depth, the burner would randomly develop strong resonances at 125 Hz. Thus the burner operation itself appears to be extremely sensitive to minor dislocations in the burner-can arrangement. For this reason, baseline data were recorded every time was a model change, and only spectra without a model change were compared in almost all suppression calculations. With this precaution taken, it is believed that the suppressions deduced from the experimental data can be considered accurate within about ± 2.5 dB.

Discussion

The combustion noise suppressor tested in this program appears, at first sight, to be nothing but a classical reactive-resistive liner. This is partially true, since the suppressor does attentuate a portion of the noise generated inside the duct like a classical liner. However, the closeness of the source (the reaction zone) to the liner, and the fact that the wavelengths of low-frequency combustion noise are large compared to the duct diameter, can make the noise-reduction process very involved. It has been shown[11] that, for a given source within a duct, the resulting far-field noise depends heavily on the duct acoustics. The muffler tested by Kazin and Emmerling,[5] in contrast to the one tested in this program, was placed few burner heights downstream of the combustor exit and hence may be expected to behave more or less as a classical acoustic liner.

It is well known in theoretical acoustic[12] that, when a noise source is enclosed in a duct, the radiation impedance of the source is modified, leading to amplification at certain frequencies determined by the duct acoustics. This happens when the transverse dimensions of the duct is comparable to the wavelength of the noise generated. However, if the duct size is much larger than the wavelength, the source would raidate as if it were in free space. In the present case, the source is the turbulent combustion taking place inside of the duct. It is known that combustion is a velocity source and that

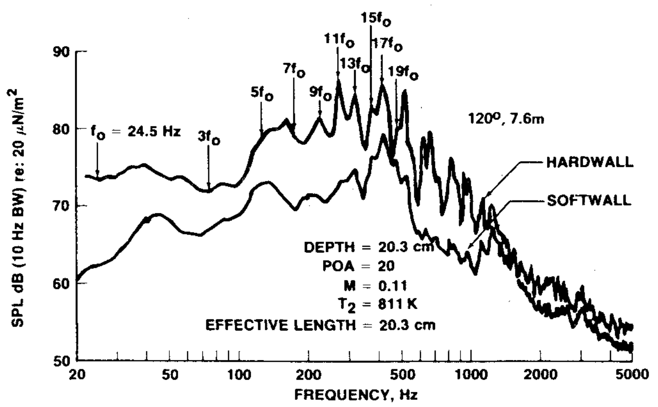


Fig. 11 Narrow-band frequency spectrum for combustion noise suppressor test.

for hydrocarbon-air flames its spectrum maximizes around 400 Hz. This typically gives a wavelength of the order of 150 cm, which is large in comparison with the duct diameter of 20.3 cm. Thus, it is possible that source-wall interactions leading to noise augmentation could occur. The amplification, in turn, depends upon the impedance characteristics of the wall, with a hard wall having the maximum influence. Therefore, if the effect of the wall is reduced by making it "soft," the noise augmentation due to the duct can be reduced. The resultant effect then would be reduced noise from the ducted combustor. For convenience, this effect will be referred to as the "source modification effect" in the following paragraphs. In addition to the source modification effect, when the duct length is finite, the longitudinal duct resonance modes also are excited. This modifies the frequency distribution of the noise radiated to the far field.

It should be stressed at this point that the noise amplification discussed so far is due to a modification of the source radiation impedance and not to the interaction between the chemical process and the sound waves. Also, the source is assumed to be a point source and a passive scatterer of sound waves for the purpose of these discussions. It is known that a feedback effect could occur and lead to various degrees of combustion instabilities in burner systems. However, from a earlier test, the rms values of the fluctuating pressures were found to be within 1% of the mean chamber pressure of this burner system under most flow conditions. Therefore, it is considered justifiable to assume that no combustion-acoustic interactions are present in the combustor setup.

With this background, the results from the present experiments will be examined to determine whether the noise reduction obtained was due to the source modification effect or simply due to the suppressor acting like a typical resistive-reactive liner. First consider the hard wall narrow-band spectrum shown in Fig. 11. The noise radiated is reasonably broadband and exhibits many small spikes at various frequencies.[¶]

Assumimg a speed of sound of 549 m/sec (1800 fps) and the fuel nozzle end as "closed" and the exit nozzle end as "open," the fundamental frequency f_0 for the organ-pipe-type resonance can be calculated. In the test setup, the distance between the nozzle exit plane and the combustor fuel nozzle end was 5.56 m(18.3 ft). This gives $f_0 = 26$ Hz. The f_0 in the real situation should be quite close to 26 Hz, and , calculating the odd multiples of the fundamental, the frequencies at which the spikes occurred in the experimental spectra could be reproduced quite satisfactorily. The arrows in Fig. 11 indicates frequencies that are odd multiples of $f_0 = 24.5$ Hz. Thus it has been demonstrated that the spikes in the spectra correspond to the longitudinal resonant frequencies of the duct.

The wall effects on a simple monopole source within a duct have analyzed in Ref. 12. Based on this, it can be seen that the amplification of noise due to the wall would be small below the frequency for the first transverse mode of the duct. In the present case, the first transverse mode would occur at approximately 1400 Hz. Therefore, the noise reduction due to the source modification effect should be of minor importance in the frequency range (100 to 1000 Hz) at which most of the noise power is concentrated. Furthermore, if the entire flame is located within the burner-can, since only the portion of the suppressor downstream of the burner-can has been shown to be effective, the liner should have no effect on the source radiation impedance. Thus, if the results obtained for a simple monopole case can be extended to the present system, one can argue that most of the noise reduction obtained is by energy dissipation by the suppressor, and only a minor part of the reduction is due to the source modification effect.

The suppressor did not alter the steady-state combustion of the test burner itself. That is, the combustion efficiency, heat release, temperature distribution, etc., were not affected. The suppressor, in fact, had a beneficial effect. The stability of the burner was found to have increased, because the burner with suppressor could handle abut 15% more air flow with blowoff compared to the hard wall baseline case. The liner, therefore, provides acoustic damping and reduces the tendency toward combustion instability. Improved stability may result in lower noise generation. It is possible, furthermore, that, by improving the stability of the burner, the temperature fluctuations leaving the burner also may be reduced. This could lead, in engine applications, to reduced entropy noise (the noise generated due to temperature fluctuations passing through the velocity gradients in the turbine). Thus a suppressor designed to reduce the direct combustion noise may decrease the entropy noise generation indirectly as well. If this should happen, the suppressor, on full-scale engine combustors, could lead to greater reductions in core engine noise levels than those demonstrated by the model suppressor tests.

Conclusions

The research test of a compact combustion noise suppressor described in this paper explored a number of flow and geometric factors. Although the combustor used was a simple laboratory test burner, the following tentative conclusions relevant to full-scale engines are drawn.

1) Relatively thin (depth of the order of 10 cm) linings may provide a combustion noise reduction of 5 to 10 dB over the 100- to 1000-Hz frequency range.

2) Single-layer liners may give much more broadband attentuation than one would predict using conventional techniques. The optimum percent open area may be of the order of 20, which is higher than usually predicted.

3) Attentuation obtained may be relatively insensitive to flow temperature and Mach number and also to cavity air temperature.

4) The test suppressor was effective only immediately downstream of the burner-can. Over the combustor it was ineffective, probably because the burner-can acted like a hard wall and prevented disturbances from reaching the suppressor. Since, in full-scale engines, there is room for the suppressor only over the combustor, modifications to improve noise transmission across the burner-can should be attempted. These modifications may be very difficult and involve excessive developmental efforts.

5) Empty cavities may be better than cavities containing bulk absorbers of the type tested in this program. Inclusions of "horns" in cavities may improve the efficiency of the suppressor. Additional tests are required before a definite conclusion can be drawn.

6) The suppressor does not affect the steady-state combustion process, that is, the combustion efficiency, tem-

¶The minima in both curves of Fig. 11 at odd multiples of 60-70 Hz may be due to wall and ground reflection effects since fiberglass mats used may not be effective at low frequencies.

perature profile, etc. It may, however, improve the dynamic stability of the combustor.

References

[1]Smith, T. B. J. and Kilham, J. K., "Noise Generated by Open Turbulent Flames," *Journal of the Acoustical Society of America*, Vol. 35, May 1963, pp. 715-724.

[2]Shivashankara, B. N., Strahle, W. C., and Handley, J. C., "Combustion Noise Radiation by Open Turbulent Flames," *AIAA Progress in Astronautics and Aeronautics: Aeroacoustics: Jet and Combustion Noise; Duct Acoutics*, Vol. 37, Editor: Henry T. Nagamatsu, Associate Editors: Jack V. O'Keefe and Ira R. Schwartz, MIT Press, Cambridge, Mass, 1975, pp. 277-296.

[3]Strahle, W. C. and Shivashankara, B. N., "Combustion Generated Noise in Gas Turbine Combustors," *Journal of Engineering for Power*, Vol. 98, Ser. A, April 1976, pp. 242-246.

[4]Ho, P. Y. and Tedrick, R. N., "Combustion Noise Prediction Techniques for Small Gas Turbine Engines," *Proceedings of the International Conference on Noise Control Engineering*, 1972, p. 507.

[5]Kazin, S. B. and Emmerling, J. J., "Low Frequency Core Engine Noise," ASME Paper 74-WA/Aero-2, Houston, Texas, 1975.

[6]Gerend, R. P., Kumasaka, H. A., and Roundhill, J. P., "Core Engine Noise," *AIAA Progress in Astronautics and Aeronautics: Aeroacoustics: Jet and Combustion Noise; Duct Acoustics*, Vol. 37, Editor: Henry T. Nagamatsu, Associate Editors: Jack V. O'Keefe and Ira R. Schwartz, MIT Press, Cambridge, Mass., 1975, pp. 305-326.

[7]Huff, R. G., Clark, B. J., and Dorsch, R. G., "Interim Prediction Method for Low Frequency Core Engine Noise," NASA TMX-71627, Nov. 1974.

[8]Woodward, R. P. and Minner, G. L., "Low-Frequency Rear Quadrant Noise of a Turbojet Engine with Exhaust Duct Muffling," NASA TMX-2718, Feb. 1973.

[9]Garrison, G. D., Russell, P. L., and Stettler, J., "Investigation of Damping Methods for Augmentor Combustion Instability," Air Force Aero Propulsion Lab., Wright Patterson AFB, Ohio, AFAPL-TR-72-84, Oct. 1972.

[10]Wirt, J. S., "Sound-Absorptive Materials to Meet Special Requirements," *Journal of the Acoustical Society of America*, Vol. 57, Jan. 1975, pp. 126-143.

[11]Strahle, W. C. and Shivashankara, B. N., "Combustion Generated Noise in Gas Turbine Combustors," NASA CR-134843, Aug. 1974.

[12]Morse, P. M. and Ingard, U., *Theoretical Acoustics*, McGraw-Hill, New York, 1968, pp. 501-503.