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FULL-SCALE ENGINE TESTS OF BULK ABSORBER ACOUSTIC INLET TREATMENT

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Abstract

Three different densities of Kevlar bulk absorber fan inlet treatment were tested on a YF 102 turbofan engine. This bulk absorber material may have potential for flight application. Far-field noise measurements were made and the attenuation properties of the three treatment densities were compared. In addition the best bulk treatment was compared to the best single degree of freedom, SDOF (honeycomb and perforated cover sheet) treatment from another investigation. Although the density was varied over a large range, (3 to 1) the effect on attenuation was small. The highest density treatment, 11.8 lb/ft^3, had a somewhat broader attenuation bandwidth. The comparison of the best bulk and SDOF treatments showed the bulk to have a greater attenuation bandwidth. At the design frequency both types of treatment had almost equal performance.

Introduction

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Bulk absorber type acoustic treatment has yielded encouraging results in engine and scale model tests. However, most bulk absorber materials have not been considered for flight hardware because of problems with accumulation of dirt, grease, water, fuel, etc., in the absorber material. One bulk absorber material, developed by the General Electric Company, may have the potential for flight application. This material is a Kevlar felt treated so as to be nonabsorbing and nonwicking with the common fluids in the engine environment.

The acoustic design of bulk absorber liners is presently based on test data with little or no theoretical understanding. Many questions as to how to design, and what performance to expect from bulk liners remain. In addition, there is little data to guide the formation of theoretical models for the bulk absorbers. To some extent the lack of a precise design method is offset by the most encouraging property of bulk absorbers, namely a broad attenuation bandwidth. Important objectives of this investigation were to obtain data on the effect of bulk density on acoustic suppression and to directly compare the performance of bulk and single degree of freedom (SDOF) liners.

Three different densities of Kevlar bulk absorber were tested for acoustic suppression performance on an Avco Lycoming YF 102 turbofan engine inlet. Empirical methods were used to define the desired acoustic impedance for maximum suppression of the blade passing frequency (BPF) of the fan near the maximum power setting. No attempt was made to maximize the perceived noise level reduction. The bulk liner designs are based on Ref. 1. This reference shows test data indicating that acoustic reactance of these liners is primarily a function of liner thickness. The acoustic resistance is shown to be a function of density and thickness of the treatment. The densities of bulk absorber were chosen so as to span the optimum resistance as defined by two different methods. The empirical method in Ref. 1 resulted in the design of the lowest density liner, 3.5 lb/ft^3. The optimum impedance was also estimated by a locally reacting theory for the Helmholtz resonator-type liners[2] that may not apply to a bulk type liner, where there is a possibility of acoustic waves traveling within the liner. This method resulted in the high density (11.8 lb/ft^3) design. A density between the two extremes (5.9 lb/ft^3) was also built. Data were taken at three speeds and three length to diameter ratios (L/D) from 0.25 to 1.0.

The YF 102 engine was previously used to investigate a series of SDOF (honeycomb and perforated cover sheet) acoustic liners. The test results of these liners are presented in Ref. 3. These SDOF results provide a convenient reference with which to compare the bulk liners.

Apparatus and Procedure

Engine

The Avco Lycoming YF 102 is a twin spoor turbofan engine with a bypass ratio of 6, a fan pressure ratio of 1.47, a fan tip speed of 1300 ft/sec at 7380 rpm, and a maximum rate thrust of 7500 lb. Fig. 1 shows a cutaway view of the YF 102 engine. The engine core consists of a combination seven-stage axial, single-stage centrifugal compressor driven by a two-stage axial turbine and external atomizing combustor. The front fan and supercharging stage are gear driven by a two-stage coaxial power turbine. The fan has 40 blades and is 40.3 in. in diameter. There are 85 fan bypass stator vanes and 84 fan core stator vanes. The blade-vane ratios for this fan lead to a cut-off rotor stator interaction tone for the BPF at fan speeds below about 6000 rpm.

Table I shows some of the engine preformance and inlet parameters of interest at the three fan speeds used in this investigation.

A very long test inlet was used in this investigation. The total length to diameter (L/D) was 3.6. A schematic diagram of the inlet assembly showing its various sections is presented in Fig. 2. This inlet consists of a large radius bellmouth and several constant diameter sections. This first section was used to measure the inlet total flow rate. The next short section, used to bleed off the boundary layer flow, was taped over and not used during the present investigation. The next four sections were designed to hold acoustically treated liners. Only sections 2 and 3 were used in this investigation. Each of these sections has an L/D of 0.5. The unused sections were made hardwall. The last section is an inlet seal and engine adapter.

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Acoustic Liner Design and Construction

An empirical design method developed by the General Electric Company and outlined in Ref. 1 was used to design a liner using a Kevlar felt bulk absorber. This method is based on curves of acoustic impedance of bulk absorber liners obtained from impedance tube and engine data.

The first step in the liner design is to select the design frequency which is then used with Fig. 3 from Ref. 1 to determine the liner thickness. The design frequency was selected to be the BPF at near maximum power (7380 rpm) and was 4920 Hz. There was no attempt in this study to maximize perceived noise level suppression.

Next, the density was determined using Fig. 4 also from Ref. 1. As indicated by Fig. 4, the design density was intended to provide a specific resistance of 1.0. Impedance tube data from Ref. 1 indicates that the face sheet should have an open area ratio of at least 22.5 percent. Table II shows the liner design parameters determined by this method along with those actually fabricated and tested.

As was indicated the specific resistance of the design treatment (3.6 lb/ft^3) was nominally 1.0. The corresponding specific reactance was estimated to be -1.1. In order to explore the bulk absorber characteristics more fully, two other densities were selected, as shown in table II, at the design thickness. These densities were selected from consideration of Fig. 5 which shows the optimum impedance loci for the design conditions as developed in Ref. 3 for the YF 102 engine. This figure is based on a point reacting theory that may not apply to bulk liners. The design liner is located on this figure according to the impedance estimates given earlier. One of the alternate designs was intended to be on the locus curve at the specific reactance of -1.1 leading to a specific resistance of about 3.0. The corresponding material density, extrapolating from estimates of the specific resistance at low densities, was estimated to be about 11 lb/ft^3 and in the fabricated liner was 11.8 lb/ft^3. The third liner was selected to have an intermediate density of 5.9 lb/ft^3 corresponding to a specific resistance of about 1.7.

Each liner section is one half of a diameter long. One section each of the 3.5 and 11.8 lb/ft^3 density and two sections of the 5.9 lb/ft^3 density were built. The type of Kevlar used in these liners is designated as Kevlar 29, type 973. The uncompressed fibrous material came in sheets 1/2 in. thick with a density of approximately 0.7 lb/ft^3. The installed density is controlled by the number of layers of this material compressed into the liner cavity. In the case of the high density material the material could not be compressed enough during the liner assembly and had to be precompressed by running it through a drop hammer first. Each liner section had eight equally spaced partitions (stringers) placed around the circumference parallel to the duct axis between the perforated inner sheet and the solid backing sheet. There were no partitions in the axial direction (ribs) between the end flanges.

Test Facility

The Lewis outdoor test facility for noise and performance testing, accommodates turbofan engines with thrust levels up to 30 000 lb. The test engine is supported by a tripoded, cantilevered, overhead support arm 9.5 ft above the ground plane. A movable shelter, on tracks, covers and protects the engine between test runs.

Engine instrument and control lines junction at a vault next to the test stand. Conditioned signals are transmitted from the vault to the operation control room. The control room, located approximately 400 ft from the engine, contains equipment to control engine operation and receives all engine aerodynamic signals. A digital data acquisition system, together with a computer system, provide on-line engine performance data.

Aft-radiated engine noise as well as jet noise, was effectively eliminated by a large exhaust muffler. Fig. 6 is a photograph showing the engine on the test stand with its exhaust ducted to the muffler. A nozzle at the entrance to the muffler was sized to provide fan operating conditions (flow and pressure ratio) that were nearly identical to those before the muffler was connected. This muffler is 60 ft long with an inside diameter of 66 in. The muffler is lined with a bulk absorber treatment that is 23.3 in. thick.

Acoustic Instrumentation and Processing

The acoustic arena is a 100 ft radius, concrete surface centered on the engine-inlet. There were 12 ground microphones on the perimeter of the arena. They were positioned at 10° intervals from 10° to 120°, measured from the engine inlet axis. Each 0.5 in. diameter microphone was mounted on 2 ft^2 composition hard board at ground level and was pointed at the inlet.

The microphone signals, transmitted over shield shielded cable to amplifiers, were conditioned for frequency modulated (FM) magnetic tape recording. The conditioned signals were recorded on a 16 to 20 second duration tape loop. This acoustic system was calibrated from the microphones through the amplifiers with a piston phone both before and after each run.

The tape loop was replayed and analyzed through a Novatronic scanner-control unit. The Novatronic separately plays each acoustic channel into a General Radio multifilter and multichannel RMS detector. Using 16 seconds integration time, one-third octave band sound pressure level (SPL) was obtained. Integration was performed over 1024 data samples to reduce uncertainty of the random signal measurement. The resulting sound pressure levels, in units of decibel (dB), are referenced to 2×10^{-5} Pa (0.002 μbar). Sound power levels (PWL) are referenced to 10^{-13} W. All further data was processed on an IBM-T55 360 computer.

The IBM computer calculates sound levels, at distances other than the measured stations, consistent with Ref. 4. All data were corrected to an atmospheric temperature of 59° F and a relative humidity of 70 percent. Ground microphone data are corrected to free-field conditions by subtracting 6 dB at all frequencies up to 20 000 Hz. This correction accounts for the effect of ground reflected signals. Theory predicts a 6 dB correction for a perfect reflecting surface. Test of the acoustic arena have indicated that the correction is approximately 6 dB.

Test Procedure

The engine was run at three fan speeds; 4500, 5900, and 7100 rpm. Physical rather than corrected fan speed was used to keep the BPF tone in a single one-third octave band from one test day to another. The 7100 rpm speed was chosen in place of the liner design speed, 7380 rpm because it was the highest speed that could be reached during the highest ambient temperatures that were likely to occur. All tests were run after 6 pm with wind speeds under 10 mph. The 7100 rpm speed was repeated twice for each configuration and the data averaged since this is nearest the design speed for all the acoustic liners.

The baseline hard wall data was taken at the be beginning of each evening's run. All configurations tested in one evening were then compared to that evening's baseline in order to obtain suppression data (differences) of high accuracy. The differences in the baseline BPF levels from one day's run to the next were generally within ±2 dB, while the repeatability of the BPF during an individual run was usually ±0.5 dB.

Aluminum adhesive tape was used to cover the acoustic liners that were not part of the configuration being tested. Thus, by removing tape several configurations could be tested in an evening's run.

Results and Discussion

The YF 102 engine was used to test bulk absorbing acoustic liners using different densities of a Kevlar material and different liner lengths. All testing was done with the engine exhaust ducted to a large muffler in order to measure only inlet noise. All the data presented is on a one-third octave band basis. Limited narrow band spectra show the BPF tone to be sufficiently strong to be represented by the one-third octave band the tone falls within. The data has been adjusted to free field and standard day conditions.

Baseline Inlet Noise

The inlet noise in the unsuppressed case is shown by the three power spectra in Fig. 7. All the baseline data shown are averages of 11 different runs that occurred over a period of several months. The data spread over this period was generally within ±2 dB. The test speeds shown are 7100, 5900, and 4500 rpm. The corresponding tip relative Mach numbers are 1.25, 1.02 and 0.765. At 7100 rpm the presence of multiple pure tones (MPT's) is very obvious between 800 and 3150 Hz. The strongest BPF tone occurs at the transonic speed of 5900 rpm. Second and third harmonics can be easily seen at the lower speeds. These spectra are typical of a high bypass turbofan engine. At very low frequencies (below 400 Hz) a significant contribution to the power spectrum is made by noise originating from within the muffler and exhaust system. Most of this low frequency noise propagates upstream through the fan nozzle, aft fan duct, fan and out the inlet.

Figure 8 shows the directivities of the BPF tone at the three test speeds. These directivity patterns give an indication of the modal energy distribution which in turn relates to acoustic suppressor performance. Reference 5 relates the mode cut-off ratio to the far-field radiation angle. Well cut-on modes (cut-off ratio >>1) radiate at angles near the inlet axis, while near cut-off modes (cut-off ratio near one) tend to radiate at angles of 60° to 70° depending on the inlet Mach number. The mode cut-off ratio can also be related to the performance of acoustic suppressors.[3] Well cut-on modes have a low maximum possible attenuation while near cut-off modes are readily attenuated.

The 7100 and 4500 rpm curves of Fig. 8 have a similar shape except around 70° where the supersonic tip speed curve shows a bulge that may be due to the rotor-locked mode. At 5900 rpm there appears to be more energy in the angles around 50° and 60°. This may indicate a modal energy distribution weighted more heavily toward cut-off.

Variation of Liner Density

The effect of density on the sound-power attenuation spectra is shown in Fig. 9 for a treatment L/D of 0.5. In general the density effect is small, less than 2.5 dB. At 7100 rpm there are almost no variations in the BPF attenuation. At frequencies above the BPF the high density liner has a better performance than the other two liners. For the MPT frequencies, the high and middle density liners seem more effective than the low density liner. At 5900 rpm the attenuation of the BPF and near by frequencies for the 5.9 lb/ft^3 density liner is lower than that of the other two liners. All the liners have higher BPF attenuations at 5900 rpm than at any other speeds. This may be a result of a modal energy distribution weighted towards cut-off as discussed earlier. Almost all the SDOF liners tested on this engine also had their peak BPF attenuations at 5900 rpm. The 4500 rpm attenuation curves show the 3.5 lb/ft^3 liner with somewhat lower performance at the BPF and at several other frequencies. An unusual feature of the curves at this speed is that the peak attenuation occurs at the 10 kHz band instead of the BPF. This results from the very large attenuation of a strong tone that is the sum of the BPF of the fan and the BPF of the supercharger stage.[6] The directivity of this tone indicates a modal energy distribution heavily weighted towards cut-off that is thus easily attenuated. It may be helpful for the reader to refer back to the baseline configuration (Figs. 7 and 8) for when examining the attenuation figures.

The directivity of the BPF tone suppression is shown in Fig. 10. At 7100 and 5900 rpm the high density liner appears to have a slight advantage at angles of 50° and less. This indicates a slightly broader bandwidth with respect to mode cut-off ratio. Although it is interesting to observe the suppression at angles greater than 70°, these results have very little effect on the overall engine noise since these angles are normally dominated by aft end noise. The 5.9 lb/ft^3 liner shows poorer performance at 5900 rpm than the other two liners for most angles. There are no obvious trends at 4500 rpm.

Each of the liners was tested at L/D's of 0.25

and 0.5 and the middle density liner was also tested at an L/D of 1.0. Fig. 11 shows the sound power attenuation of the BPF as a function of treatment L/D. The curves for 7100 and 4500 rpm are similar in attenuation levels while, the 5900 rpm data shows higher attenuations. At each length the high density liner has better performance than the other liners. There appears to be little or no increase in sound power attenuation with increasing length, at an L/D of 1.0. To some extent the decrease in slope with increasing L/D is a result of the sound power for the BPF being controlled by the well cut-on modes. Even through these modes tend to propagate to far-field angles near the inlet axis they can dominate the sound power when large amounts of supression are used on the inlet. These angles near the axis are less important to sideline or flyover noise.

Comparison of Bulk and SDOF Liners

The potential for flight applications of the Kevlar bulk treatment makes a comparison with the flight rated SDOF type treatment useful. The best SDOF liner of Ref. 3 was used for comparison to the high density bulk liner, which generally gave the best suppression of the three liners. It should be noted here that although the SDOF liner chosen as a reference was designed for near cut-off modes, it acoustic resistance was estimated to be only half of the optimum value (based on the locus of single mode optima in Fig. 5). Because of this it seems likely that a still better SDOF liner is possible. Of course, there is no way of knowing whether the bulk liner used in this comparison is optimum.

A comparison at the three test speeds of the sound power attenuation spectra of the bulk and SDOF liners is shown in Fig. 12. The bulk liner has higher or equal attenuations than the SDOF liner at most frequencies and speeds. The biggest advantage of the bulk liner however, is its greater attenuation bandwidth at all speeds. This greater bandwidth occurs at frequencies both above and below the BPF. At 7100 rpm the attenuation of the BPF is slightly higher for the bulk liner, while there is a dramatic difference in their performance at both higher and lower frequencies. Between the BPF and 10 kHz the bulk liner has a roll-off in attenuation of less than 1 dB per band while the SDOF liner has a roll-off of about 2 dB. At frequencies between the BPF and 1 kHz the spectrum is dominated by MPT's which have most of their energy in near cut-off modes. Although both liners have no difficulties in obtaining high attenuation of these near cut-off modes the bulk liner does much better. At 5900 rpm, the bulk liner has higher attenuation below but the BPF, but without MPT's the difference is not as dramatic. At 4500 rpm, the BPF performance of the bulk liner is somewhat better than the SDOF liner. The large difference in attenuation at 10 kHz seems to be due to the bulk liners ability to attenuate the fan-superchanger sum tone in this band as previously discussed.

A comparison of the directivity of the BPF suppression for the three test speeds is shown in Fig. 13. At 7100 and 5900 rpm both liners have almost the same pattern even though they represent entirely different attenuation concepts. The shape of this curve is to a large extent a result of the modal energy distribution of the source with the attenuation characteristics of the liner having a smaller effect. There does appear to be a slight advantage to the bulk liner in the vicinity of 50°. At 4500 rpm the SDOF liner has lower attenuation than the bulk liner at most angles. Because the BPF at this speed is further from the design frequency and the SDOF liner has less attenuation bandwidth it is not surprising that the SDOF liner gave the lower attenuation.

Concluding Remarks

The results of an investigation of a series of Kevlar bulk absorber liners used in a turbofan engine inlet have been presented. Far-field noise measurements were used to compare the attenuation properties of three different treatment densities. In addition the best bulk treatment has been compared to the best SDOF treatment from another investigation using the same engine.

The variation in liner density, which should result in a variation in liner acoustic resistance, had only a small effect on the attenuation properties. The somewhat broader bandwidth attenuation of the high density liner is the most noteworthy effect of density. The density was varied over approximately a 3 to 1 range. Since acoustic resistance has been shown to be proportional to density over a small range of density,[1] it might be expected that the resistance change for the test liner would be in the vicinity of 3 to 1. This was sufficient to produce significant attenuation changes for SDOF liners varied over a similar range of resistance.[3]

The comparison of the best of the SDOF and bulk liners shows a significantly broader attenuation bandwidth for the bulk liner. It is felt that the SDOF liner does not have the optimum impedance and may not be the best liner to represent its type. By the same token there is no way of knowing if the high density bulk liner is optimum. Even if there is more room for improvement of the SDOF liner than the bulk liner, it still seems likely that the bulk absorber type liner will have broader bandwidth attenuation than SDOF liners.

References

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5. Rice, E. J., Heidmann, M. F., and Sofrin, T. G., "Modal Propagation Angles in a Cylindrical Duct

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TABLE I. - YF 102 ENGINE AND INLET PERFORMANCE

AT SEA-LEVEL-STATIC, STANDARD DAY CONDITIONS

Test fan speed, rpm	7100	5900	4500
Thrust, lb	7000	4550	2500
Core speed, rpm	18 900	17 600	15 800
Fan bypass pressure ratio	1.44	1.28	1.15
Total fan airflow, lb/sec	262.0	214.5	162.5
Inlet duct Mach number	0.375	0.298	0.221
Fan tip relative Mach number	1.25	1.02	0.765
Blade passing frequency, Hz	4733	3933	3000

TABLE II. - KEVLAR 29 BULK ABSORBER TEST

LINERS, INLET DIAMETER = 40.3 in.

	Design	Actual
Frequency, Hz	4920	4733
Mean flow Mach number	0.39	0.38
Treatment thickness, in.	0.305	0.3125
Treatment density, lb/ft^3	3.63	3.5 (5.9,11.8)
Perforated sheet open area	≥22.5%	22.5%
Perforated sheet hole diameter, in.	------	0.0625
Perforated sheet thickness, in.	------	0.032

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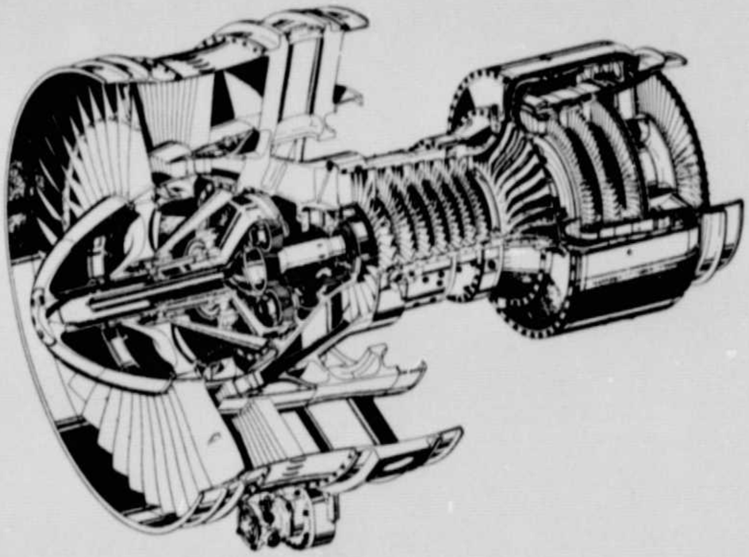

Figure 1. - Cutaway view of the YF102 turbofan engine.

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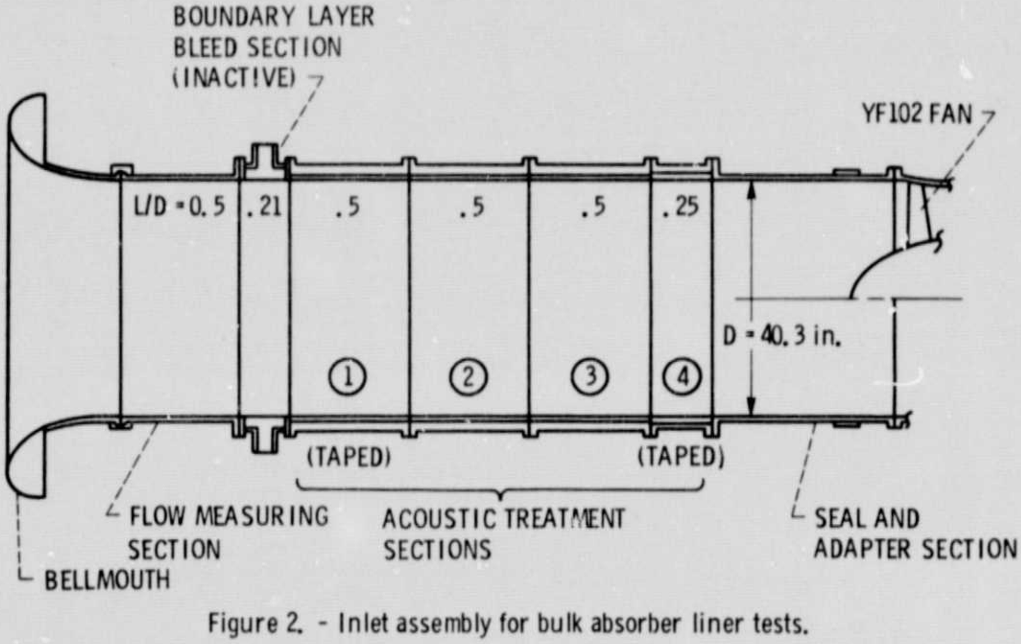

Figure 2. - Inlet assembly for bulk absorber liner tests.

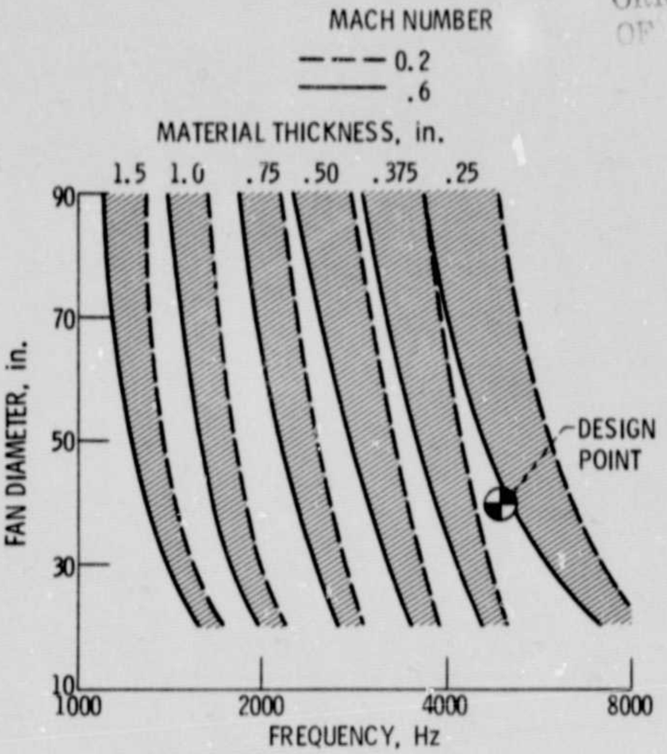

Figure 3. - Bulk absorber thickness requirement for peak suppression as a function of fan diameter, frequency and Mach number (from ref. 1).

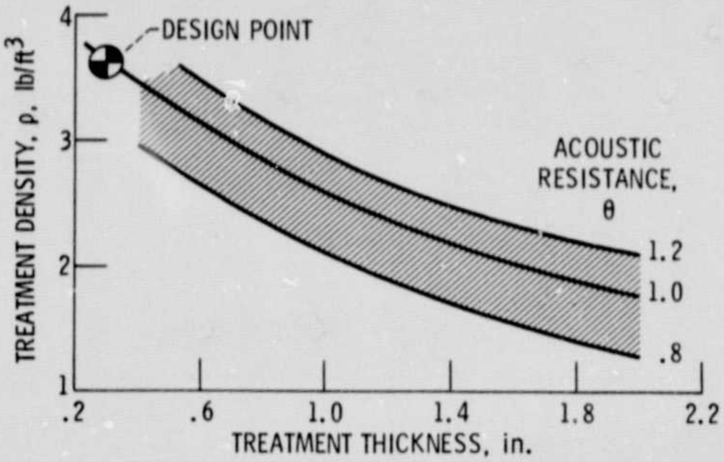

Figure 4. - Acoustic resistance as a function of material thickness and density for Kevlar 29, 22.5% face sheet open area ratio (from ref. 1).

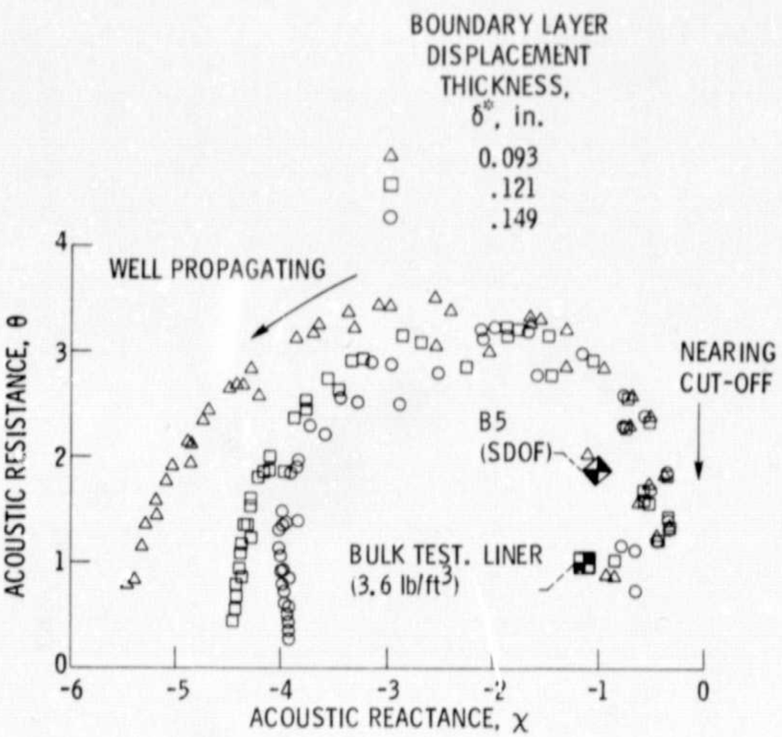

Figure 5. - Impedance optima and test liner design impedance for the YF 102 inlet at a BPF of 4920 Hz (7380 rpm), inlet Mach no. = 0.39.

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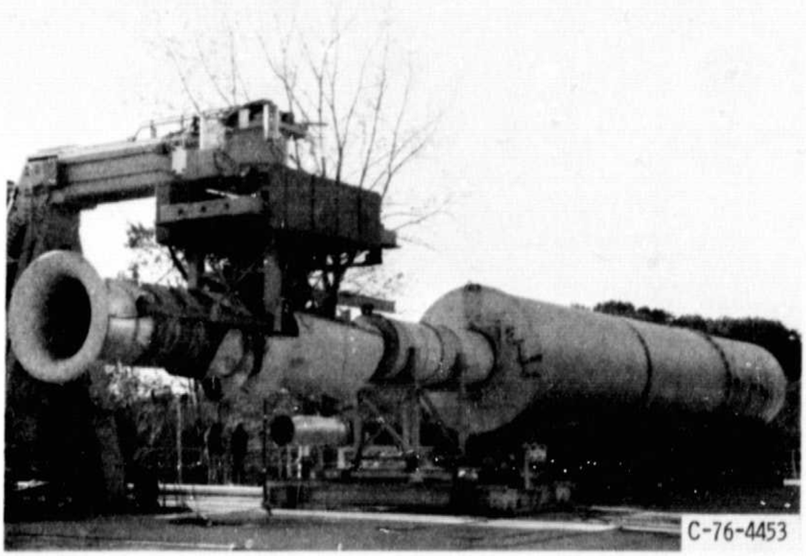


Figure 6. - Engine on test stand with exhaust muffler installed.

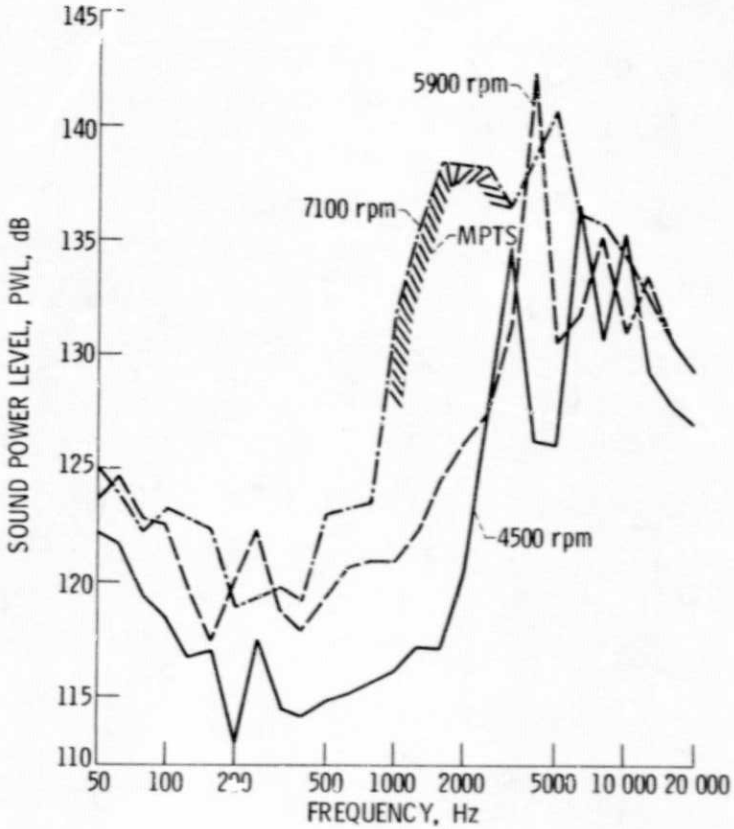


Figure 7. - YF 102 unsuppressed inlet power spectra, averaged data, front quadrant.

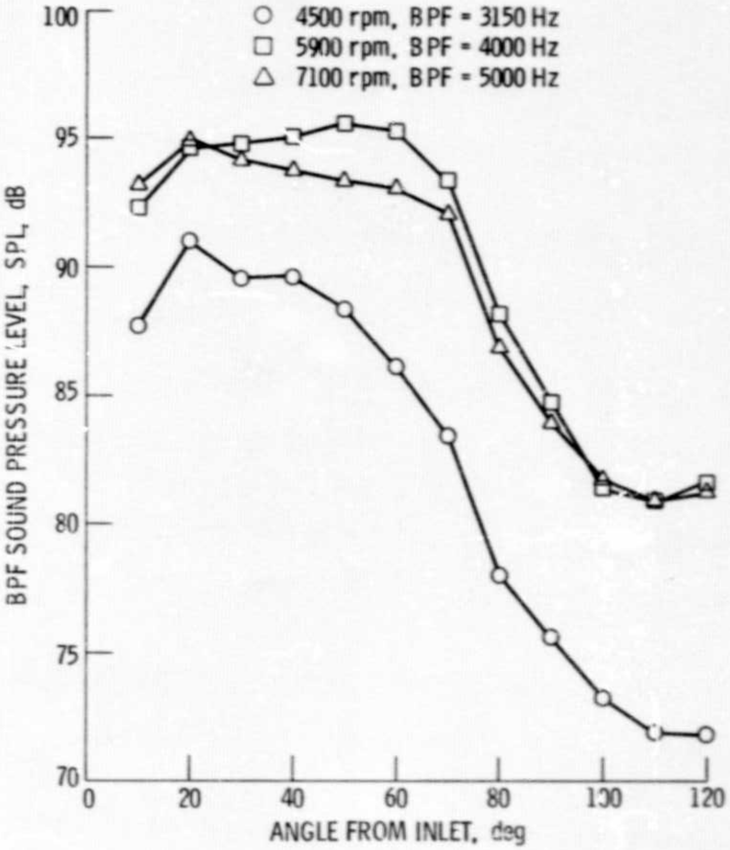


Figure 8. - BPF directivity for the unsuppressed YF 102 inlet, std. day, 100 ft.

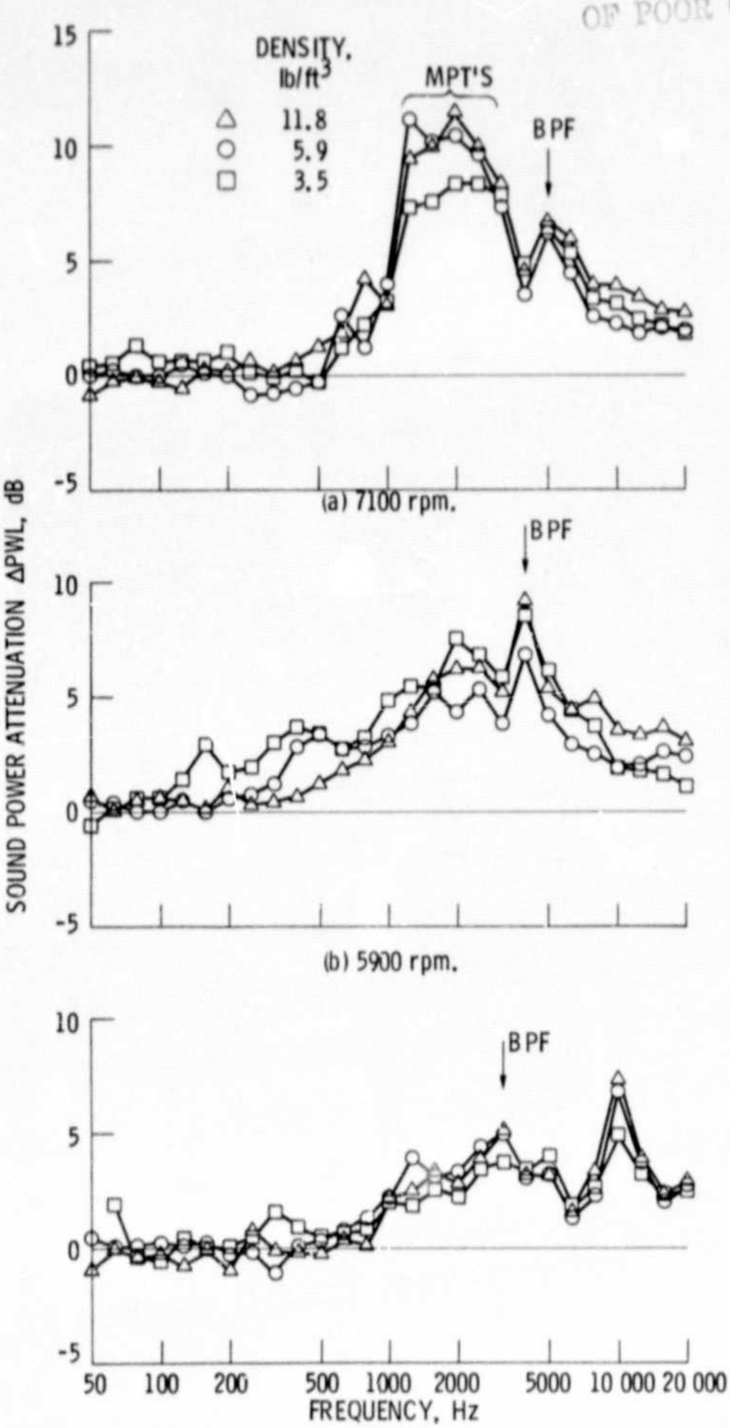


Figure 9. - Sound power attenuation spectra for various density bulk liners, L/D = 0.5.

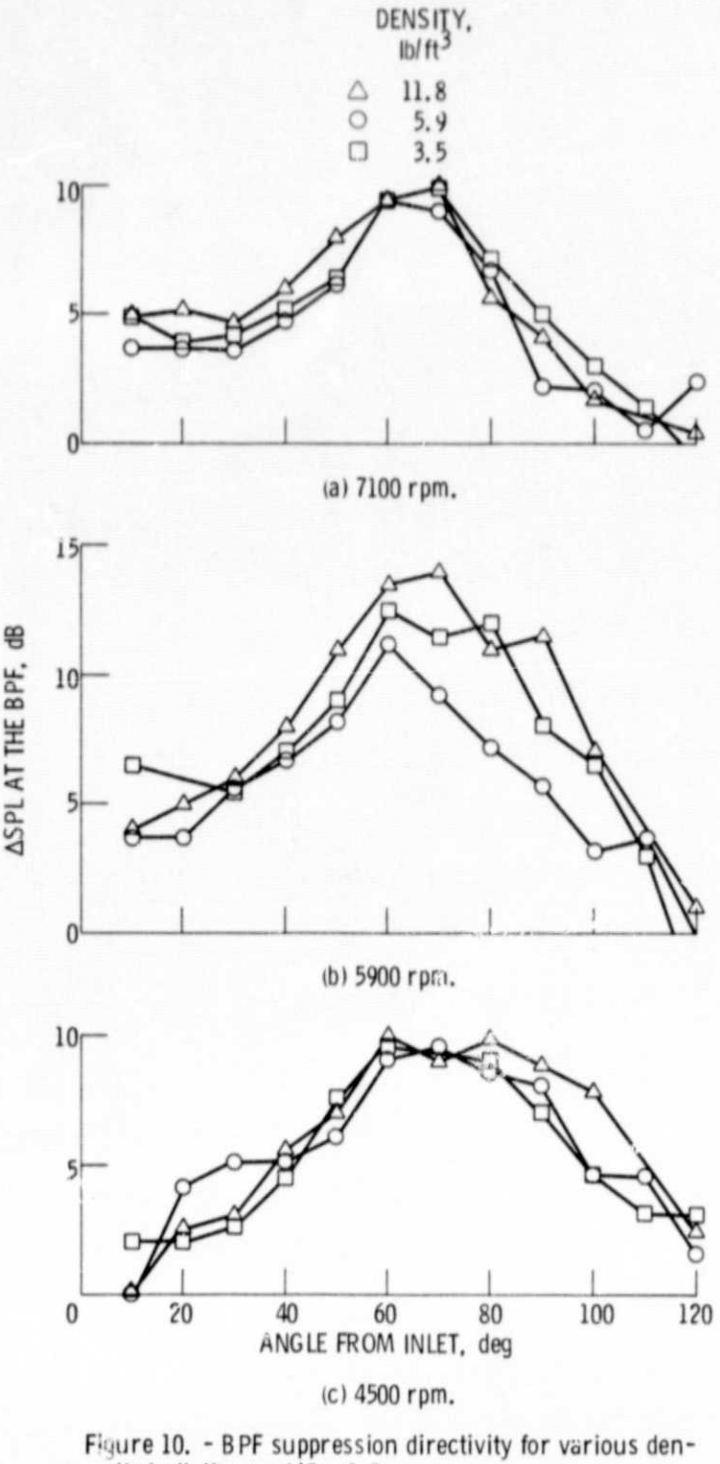
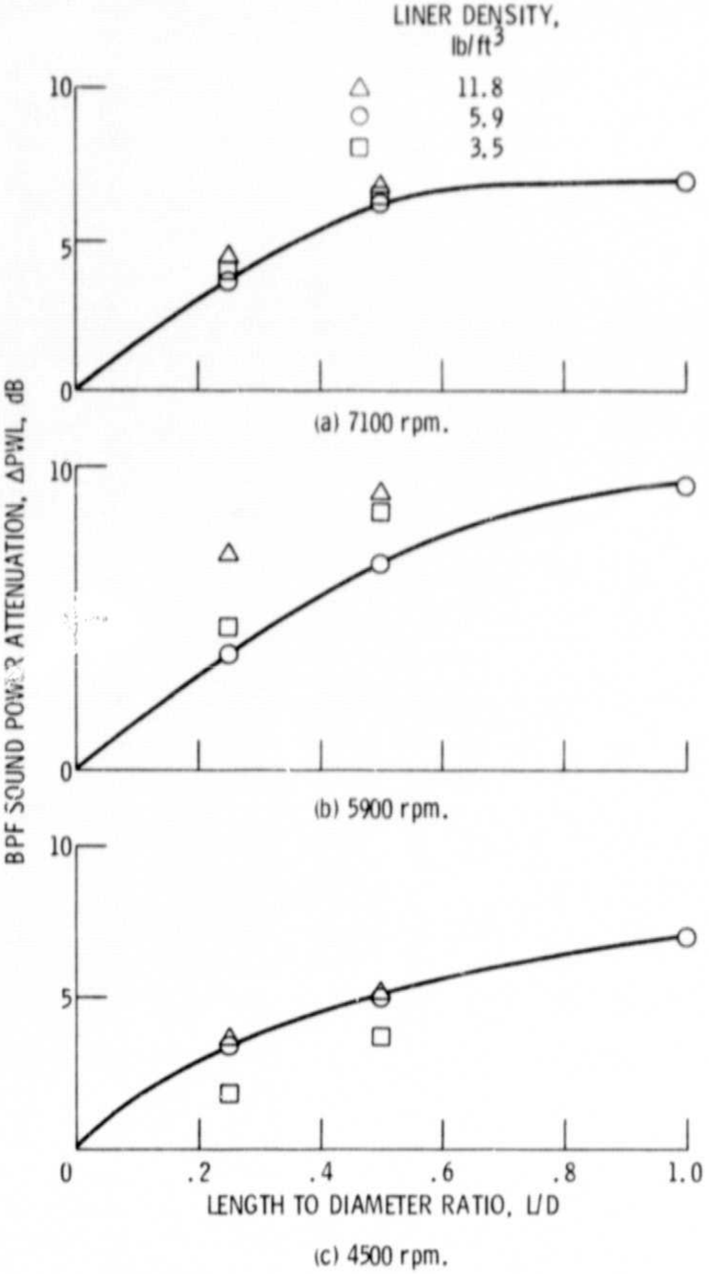


Figure 10. - BPF suppression directivity for various density bulk liners, L/D = 0.5.



(c) 4500 rpm.

Figure 11. - Effect of length on the BPF sound power attenuation.

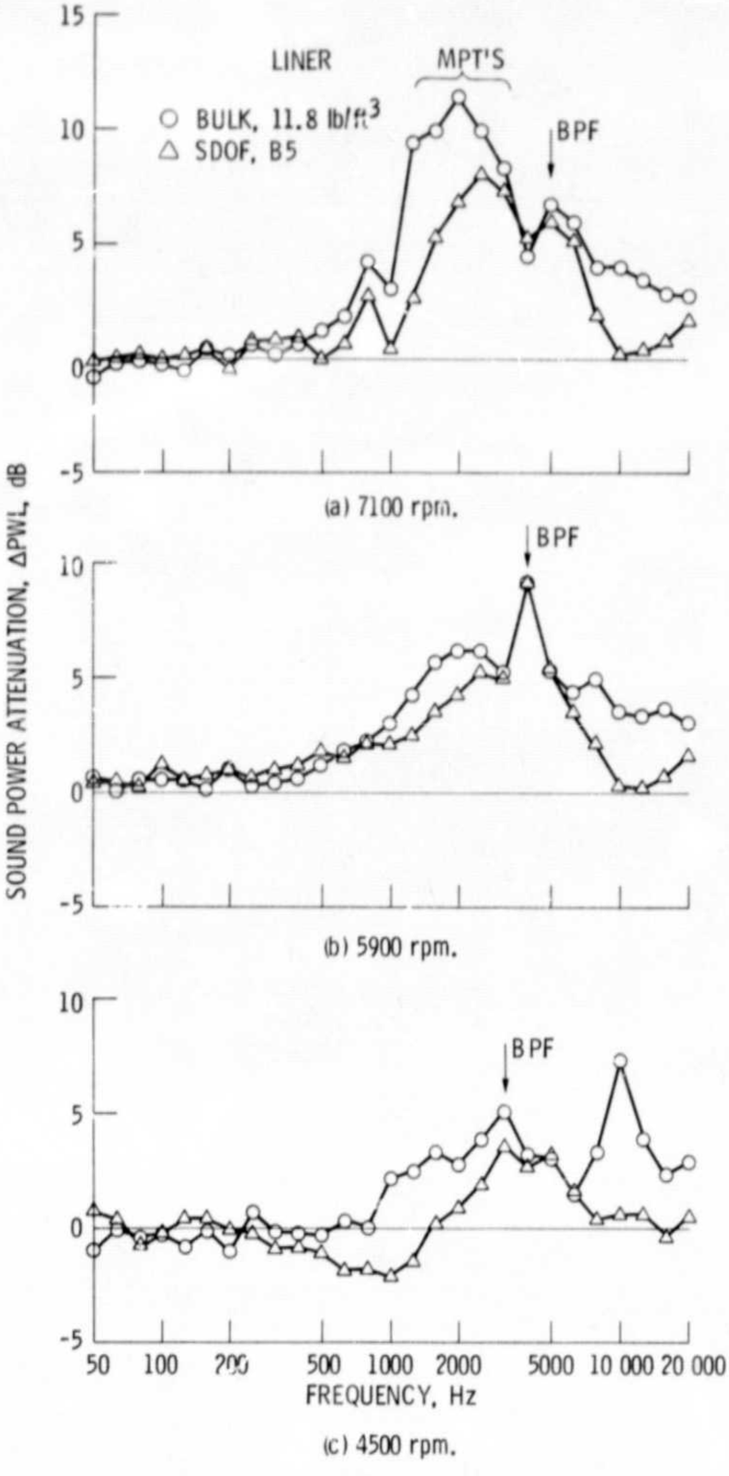


Figure 12. - Comparison of sound power attenuation spectra for bulk and SDOF liners, L/D = 0.5.

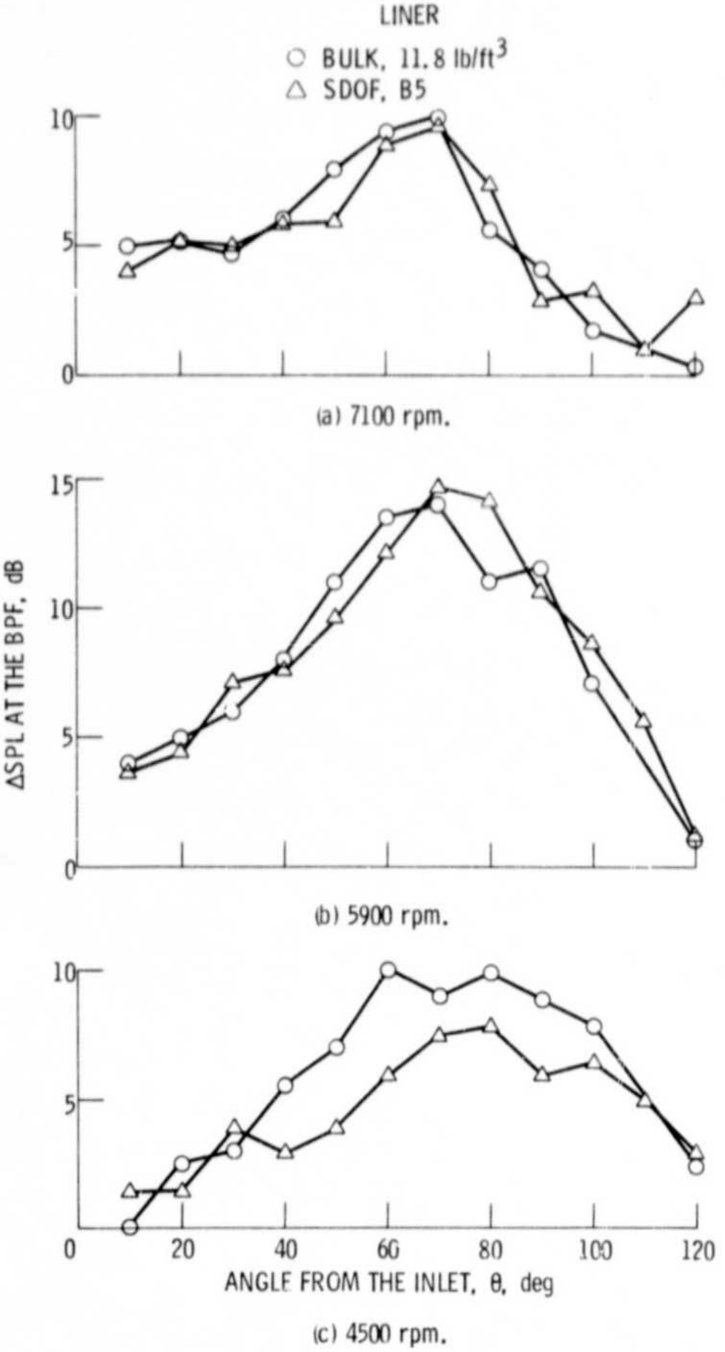


Figure 13. - Comparison of the BPF suppression directivities for bulk and SDOF liners, L/D = 0.5.

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