



Acoustic Directivity and Insertion Loss Measurements of Advanced Liners Installed the Inlet of the DGEN Aeropropulsion Research Turbofan

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Abstract

The NASA Glenn Research Center's DGEN Aero-propulsion Research Turbofan (DART) is based on the Price Induction DGEN380—a small, ~500-lbf thrust class, high-bypass, geared-turbofan engine with a separate flow nozzle. The general characteristics of the DART make it an ideal candidate for utilization as a test bed for engine aeroacoustic research in a relevant performance environment. The DART was used to document the efficacy of acoustic liners installed in the inlet of the DGEN380. An advanced multi-degree-of-freedom liner (MDOF) was designed and tested, along with a traditional single-degree-of-freedom liner (SDOF), and those results compared to a hard-wall baseline inlet. Farfield acoustic data were acquired from an external array, evaluated, and reported here-in terms of overall, broadband, and tonal components of the insertion loss.

Nomenclature

AAPL	Aero-Acoustic Propulsion Laboratory
DART	DGEN Aero-propulsion Research Turbofan
FADEC	full authority digital engine control
HP	high-pressure
HW	Hardwall
LP	low-pressure
MDOF	Multi-Degree-of-Freedom
OAPSL	Overall Sound Pressure Level
PWL	Acoustic Power Level
RPM	Revolutions per minute
SDOF	Single-Degree-of-Freedom
SPL	Sound Pressure Level
TRL	Technology Readiness Level

Introduction

The Price Induction DGEN380 is the primary component integrated into the NASA Glenn Research Center's DGEN Aero-propulsion Research Turbofan (DART) test bed. It serves as a flexible, relevant, experimental aero-acoustic and aero-performance test bed that can provide valuable information throughout NASA's technology maturation process.

The DGEN380 engine is a high by-pass ratio turbofan engine proposed and designed for powering small personal jets. It is optimized for a cruise altitude of about 10,000 ft (3048 m) and Mach 0.35. It is manufactured by the Price Induction Company situated in France and is capable of producing approximately 575 lbf (2580 N) of thrust. The engine features a two-spool flow architecture with a 3.32 ratio gearbox that links the low-pressure turbine to the fan spool. The high-pressure turbine runs the compressor and reaches rotational speeds up to about 50,000 revolutions per minute (RPM).

An advanced multi-degree-of-freedom (MDOF) liner was designed by NASA Langley Research Center and manufactured by Hexcel, Inc. A typical single-degree-of-freedom (SDOF) liner was also designed and tested to provide a comparison and more information for validation of the design and prediction process. The detailed design characteristics of these liners are presented in a companion paper (Ref. 1). The liners were installed in the inlet as an insert that extended the inlet length. While not necessarily a representation of a flight configuration, this was done to isolate the insertion loss, and due to the relatively short test window available for design and manufacture. To provide an accurate baseline, a hardwall insert of the same axial length was likewise tested in the same location in the inlet.

Farfield acoustic directivity data from all three configurations were acquired from an external array of microphones. The acquired time history data were processed using processing techniques to separate the tone and broadband noise components from the raw acoustic test data.

Experimental Setup

Aero-Acoustic Propulsion Laboratory Facility

The Aero-Acoustic Propulsion Laboratory (AAPL) dome (Ref. 2) is 65-ft high and 130-ft in diameter, providing an anechoic testing environment for engine component research and development. To provide an anechoic environment, custom-designed 2-ft thick fiberglass wedges are mounted on the dome's interior walls, and floor areas adjacent to the test rigs. These wedges provide an anechoic environment down to 125 Hz. Figure 1 shows an exterior photograph of the AAPL facility with the main access door open. Figure 2 is an overhead schematic of the AAPL showing the notional arrangement of the facility with available DART locations.



Figure 1.—Aero-Acoustic Propulsion Laboratory.

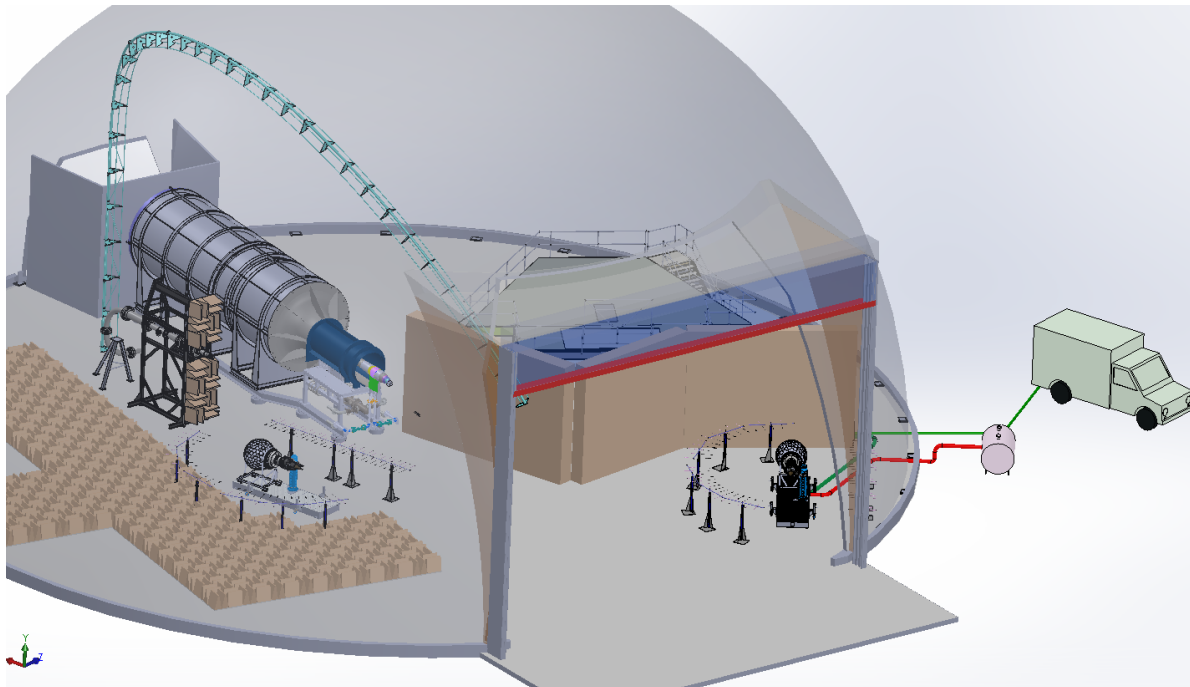


Figure 2.—Schematic of DART in the Aero-Acoustic Propulsion Laboratory Showing the Two Test Locations.

Farfield Array

Acoustic data were acquired from 30 microphones, which were located on a 10-ft radius arc at the engine vertical centerline. This arc was in two segments; a forward arc centered about the inlet plane, and an aft arc centered about the bypass nozzle exit plane. The microphones in these arcs were 1/4 in.-Electret-style PCB[®] model 378C01 microphones/preamp combination. These microphones were Transducer Electronic Data Sheet (TEDS[®]) capable and current-supplied at 6 mA. Figure 3 shows this array relative to the DGEN380 location and Table I lists the geometric information.

The time-histories were acquired from the microphones at a sampling frequency of 250 kHz using a band-pass filter set at (40 Hz to 50 kHz) on a HBM GEN2i[®] data acquisition recorder. The acquisition time was 15 s at each engine speed point in the preprogrammed automatic sweep. The data analysis method used in this paper is based on the technique recently developed by Sree and Stephens (Ref. 3). The technique was developed to separate tone and broadband noise components from raw acoustic data generated from a hobby mini open-rotor having four forward and three aft blades, and a counter-rotating open-rotor model (F31A31) having 12 forward and 10 aft blades (Ref. 4).

DGEN Aeropropulsion Research Turbofan

The DGEN380 is a geared two-spool, unmixed-flow turbofan, with a maximum static thrust of 250 daN (560 lbf) and a high bypass ratio (7.6). It is a small engine, with a length of 1.126 m (44.3 in.), a fan inlet diameter of 350 mm (13.78 in.), and a maximum diameter of 0.469 m (18.5 in.) (at the exit plane of the bypass nozzle). It is designed for use with vehicles classified as a Personal Light Jets (defined as jets capable of seating from 2 to 5 passengers and cruise at an altitude of up to 25,000 ft at a velocity of Mach 0.45). The maximum takeoff weight of such aircraft is approximately 1,600 kg (3,550 lb), for a range of more than 450 Nm. At the design point (10,000 ft, 0.338 MN, ISA), its thrust is 107 daN (240 lbf) for a specific fuel consumption of 0.768 kg h⁻¹daN⁻¹ (0.771 lbm hr⁻¹ lbf⁻¹). The maximum overall pressure ratio is of 5.3 (1.2 from the fan, 4.6 from the centrifugal compressor). Figure 4 shows these dimensions of the DGEN380.

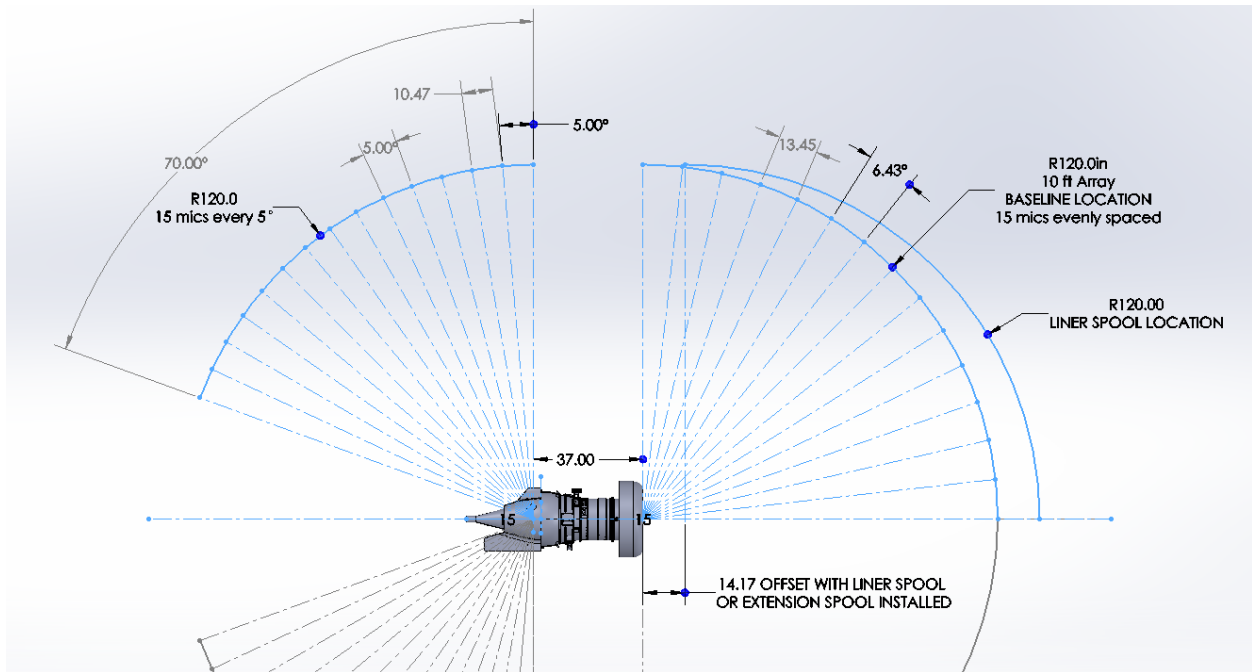


Figure 3.—Circular Array about DGEN380 Engine (shown on LHS). Note: Adjustment of Forward Arc as Engine Inlet is Extended.

TABLE I.—CIRCULAR MICROPHONE ARRAY GEOMETRY

Microphone no.	Referenced to inlet plane, deg	Microphone no.	Referenced to exhaust plane, deg
1	0	16	90
2	6.4	17	95
3	12.9	18	100
4	19.3	19	105
5	25.7	20	110
6	32.1	21	115
7	38.6	22	120
8	45.0	23	125
9	51.4	24	130
10	57.9	25	135
11	64.3	26	140
12	70.7	27	145
13	77.1	28	150
14	83.6	29	155
15	90.0	30	160

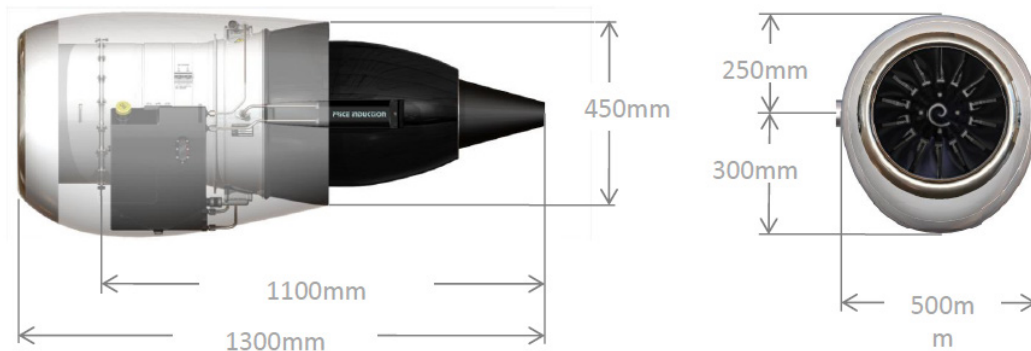


Figure 4.—Price Induction DGEN380 Turbofan Engine Dimensions.

Among its unique features is the all-electric concept. The high-pressure (HP) spool is equipped with a reversible electrical drive, enabling engine ignition and power generation for the aircraft’s requirements. The low-pressure (LP) spool is equipped with a gearbox of reduction ratio 3.32, which enables the LP turbine to reach speeds close to 44,000 RPM, while the fan blade tip speeds remains subsonic (fan diameter is equal to 0.350 m). This allows for a more compact design. The HP spool speed reaches 52,000 RPM at takeoff power. Table II lists the blade/vane counts of these rotating sources.

The DGEN380 was integrated into the AAPL facility by mounting the engine and its associated pylon on a platform. Figure 2 is a schematic of the DART system showing the two locations where the DGEN380 component of DART can be located. For the test program, DART was located in the center location. Measurement of the initial acoustic base lining of the DART was presented in References 5 to 7.

The full authority digital engine control (FADEC) automatic sweep was programmed to achieve 50%... 90%, 92.5%, then 95.6%, return to 50%, and then repeat the 92.5% corrected fan RPM. The 95.6% max speed was initially chosen based on this being the maximum continuous high-pressure turbine speed permitted at standard day conditions (higher HPT speeds would be time-limited for brief durations such as take off). However, operating on hotter days, and the addition of an internal containment shield in case of turbine tri-hub failure (extremely unlikely—but an additional safety requirement when operating in a research paradigm) resulted in the inability to reach 95.6% consistently. The automatic sweep was reprogrammed to stop at a designated max-EGT, which often was lower than 95.6% (Table III).

TABLE II.—DGEN380 BLADE COUNTS

Component	Blades	Vanes
Fan	14	40
Compressor	11	19
HP-turbine	38	19
LP-turbine	38	16

Note: Compressor and HP-turbine are coupled.
LP-turbine and fan are coupled by a 3.32 ratio gearbox.

TABLE III.—DGEN380 TEST SETTINGS

Nominal	Nfan-corr, percent
1	Idle
2	50
3	60
4	70
5	80
6	90
7	92.5
8	^a 95.6
9	50
10	^a 95.6
11	Idle

^aMax fan speed limited by HPT/EGT temperature limits.

Liner Description

Two liner concepts were considered for this study. Figure 5 is a close-up photo of the liner cores showing the spectra. The first is a 2DOF liner that contains a septum of sufficiently high resistance to effectively eliminate sound transmission into the lower chamber (Figure 5(a)). Thus, from an acoustics point of view, it should be considered as an SDOF liner. The second is a MDOF liner that contains two septa in each honeycomb chamber (Figure 5(b)). Each septum has a unique resistance and location within the chamber, and the same distribution is used in each chamber. The liner cores are shown in Figure 5(c). The detailed design characteristics of these liners are presented in the companion paper (Ref. 1).

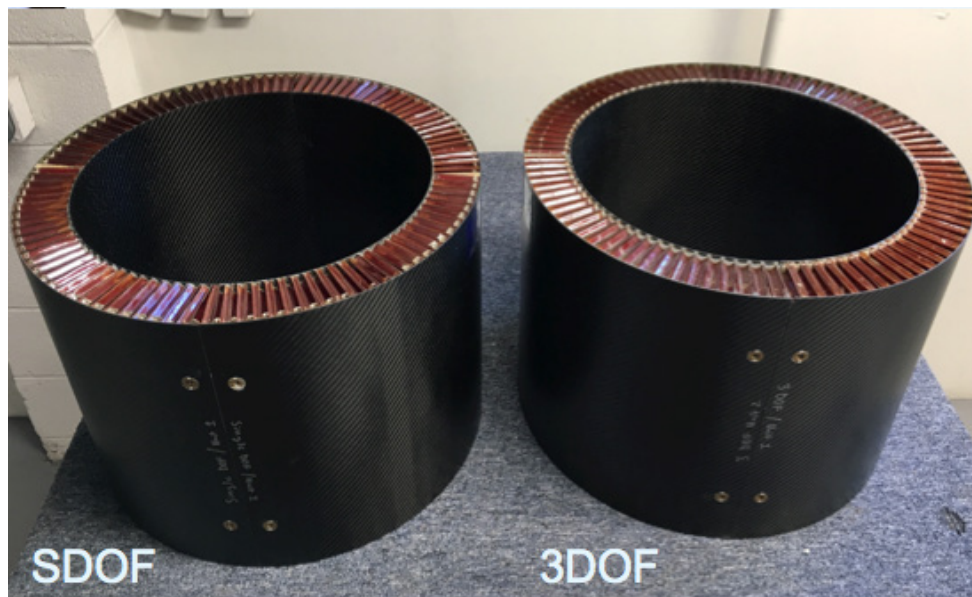
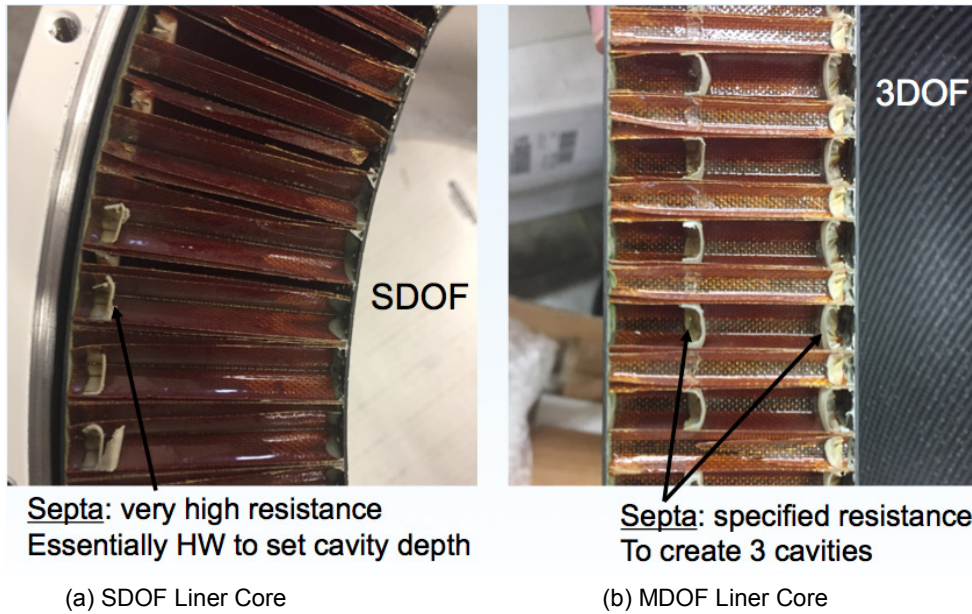
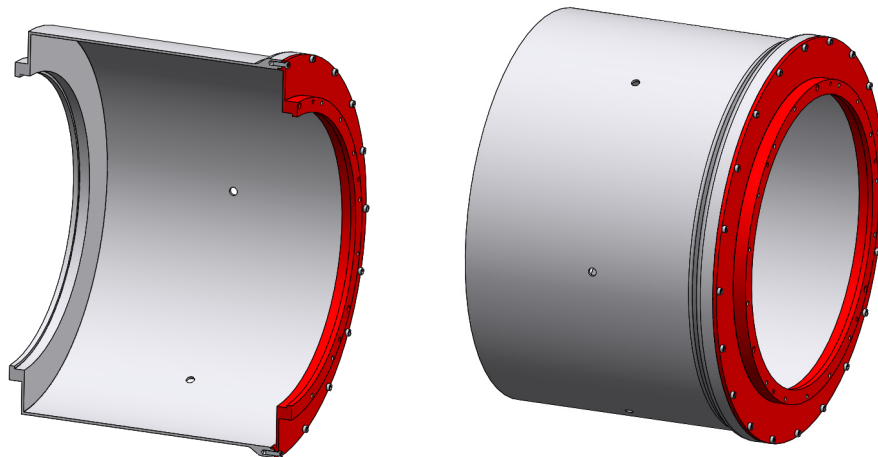


Figure 5.—Photos of the Liner Cores.

A number of MDOF liner concepts have previously been tested successfully (Refs. 8 to 11) at several technology readiness levels TRLs. However, this test addressed a number of new challenges. First, the liners were designed for installation in the inlet of a DGEN380 engine. Because of the small diameter of the engine (~14 in.), it becomes a significant challenge to bend the core to achieve a flush fit. This limited some of the choices for manufacturing the liners. Also, very little information was available regarding the test conditions and source sound fields. Further, the MDOF liner design concept is more suited to the exhaust acoustic/flow environment (Ref. 1). Therefore, a goal of this test was to acquire sufficient data to demonstrate the validity of the liner design process, and to gain insight that could be used to better optimize liners for future tests with this engine.

An inlet spool was designed and manufactured by the DGEN380 vendor, Price Induction, to accommodate the liner cores. The liner cores were placed in this liner-holder spool. This holder was a full cylinder with a removable end cap that allowed for insertion of the liner. Figure 6(a) and (b) are drawings of the holder-spool, with the end cap shown in red. The depth of the holder was chosen to allow for some future additional liner inclusion. Figure 6(c) shows the thin walled, hard-wall, inlet extension spool—this spool is the same axial length as the liner holder spool to provide a new hardwall baseline. Figure 6(d) is a photo of the liner-holder spool with a core installed and the end cap fastened. This spool had a pocket extending from the outer flow path to accommodate the liner cores. A removable end cap was incorporated to allow for quick insertion/removal of the liner cores. Figure 7 is a drawing illustrating the liner spool holder installed in the inlet. Figure 8 is a photo of the extension spool installed in the inlet of the DGEN380 engine.



(a) Half View of Liner Holder Spool

(b) Full View of Liner Holder Spool



(c) Hardwall Inlet Extension Spool



(d) Assembled Liner Holder Spool with Core Installed

Figure 6.—Photo of the Inlet Spool Holder.

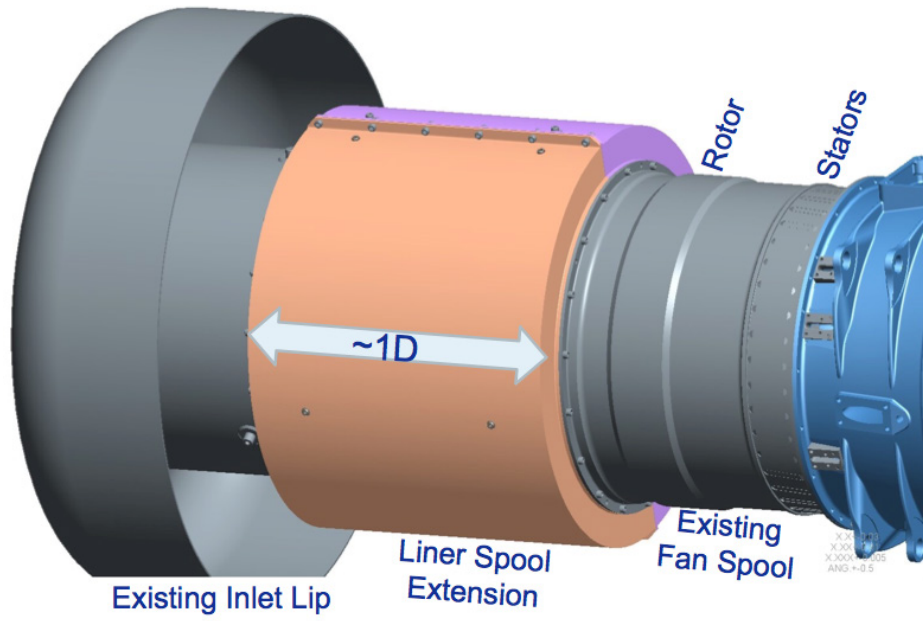


Figure 7.—Schematic of the Inlet Spool Holder Installed in the Inlet of the DGEN380.

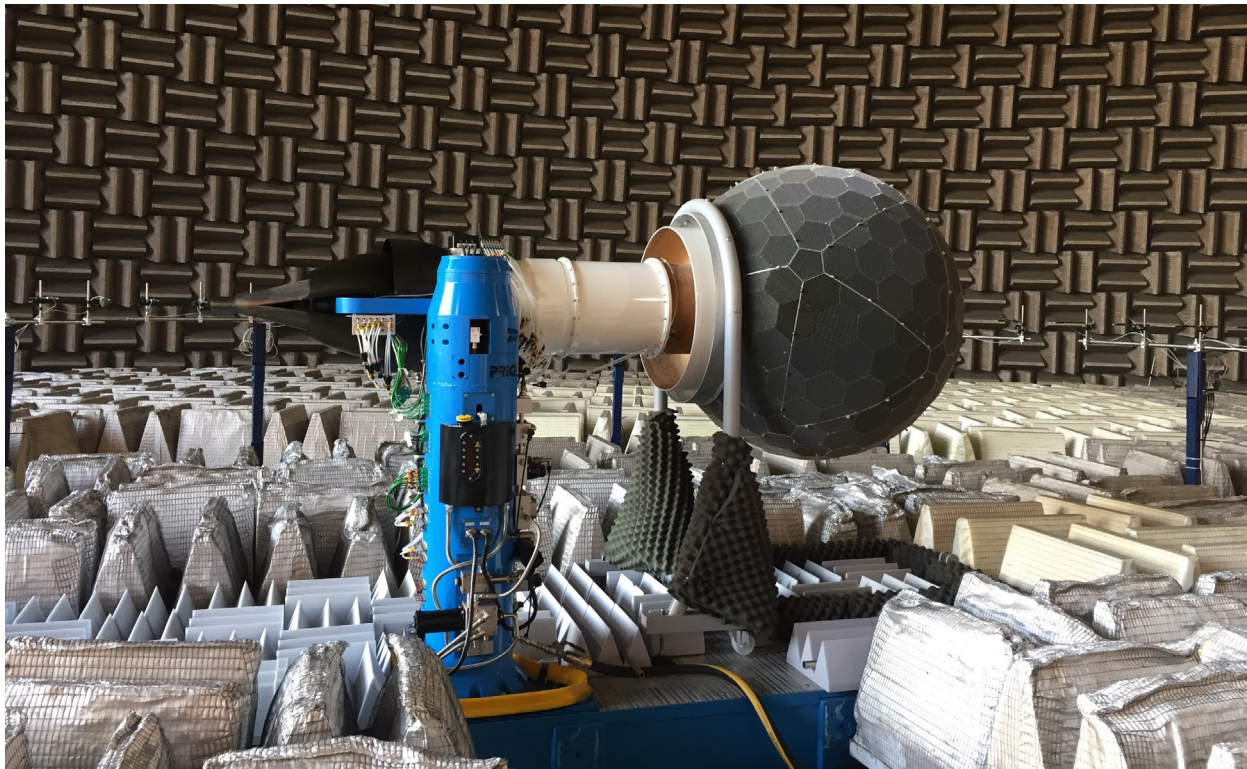


Figure 8.—Photo of DART in the Center of the Aero-Acoustic Propulsion Laboratory. Hardwall Inlet Extension Shown.

TABLE IV.—LINER CONFIGURATIONS TESTED

Date	DGEN configurations	Array
1-Aug-07	Extended inlet/Hardwall (HW)	10 ft arc—LHS
2-Aug-17	MDOF liner	10 ft arc—LHS
3-Aug-17	SDOF liner	10 ft arc—LHS

Configurations Tested

The hardwall inlet insert was tested first to rebaseline the acoustic levels resulting from the additional inlet length. An insert was chosen because the project window-time line did not allow for a design to be integrated in to the DGEN lip/forward fan casing or the more complicated exhaust environment. The paradigm was to evaluate the insertion losses of the liners and compare to the predictions as a validation of the concept, and design tools, not necessarily as a direct proof-of-greater efficacy of the MDOF to SDOF liners. The two liners were then tested on separate days in the center location of the AAPL facility. The same automated FADEC programmed corrected fan speed points were acquired for all three configurations (Table IV).

Results

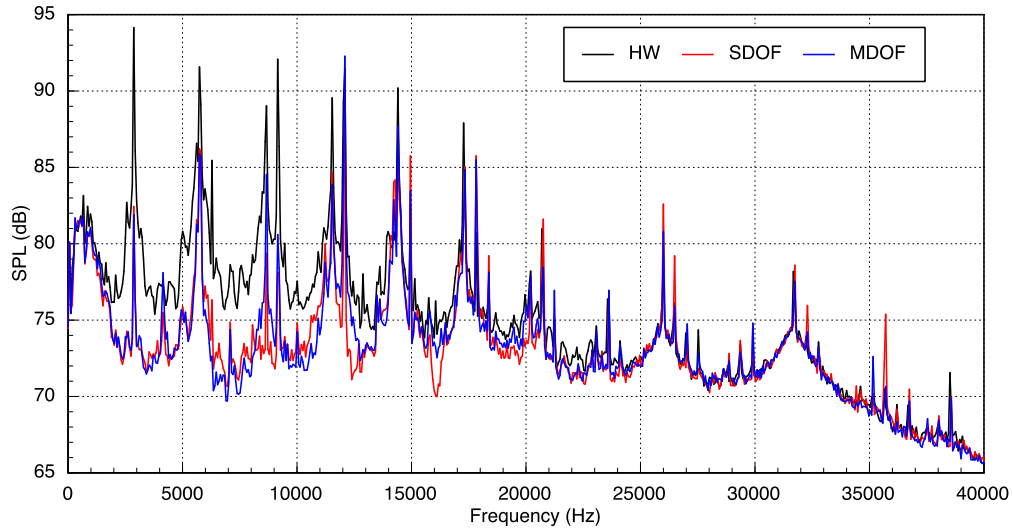
The acoustic directivity results as measured by the circular, 10-ft constant radius microphone array for each of the configurations are presented in this section. The Overall Sound Pressure Level (OASPL) obtained by integrating the spectra over the 100 Hz to 40 kHz frequency range for both the forward quadrants is presented (limited aft quadrant arc directivity is presented as a check). The spectral components are separated into total, broadband, and tonal components as described in Reference 3. In addition the individual tones of the rotating components (fan, compressor, and turbines) and some interaction tones are presented. These data are at 92.5% corrected RPM of the fan.

Representative spectra (microphone no. 9 at 51.4°) for the three configurations are presented on Figure 9. Figure 9(a) presents the full frequency range. It can be seen that the liner attenuation occurs primarily between 2 to 14 kHz; though the SDOF liner has a small additional attenuation at 16 kHz. At very high frequency, the spectra are essentially unchanged. Figure 9(b) zooms in on the frequency axis in order to better illustrate the frequency of interest—also the tones are called out (Table V and Ref. 6). The attenuation from the two liners is very similar and most notable between 2 to 13 kHz.

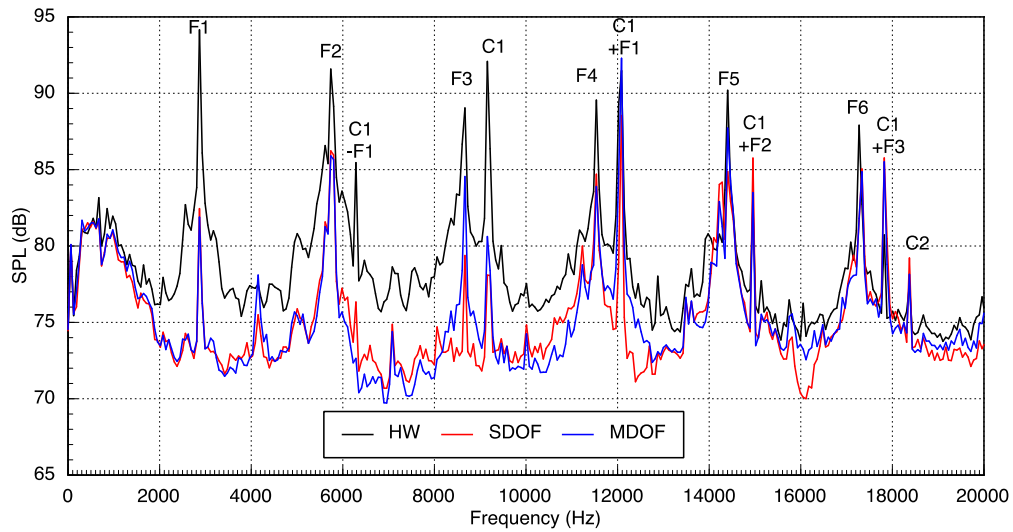
Figure 10 presents the OASPL integrated over the 100 Hz to 40 kHz frequency range. The directivity of the three configurations is presented over both arcs for the total spectral component. The attenuation in the forward quadrant (right arc of polar plot) is apparent, a consistent 1.5 to 3.2 dB attenuation in that arc depending on the propagation angle. As expected the aft directivity levels are unchanged.

Figure 11 shows the OASPL integrated over the 1 to 10 kHz frequency range for the forward quadrant only, and separates the total, broadband, and tonal spectral components. “Zooming-in” on the 1 to 10 kHz frequency is more illustrative of the design target bandwidth of the liners. Figure 11(a) shows the total component. Over this more representative frequency range, the insertion loss of the liners are ~2 to 6 dB, with a peak attenuation of 5.9 dB (MDOF) / 6.2 dB (SDOF) at an angle of 51.4° relative to the engine centerline. The broadband component peak attenuation (Figure 11(b)) is 4.3 dB (MDOF) / 4.2 dB (SDOF) also at 51.4° with a general range of 1.2 to 4.3 dB attenuation. As is typical, the tonal component exhibits more variation due to the complex azimuthal interactions of coherent tones (Figure 11(c)). The range is about 0.5 to 7.5 dB attenuation over the arc, with peak attenuations also at 51.4°: 7.0 dB (SDOF) / 7.5 dB (MDOF). The general observation is the directivity of the two liners insertion loss is completely over the forward quadrant and approximately similar, qualitatively and quantitatively.

Several of the tones in the relevant spectral range were extracted from the spectra. The frequencies of these are listed in Table V. Figure 12 shows the directivity of extracted tones.



(a) Spectra of Full Frequency Range



(b) Spectra Over Effective Design Range of Liners Highlighting Tonal Components

Figure 9.—Representative Spectra (Microphone no. 9 at 51.4°) of the Three Configurations.

TABLE V.—FREQUENCY OF TONAL COMPONENTS

Tonal component	Frequency, Hz
F1 (1 st fan fundamental)	2,837
F2 (2 nd fan fundamental)	5,673
F3 (3 rd fan fundamental)	8,510
F4 (4 th fan fundamental)	11,347
C1 (1 st compressor fundamental)	9,079
C2 (2 nd compressor fundamental)	18,158
C1-F1 (Interaction sum tone)	6,242
C1+F1 (Interaction difference tone)	11,915

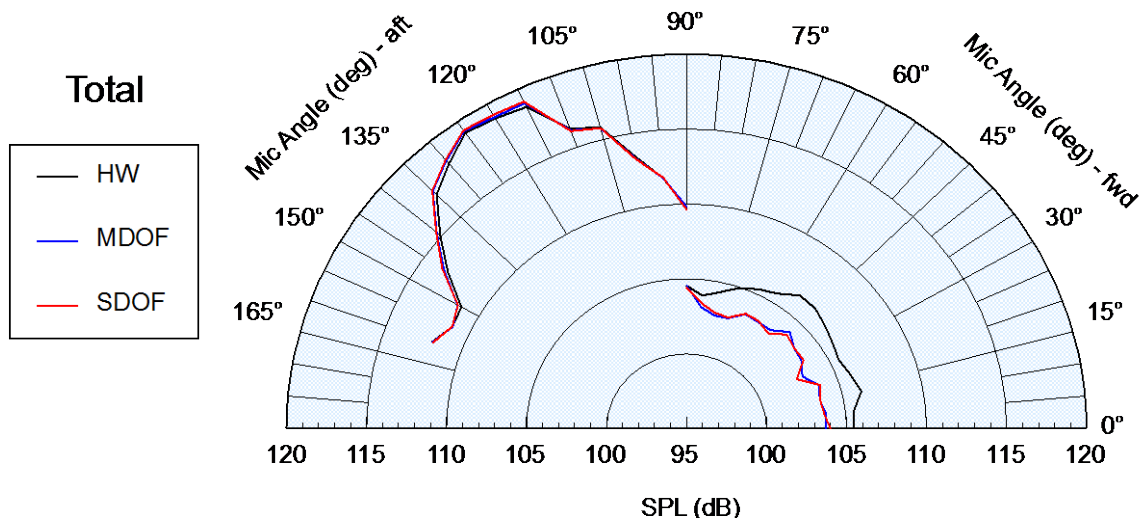
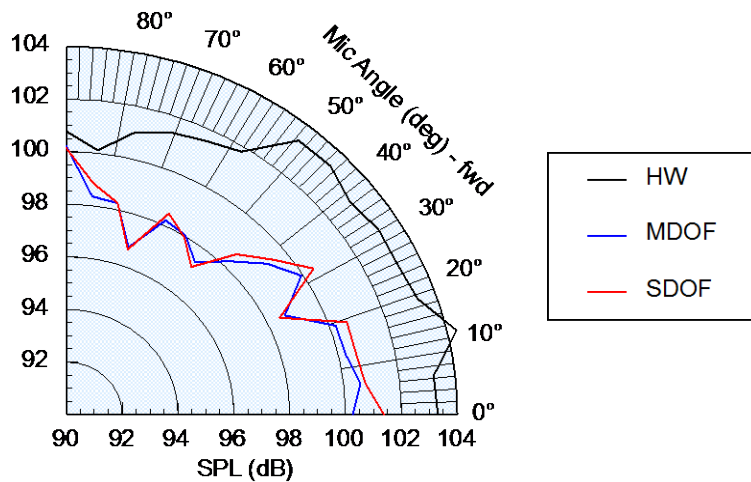
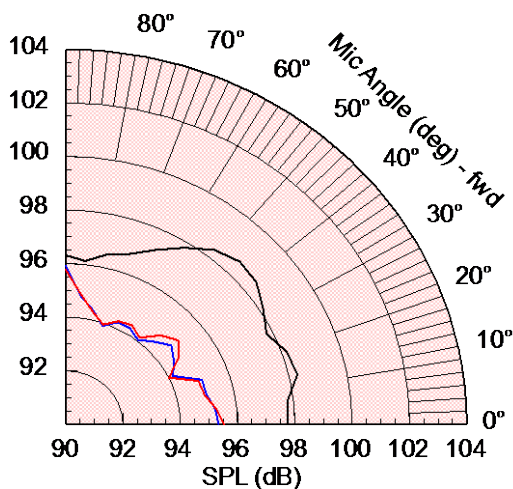


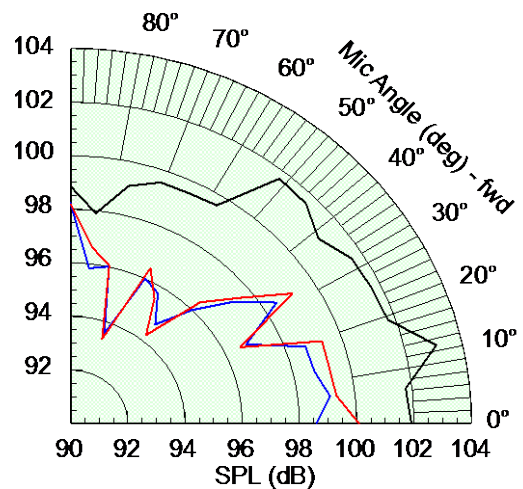
Figure 10.—Farfield Acoustic Directivity of the Three Configurations Tested. (Total—OASPL 100 Hz to 40 kHz).



(a) Total—OASPL 1 to 10 kHz.

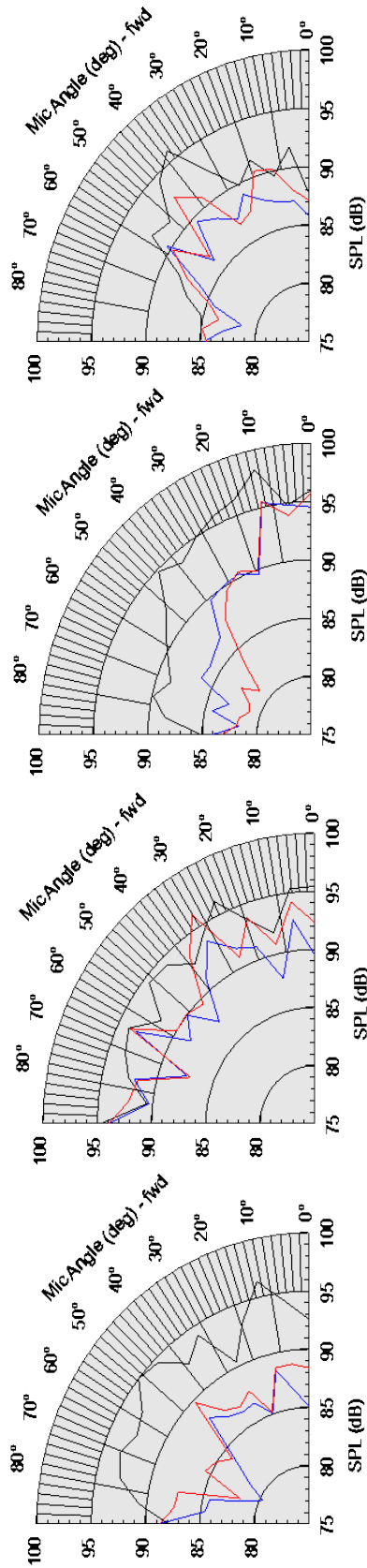


(b) Broadband—OASPL 1 to 10 kHz.



(c) Tonal—OASPL 1 to 10 kHz.

Figure 11.—Separated Spectral Components Forward Arc Acoustic Directivity of the Three Configurations Tested.

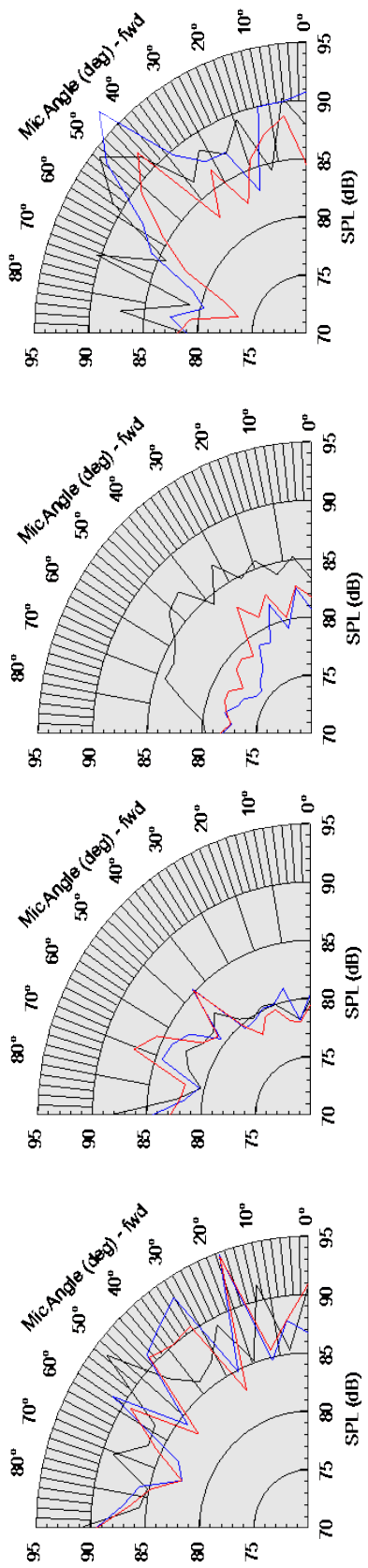


(a) F1 Tonal Insertion Loss

(b) F2 Tonal Insertion Loss

(c) F3 Tonal Insertion Loss

(d) F4 Tonal Insertion Loss



(e) C1 Tonal Insertion Loss

(f) C2 Tonal Insertion Loss

(g) C1 - F1 Tonal Insertion Loss

(h) C1 + F1 Tonal Insertion Loss

Figure 12.—Farfield Acoustic Insertion Loss—Tonal Directivity of the Interaction Tones.

The directivity of the first four fan harmonics is shown in Figure 12(a) to (d). F1 is attenuated significantly, as is F3. These are well within the liner design frequency range. F4 is more modestly attenuated, which is on the edge of the liner bandwidth, so that is a reasonably expected result. F2, however, is within the liner design frequency range and should be attenuated, but shows little or no attenuation.

The first and second compressor harmonic extracted tonal directivities are shown in Figure 12(e) and (f). C1 is within the liner design bandwidth and could be assumed to show attenuation because of its frequency, but does not; in fact, a 4 to 5 dB increase is noted between 30° to 45° radiated angle. C2, well outside the liner frequency design, shows a variation in the tone—most likely unrelated to the liners.

The acoustic directivity of the compressor/fan interactions is shown on Figure 12(g) for the difference tone (C1-F1) and Figure 12(h) for the sum tone (C1+F1). The difference tone is attenuated substantially, an expected result as its frequency is between F2 and F3. The sum interaction tone variation also appears to be due to tonal variation, as it is close in frequency to F4. Referring to the earlier plots in this figure, it is apparent the attenuation in the interaction tones is due to a reduction in the fan tone.

Figure 13(a) is the forward Acoustic Power Level (PWL) obtained from the integration of the directivity curves in Figure 12. The bar graphs confirm the strong attenuation of the fan harmonics (though F2 seems lower than expected) and lack of attenuation of the compressor fundamental. The compressor/fan interaction shows similar results to the fan harmonics, possibly indicating that interaction is dominated by the fan tone. The aft levels are included in Figure 13(b). F1 and F3 show slight increases. Potentially this is due to interaction of the liner splice with the fan, radiating aft, though there is no evidence available to support that conjecture. More probably, it is due to measurement uncertainty or repeatability.

Figure 14 shows the insertion PWL loss of each liner for the range of RPM tested. This is obtained by integrating over the forward microphone array, weighting by the sub-tended area. The insertion loss measured in the forward quadrant for the total, broadband, and tonal components is shown in Figure 14(a) to (c), respectively. The Total PWL insertion loss for the SDOF liner increases as the fan-RPM decreases, mostly due to the variation in tonal attenuation. The broadband PWL insertion is consistent between the two liners across the RPM range ($2.5 < \Delta PWL < 3.4$). For the aft array, the PWL losses are shown on Figure 14(d) to (f). At the lower RPM, a very slight loss is measured, particular at the lower fan speeds, most of which is from the tonal component. It is unlikely if these levels are significant, due to tonal variation, and the measurement uncertainty. A more relevant observation is that the aft levels are unaffected.

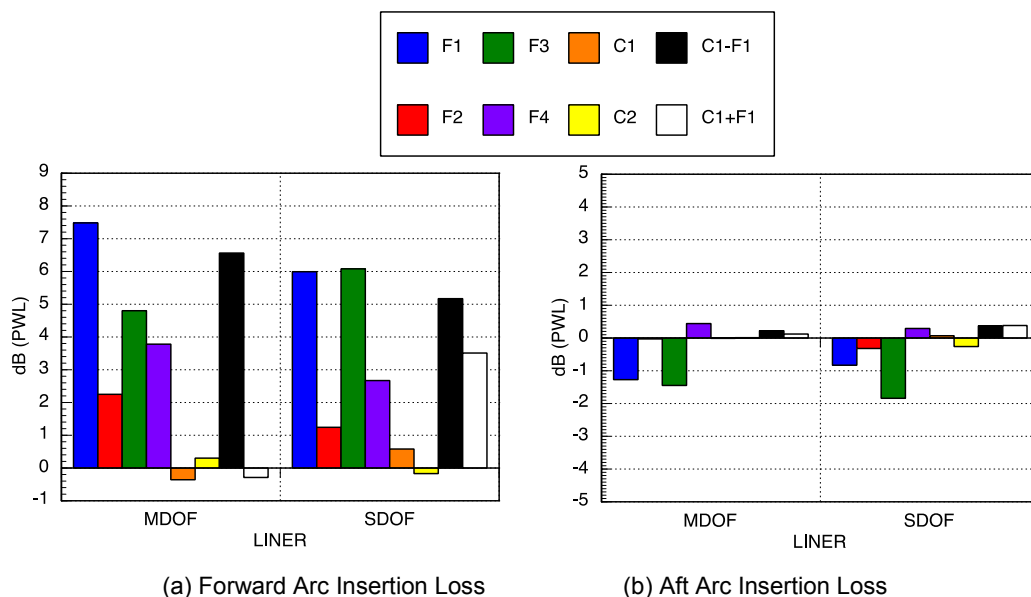
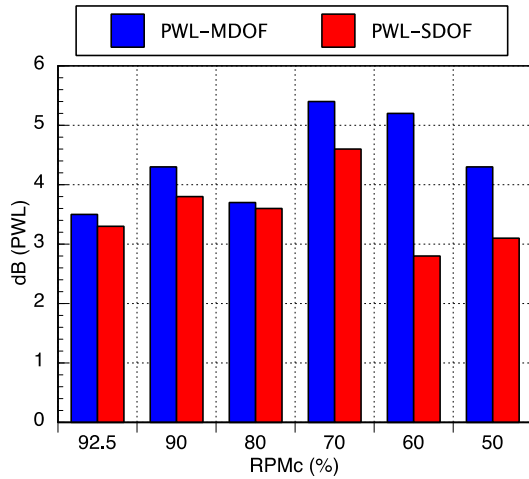
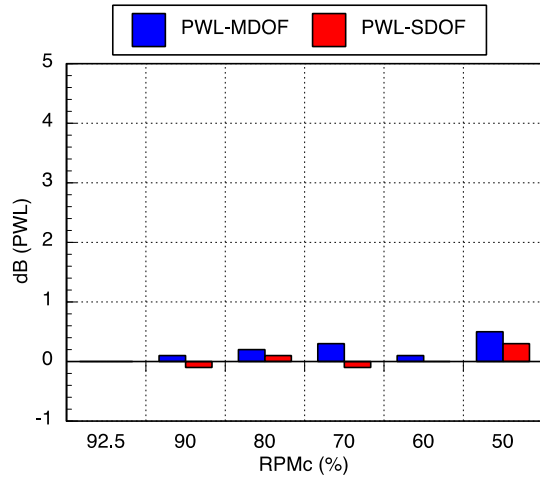


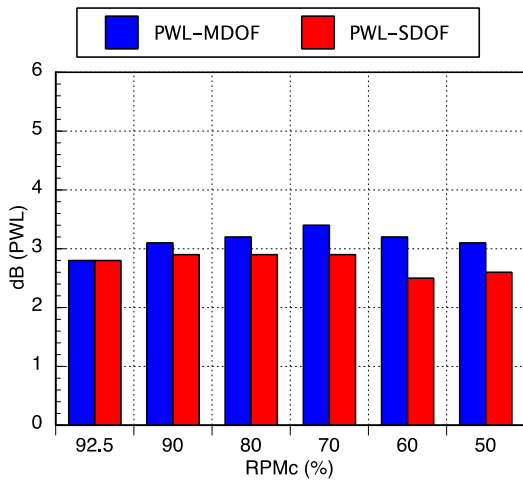
Figure 13.—Farfield Acoustic Insertion Loss Tonal Directivity of the Interaction Tones.



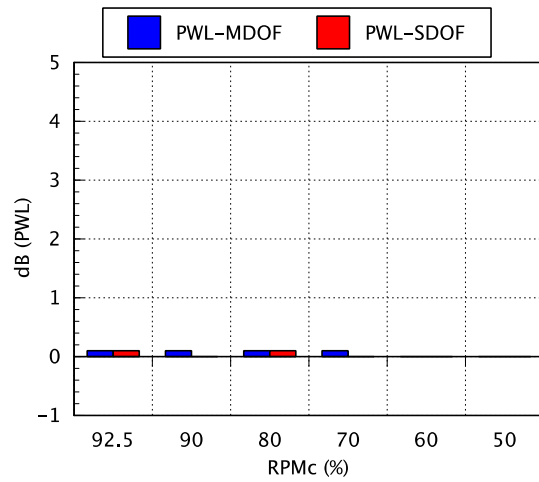
(a) Total PWL Insertion Loss—Forward Arc



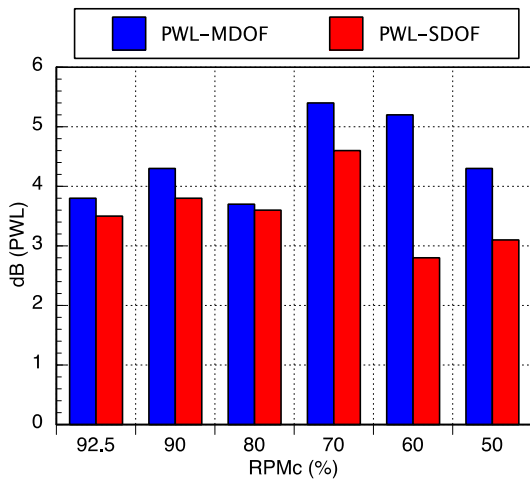
(d) Total PWL Insertion Loss—Aft Arc



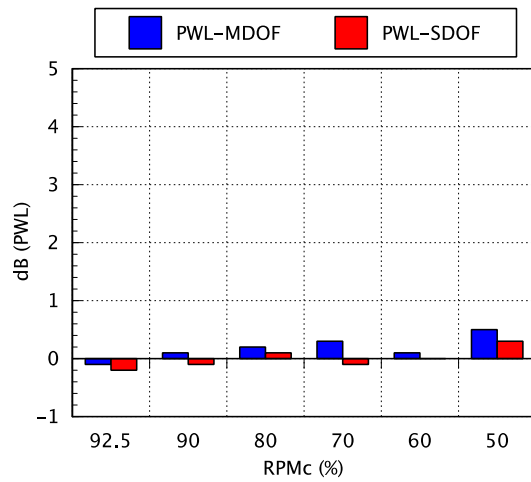
(b) Broadband PWL Insertion Loss—Forward Arc



(e) Broadband PWL Insertion Loss—Aft Arc



(c) Tonal PWL Insertion Loss—Forward Arc



(f) Tonal PWL Insertion Loss—Aft Arc

Figure 14.—Insertion Losses vs. RPMc.

Conclusion

The NASA Glenn Research Center's DGEN Aeropropulsion Research Turbofan (DART) test rig was utilized to evaluate the acoustic performance of an advanced MDOF liner in the NASA Glenn Aero-Acoustic Propulsion Laboratory. Farfield acoustic directivity from a constant radius microphone array was obtained. A proven-tone separation technique provided tonal and broadband analysis of the insertion losses. Interaction tones were isolated from the spectra and evaluated independently.

The insertion loss of the MDOF liner was measured at 3.5 dB PWL at 92.5% fan-RPMc and slightly higher at the lower operating range of the engine. These levels were slightly better than a traditional SDOF liner installed on the DART using the same design process. However, this was a result of the aero-acoustic environment in the inlet limiting the amount of attenuation potential.

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