Validation of a polyimide foam model for use in transmission loss applications

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1 INTRODUCTION

In this paper, the use of polyimide foam as a lining in double panel applications is considered. The material used in the present work was a PolyuMAC polyimide foam that was the result of a joint development between PolyuMAC TechnoCore, Inc. and the NASA Langley Research Center (LaRC) Advanced Materials and Processing Branch. Polyimide foam has a number of attractive functional attributes, not the least of which is its high fire resistance, thus making its use desirable in some sound transmission applications, including aircraft sidewall treatments. However, in initial testing, it was found that the flow resistivity of the foam was too high to provide optimal acoustic dissipation. As a result, a process was developed to reduce the foam's flow resistivity by crushing it in a systematic manner. All of the results presented here are for polyimide foams that have been treated in this way. The particular configuration studied here consisted of two 1 mm (0.04 in.) thick, flat aluminum panels separated by 12.7 cm (5.0 in.), with a 7.6 cm (3.0 in.) thick layer of foam centered in that space. Random incidence transmission loss measurements were conducted on this buildup, and conventional poro-elastic models were used to predict the performance of the lining material. The Biot parameters of the foam were determined by a combination of direct measurement (for density, flow resistivity and Young's modulus) and inverse characterization procedures (for porosity, tortuosity, viscous and thermal characteristic length, Poisson's ratio and loss factor). The inverse characterization procedure involved matching normal incidence standing wave tube measurements of absorption coefficient and transmission loss of the isolated foam with finite element predictions. When the foam parameters determined in this way were used to predict the performance of the complete double panel system, reasonable agreement between the measured transmission loss and predictions made using a commercial statistical energy analysis code was obtained. Note that previously published work related to polyimide foams has concentrated on its anisotropy[1] and the effect of rear surface mounting conditions in standing wave tubes.[2]

2 POLYIMIDE FOAM

PolyuMAC polyimide foam insulation is the result of a joint development between PolyuMAC TechnoCore, Inc. and NASA LaRC, and is being commercialized by PolyuMAC under a joint ownership agreement. A previously developed NASA LaRC foam, given the designation TEEK, is a higher density, structural foam that is relatively expensive to produce. A need was identified by both LaRC and PolyuMAC TechnoCore, Inc. for a lower cost, low-density, flexible polyimide foam, which was designed to have excellent thermal and acoustical insulation properties for naval shipboard applications. This newly co-developed polyimide foam insulation[3,4] had the physical property characteristics to meet the requirements of the applications of interest, including aircraft sidewall insulation. These new polyimide foams are produced at low densities ranging from 3.2 to 16 kg/m^3 (0.2 to 1.0 pounds per cubic foot (pcf)) and can be utilized as thermal and/or acoustical insulation. It is important to note that polyimide materials are inherently fire retardant due to their chemical composition. This new foam technology has the advantage over previous polyimide foams of being manufactured and cured using microwave energy at a lower cost and faster production rate. Figure 1 shows the general flow by which the polyimide foam is manufactured. This technology allows production of both rigid and flexible foam insulation while the previous technology (TEEK) could only be used to produce rigid, structural foam. This technology represents the first polyimide foams that rise at room

temperature and are then cured using a microwave, thus producing foam insulation with acceptable thermal and acoustic insulating properties.
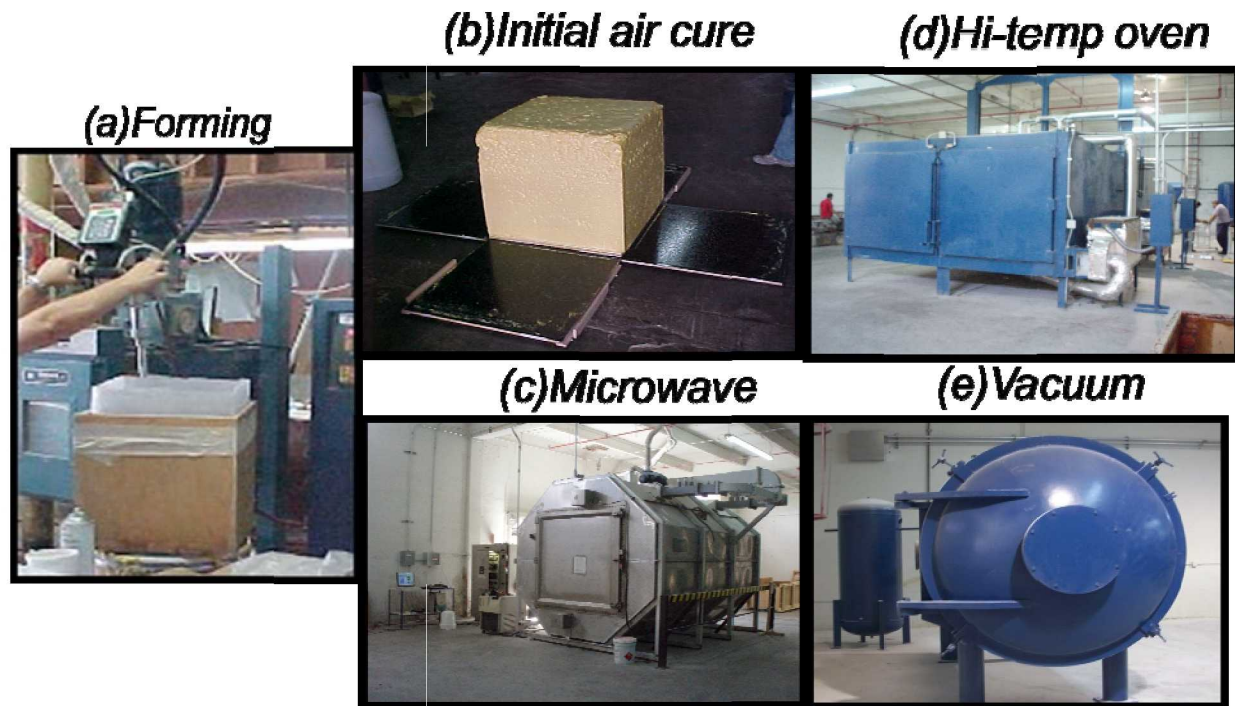
Figure 1. *Process flow for polyimide foam currently being produced by PolyuMAC TechnoCore Inc.*

3   MATERIAL CHARACTERIZATION

3.1 General Approach

It was of interest here to establish whether the acoustical performance of the processed polyimide foam could be predicted using conventional predictive tools. Here the foam was modeled as a homogeneous, isotropic poro-elastic medium, whose macroscopic properties are represented by the so-called Biot parameters. Those parameters include the bulk density, flow resistivity, Young's modulus, porosity, tortuosity, viscous and thermal characteristic length, Poisson's ratio and structural loss factor. In the present work, the first three of these parameters were determined by direct measurement: details regarding the flow resistivity and Young's modulus measurements are given in the next two sections. The remaining six parameters were determined through an inverse characterization process, in which model predictions were compared with measurements of normal incidence absorption coefficient and transmission loss made in a standing wave tube: that process is described in Section 3.4, below. Note that all of the Biot parameters given in this section are for foams that have been processed by crushing, as described in Section 3.3, below.

3.2 Flow Resistivity Measurement

Flow resistivity data was acquired using a raylometer operated by the Structural Acoustics Branch at NASA LaRC (Fig. 2). The raylometer determines flow resistance by measuring the

difference in static pressure across a material sample for a given incident air velocity. The ratio of the static pressure difference to the incident velocity (in MKS units on a per meter basis) is the flow resistivity. A series of electronic mass flow controllers are used to meter out the precise amount of air required for a desired incident velocity. High-accuracy pressure transducers record the differential pressure from a series of static pressure taps located upstream and downstream of the sample. Figure 3 shows a representative sample of foam and the holder used to constrain the sample in the raylometer. Note that the sample is retained in the holder by high-porosity, phenolic honeycomb with negligible flow resistance. For this investigation, ten, 5.08 cm (2 in.) cubic samples of the foam material were tested at incident flow velocities between 0.2 cm/sec and 2 cm/sec. These incident velocities correspond to particle velocities that would bracket the range experienced in an aircraft sidewall installation. The ten samples were cut from 5.08 cm thick, 10 cm dia. impedance tube samples tested previously at Purdue.

Results from the resistivity measurements are shown in Table 1 and Fig. 4. Nominal average flow resistivity (extrapolated to 0 cm/sec) was approximately 28000 MKS Rayls/m with significant sample-to-sample variability. The standard deviation in resistivity for any given velocity was on the order of one-third of the average value. Also of note, the resistivity values for sample S4 were substantially lower than for the other samples as shown in Fig. 4. When treating that data set as an outlier and recalculating the averages, the extrapolated 0 cm/sec value increased to approximately 29000 MKS Rayls/m. That resistivity value was used as one of the measured parameters in the acoustic model.

Figure 2. NASA Langley Raylometer.
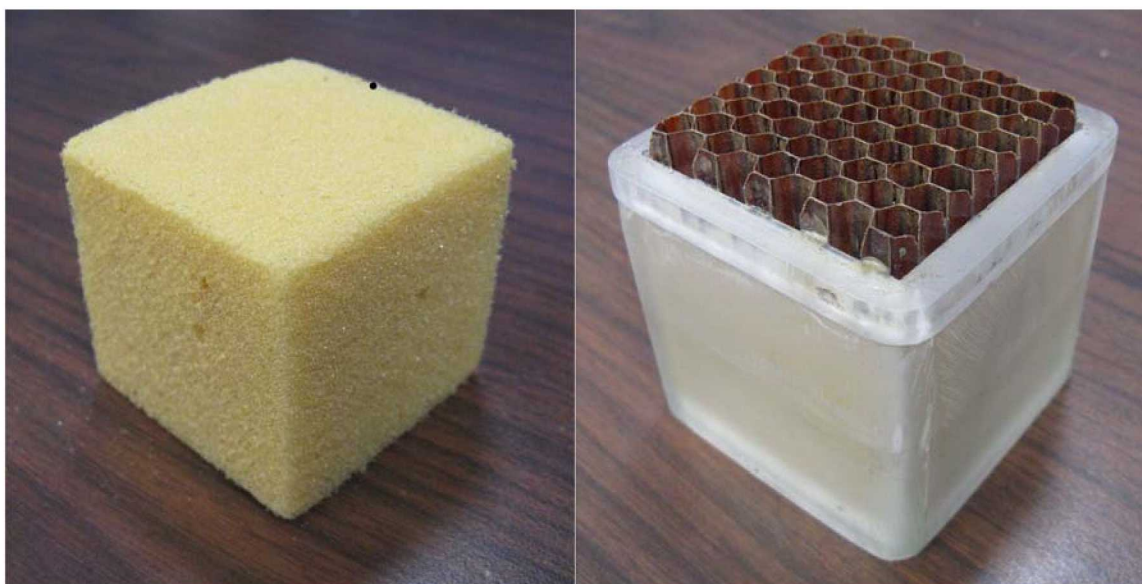
Figure 3.   Representative polyimide foam sample and sample holder with honeycomb retainer.

Table 1. Flow resistivity data for 9.6 kg/m³ (0.6 pcf) crushed polyimide foam.

| Velocity (cm/sec)	Flow Resistivity (MKS Rayls/m)									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
2.0	48078	42455	23380	13702	40035	36315	32759	32637	34638	26108
1.0	45386	39098	21593	11326	40775	33327	32252	29844	32353	25004
0.7	41390	41107	23478	8791	38089	34589	27922	27309	31786	15556
0.5	49181	37651	20634	10581	37165	30809	29410	29115	30121	24489
0.3	39619	34173	18106	2773	41695	26663	21860	20570	32676	22733
0.2	46031	35683	21175	21706	17750	36762	27946	30291	27659	20404
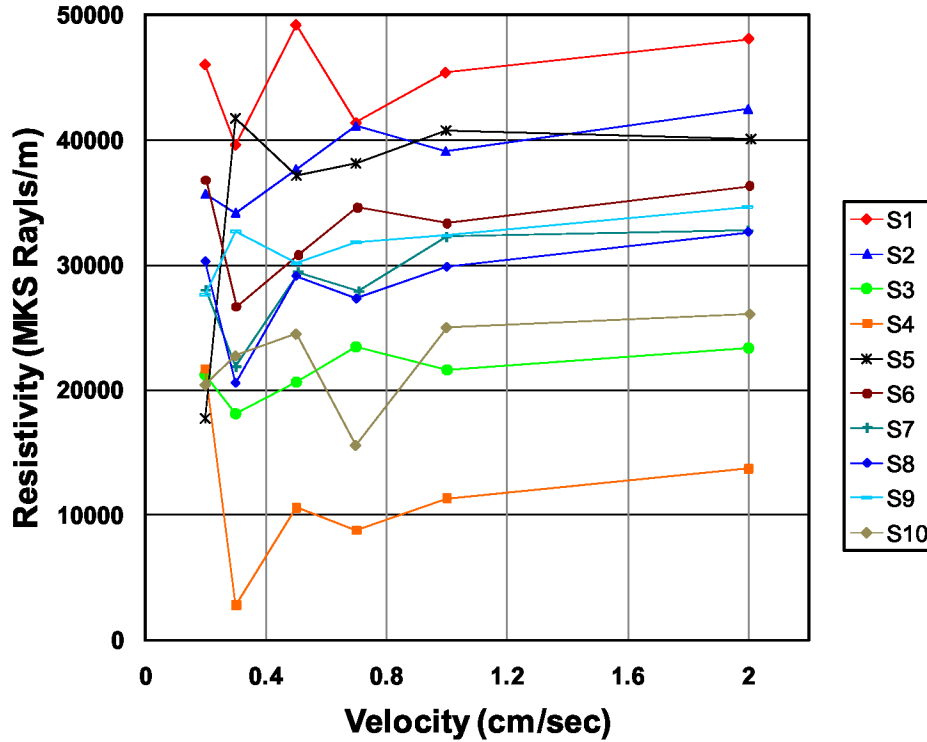
Figure 4. Flow resistivity data for 9.6 kg/m^3 (0.6 pcf) crushed polyimide foam.

3.3 Stiffness Measurement

Compression tests to obtain the Young's modulus of the foam were performed using an Instron 5848 MicroTester fixture. Samples were measured in inches in three directions to two decimal places and then loaded into the test fixture. The Load and Gauge Length were zeroed. Samples were pre-loaded to 140 Pa, and the plates were loaded at 25 mm/min. When this pre-load is tripped, the Compressive Strain is zeroed, and the rate reduces to 5 mm/min to 10 percent Compressive Strain. At test completion the anvil returns to gauge height.

Table 2 shows the effect of compressing 11.9 kg/m^3 (0.74 pcf) as-received foam from PolyuMAC on the resultant modulus. Crushing the foam once in the *Z*, or rise, direction to 10 percent of its original thickness then allowing it to recover (nominal > 90 percent recovery of height within 24 hours) results in a measured modulus reduction of 80 percent. Additional crushing in the other two directions further reduces the modulus. However, the further reduction in modulus is not significant enough to warrant the additional processing. Therefore, it was determined that a compression cycle to 10 percent of the foam's original height/thickness would provide the proper tailoring effect. As shown in Fig. 5, the compression cycles caused the cell membranes to open and most likely buckled the cell struts as well. This tailoring process not only reduces the modulus and improves its flexibility; it also reduces the flow resistivity by breaking many of the membranes that partially close the foam's cells.

The foam utilized for this study was provided by PolyuMAC as precut specimens that were compressed at NASA LaRC to 10 percent of their thickness, allowed to recover then shipped to Gulfstream for full-scale transmission loss testing. The same material samples were subjected to

further testing at Purdue and then shipped back to NASA where samples were cut to measure the flow resistivity and the modulus of the compressed foam. The 0.6 pcf foam had an average modulus of 134.67 kPa ± 14.63 kPa. The individual sample results are shown in Table 3.

Figure 5. SEM Photographs of uncrushed and crushed/recovered polyimide foam samples.

Table 2. Effect of compression on modulus of 11.9 kg/m³ (0.74 pcf) polyimide foam.

Condition	Modulus
Uncrushed	462.0 kPa ± 128.0 kPa
Crushed once in the Z direction	96.9 kPa ± 4.9 kPa
Crushed once in 3 directions	63.6 kPa ± 22.8 kPa

Table 3. Measured modulus for individual 9.6 kg/m³ (0.6 pcf) foam specimens (samples taken from same foam tested at both Gulfstream and Purdue).

Sample	1	2	3	4	5	6	7	8	9	10
Modulus (kPa)	121.53	140.33	125.60	125.44	111.60	134.92	140.12	158.17	133.44	155.62

3.4 Inverse Characterization

The properties other than bulk density, flow resistivity, Young's modulus and porosity were estimated by using an inverse characterization procedure. Note that the porosity was fixed at 0.99, which is typical for sound absorbing materials. In this approach, samples of foam were tested in both two and four-microphone standing wave tubes[5,6] to measure their normal incidence absorption coefficient (with the sample placed flush against a hard backing) and normal incidence transmission loss. Ten, 5 cm deep samples of both 10 cm and 2.9 cm diameters were tested, to produce average absorption coefficients and transmission losses. The measurements were then provided as input to a version of the software COMET/Trim that matches transmission loss and absorption coefficients by adjusting model parameters. In this case, density, flow resistivity and Young's modulus were fixed at their measured values, and the porosity was fixed at 0.99 as noted. The remaining five parameters were estimated by using an optimization procedure built in to COMET/Trim. The version of COMET/Trim used in this work was based on the finite element software COMET/Safe that implements the Biot poro-elastic theory. It is necessary to use a finite element-based procedure to account for the effects of the sample constraint by friction around its circumferential edge.[7,8] The latter constraint can introduce a low frequency, shearing resonance of the sample, which is particularly noticeable in transmission loss measurements. A finite-element-based inverse procedure can reproduce the latter feature, and enhances the ability of the inverse characterization to identify the stiffness properties of the material. This procedure is described in detail in Ref. 5, along with guidelines to establish how many parameters can be successfully identified by inverse methods.

3.5 Summary of Material Properties

The Biot parameters for the polyimide foam considered here, determined from the combination of direct measurements and the inverse characterization described above, are listed in Table 4.

Table 4. Biot parameters for polyimide foam.

	9.6 kg/m^3 (0.6 pcf) polyimide foam
Density (kg/m^3)	9.6
Flow resistivity (MKS Rayls/m)	29000
Porosity	0.99
Tortuosity	3.11
Viscous characteristic length (10^{-6}m)	66.9
Thermal characteristic length (10^{-6}m)	268
Young's modulus (kPa)	135
Loss factor	0.42
Poisson's ratio	0.21

4   MEASUREMENT OF TRANSMISSION LOSS

The sound transmission loss of a double-wall structure, in which the foam acts as the absorptive layer, was measured in the Gulfstream Aerospace Corporation (GAC) Acoustic Test Facility (ATF) using the ASTM E2249 standard.[10] The test setup consisted of the test structure mounted in a 1.2 m × 1.2 m × 0.14 m transmission loss tunnel between a 252 m^3 reverberation chamber and a 215 m^3 hemi-anechoic chamber. The test structure, shown in Fig. 6 comprised two, 1 mm aluminum panels, one layer of 7.6 cm thick polyimide foam and two 2.54 cm air gaps between the foam and each aluminum panel. The foam was supported on both sides at the perimeter by 2.54 cm × 2.54 cm wood spacers, which also acted as the standoff for the aluminum panels. An acoustic duct sealant was used at the edges to provide protection against acoustic flanking.

The noise level in the source reverberation room was measured with a rotating boom microphone, and the transmitted energy was measured by a scanning sound-intensity probe. The transmission loss was calculated according to Ref. 10 and the results are shown in Fig. 7.
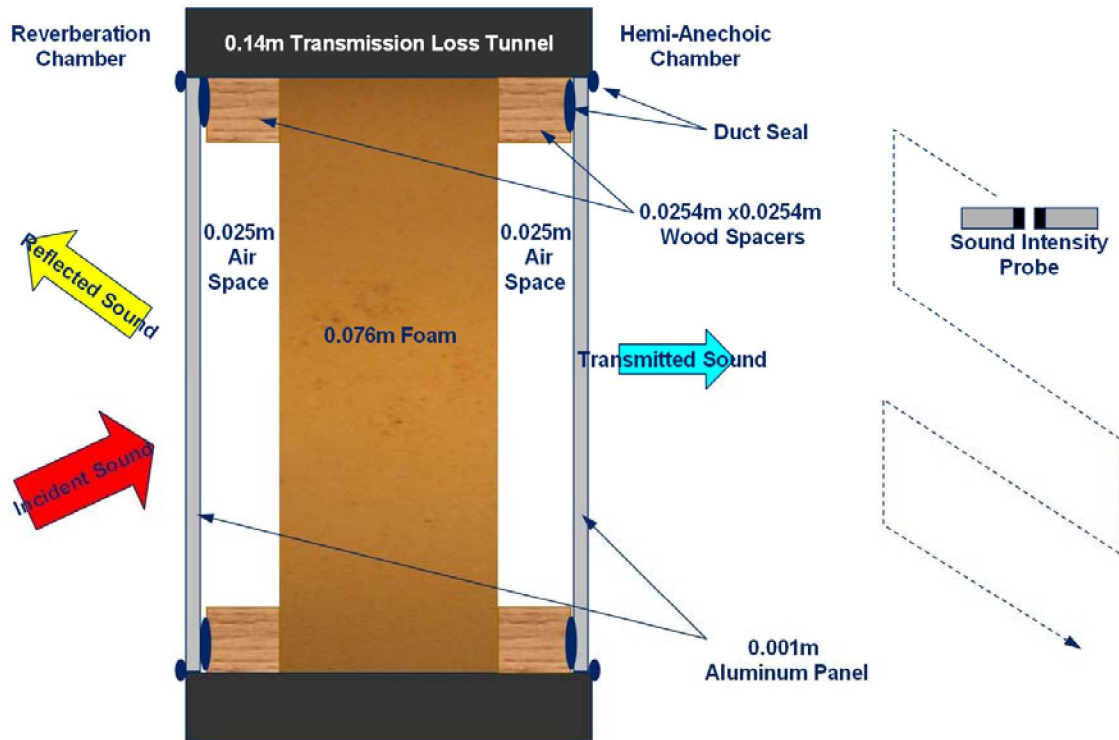

Figure 6. Transmission loss test setup of the double-wall structure.

5   COMPARISON OF MEASURED AND PREDICTED TRANSMISSION LOSS

The transmission loss of the double-wall structure shown in Fig. 6 was predicted with the Statistical Energy Analysis (SEA) software VA One.[11] The TL prediction method is based on simulating the ASTM E-90[12] sound transmission loss standard using two reverberation rooms: see Fig. 8. The modeled configuration was a double wall system with 1mm thick aluminum face

sheets, 2.54 cm air gaps and a centered 7.6 cm thick polyimide foam layer, using the foam properties as defined in Section 3.
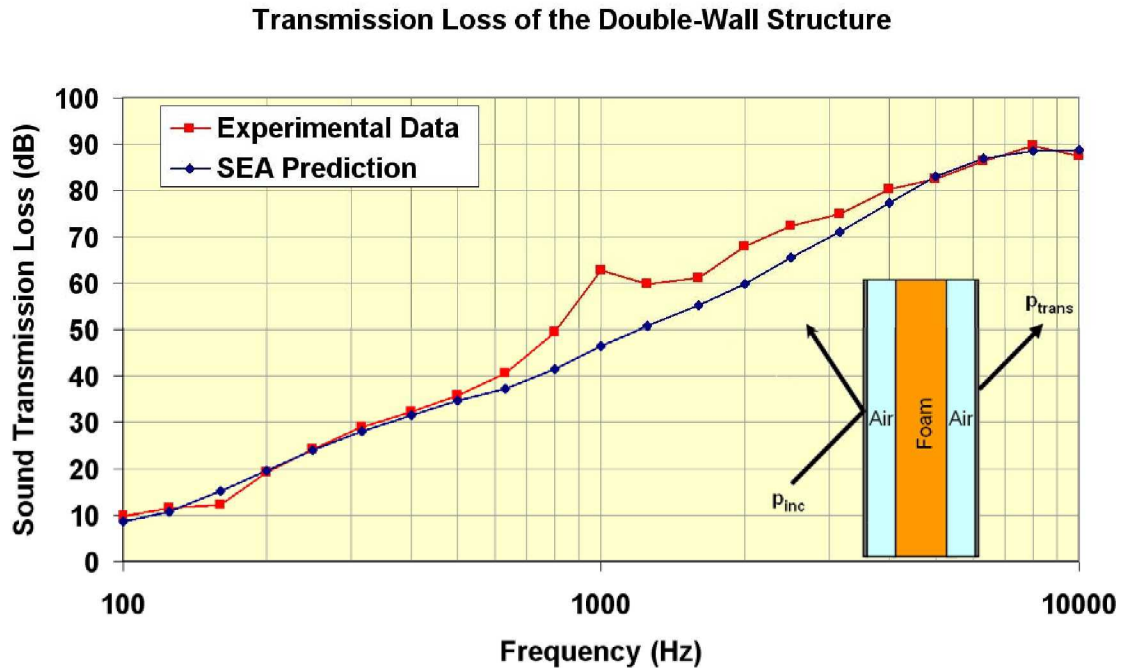
Transmission Loss of the Double-Wall Structure

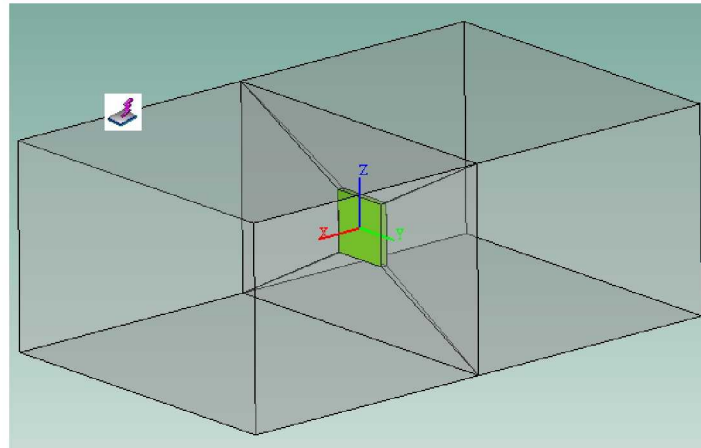*Figure 7. Comparison of the SEA predictions to the experimental data.*

Figure 8. Double wall TL model in VA One.

The VA One prediction is compared to the experimental data in Fig. 7. The prediction correlates well with the experimental data below 630 Hz and above 4000 Hz. However, the transmission loss is under-predicted in the mid-frequency range: the origin of that discrepancy has not yet been identified.

6   CONCLUSIONS

The work described in this paper was focused on the use of a new polyimide foam in a double wall sound transmission loss application. Recall that polyimide foams are functionally attractive, compared to polyurethane foams, for example, owing to their fire resistance. The foam

considered here was found to have a flow resistivity that was too high for conventional acoustical applications, and as a result, it was processed by partial crushing to lower the flow resistivity into an acceptable range. Procedures for measuring the flow resistivity and Young's modulus of the material have been described, as was an inverse characterization procedure for estimating the remaining Biot parameters based on standing wave tube measurements of transmission loss and absorption coefficient. The inverse characterization was performed using a finite element model implementation of the Biot poro-elastic material theory. Those parameters were then used to predict the sound transmission loss of a double panel system lined with polyimide foam, and the predictions were compared with full-scale transmission loss measurements. The agreement between the two was reasonable, especially in the high and low frequency limits; however, it was found that the SEA model resulted in an under-prediction of the transmission loss in the mid-frequency range. Nonetheless, it was concluded that the performance of polyimide foam could be predicted using conventional poro-elastic material models and that polyimide foam may offer an attractive alternative to other double wall linings in certain situations: e.g., when fire resistance is a key issue. Future work will concentrate on reducing the density of the foam to values similar to those used in current aircraft sidewall treatments, and developing procedures to improve the performance of the foam in transmission loss applications.

7   ACKNOWLEDGEMENTS

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