On the Alleviation of Background Noise for the High-Lift Common Research Model Aeroacoustic Test

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Abstract

Microphone array measurements of the airframe noise from the High-Lift Common Research Model (CRM-HL) in the NASA Langley 14- by 22- Foot Subsonic Tunnel were initially hindered by extraneous noise sources. The steps taken to reduce the **background noise in the open-jet test section for the aeroacoustic test are described in this paper. Adhesive-backed felt was used to attenuate noise resulting from the interaction of the test section shear layer with the collector and diffuser surfaces, scrubbing noise from the floor perforated panels, as well as an extraneous noise source produced near the junction of the model and the floor when the model was producing significant lift. The effects of the felt-on noise attenuation and acoustic reflections are discussed. Following the CRM-HL test, scrubbing noise measurements from a floor basket top were acquired in the Quiet Flow Facility to compare the performance of different perforated panel covers and their respective effects on the noise spectra. Aside from a smooth, hard wall, the felt cover was found to produce the minimum scrubbing noise of all the materials tested.**

1. Introduction

An aeroacoustic test was conducted in the 14- by 22- Foot Subsonic Tunnel (14x22) at the NASA Langley Research Center to evaluate slat noise reduction concepts on the High-Lift Common Research Model (CRM-HL) [1]. Results from this test are reported in References 2-6. Prior to and during this test entry, steps were taken to reduce background noise in the facility's acoustic testing configuration, especially scrubbing noise from the test section floor, as well as flow/structure interaction noise from the collector region. These efforts are the subject of this paper. When configured for aeroacoustic testing, the side walls of the 14x22 test section are removed, the ceiling is raised above the flow shear layer, and surfaces away from the tunnel flow are covered with acoustic treatment. The test section floor, which consists of gridded baskets that are recessed and filled with foam, provides an acoustically absorbent and streamlined surface for the wind tunnel flow. Prior to the CRM-HL test entry, modifications to the test section attempted to address some background noise and acoustic reflection issues that had been noted in past tests. Figure 1 shows photographs and a sketch of recent modifications applied to the test section. The solid leading edges of the collector and diffuser were replaced with acoustic treatment consisting of perforated contoured surfaces with fiberglass backing. Additionally, perforated panels were added to the top of the floor baskets to alleviate the scrubbing noise produced by the foam and grid that were previously exposed to the test section flow. This floor treatment modification originally called for a fine stainless steel mesh cover to be fused to the perforated panels. However, because of concerns about cost and lead time for material delivery,

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the perforated panels were installed without the fine mesh covering. Close-ups of the top of the floor baskets before and after the installation of the perforated panels are also shown in Figure 1.

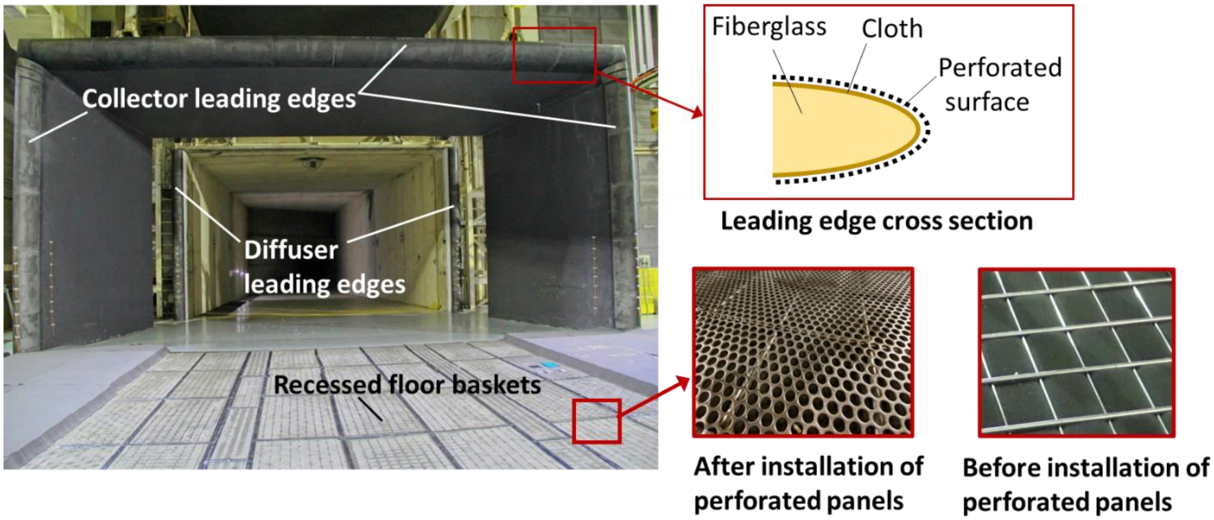

Figure 1. NASA LaRC 14x22 collector and diffuser leading edge treatment, and close-up photos of top of floor baskets before and after the installation of perforated panels.

Although this recent addition of the perforated panels to the floor baskets was expected to reduce scrubbing noise in the high frequency range (above 20-25 kHz, based on past experiments), it was also expected to lead to an increase in noise in the lower frequency range because of the absence of the fine steel mesh cover. Concerns were also raised about the lower frequency noise being further exacerbated by the presence of gaps between the baskets' foam filling and the perforated panels, as the grid that formed the top of each basket kept the foam from being perfectly flush with the back of the perforated panels (as illustrated in Figure 2a). To address this concern, an experimental study was conducted in the NASA Langley Quiet Flow Facility (QFF) prior to the CRM-HL test entry in the 14x22 to try to minimize this expected low frequency noise increase by evaluating different materials in the gap between the foam and panel. Scrubbing noise measurements were also acquired in the QFF following the 14x22 CRM-HL test to investigate different materials as covers on top of the perforated panels.

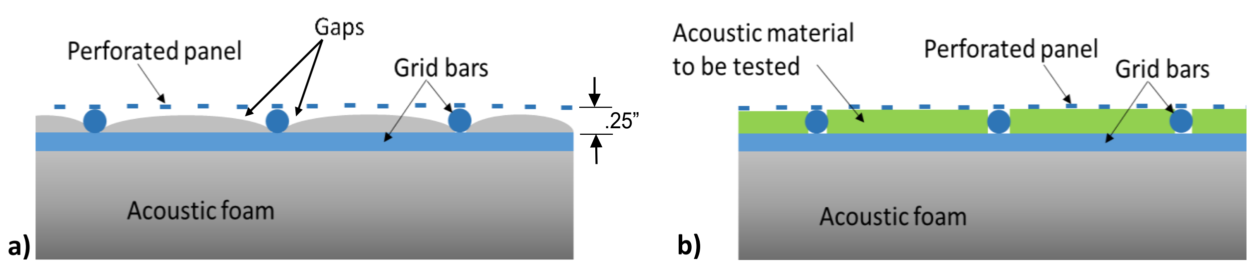

Figure 2. Sketch of cross section of a floor basket's top portion; a) after installation of the perforated panels; b) with acoustic inserts.

All QFF scrubbing noise studies and results are presented collectively in Section 2, irrespective of when the measurements were made, while the corresponding and additional steps that were taken in the 14x22 to reduce background noise are presented in Section 3.

2. Quiet Flow Facility Scrubbing Noise Test

The objectives of the initial QFF experiment were to measure the scrubbing noise from the recently modified floor basket configuration (i.e., gridded basket with an exposed perforated panel welded to the top), determine the acoustic effects of inserting strips of acoustic material between the perforated panel and the grid bars (as illustrated in Figure 2b) for the flush configuration, and downselect the best material to use for the inserts if the flush configuration was determined to be acoustically beneficial. These test results are presented in Section 2.2. Following the CRM-HL 14x22 test entry, additional scrubbing noise measurements were acquired from a perforated panel covered, respectively, with a steel mesh, Kevlar, and felt to quantify the acoustic effect that would be provided by the installation of these covers. These results are also presented in Section 2.2.

2.1 Experimental Set-up

The top of one of the 14x22 floor baskets was brought to the QFF and installed as a third wall in the QFF test section. A picture of the QFF test chamber is shown in Figure 3. The chamber is equipped with a 2 by 3 ft rectangular open jet nozzle with 72” tall vertical side walls on the 2 ft sides of the nozzle. The basket top was attached to one of the open sides of the nozzle, between the two side walls (as indicated in Figure 3). The basket top was approximately 32” wide by 63” long. A 9” wide wood board and a section of a 2” radius aluminum quarter round were mounted above the top edge of the basket top to match the height and edge geometry of the side walls. The acoustic measurements were acquired from microphones distributed on the opposite side of the test section in the nozzle midspan plane, as well as from an additional microphone positioned 25 deg from the midspan plane, as illustrated in Figure 4. Because of contamination from reflections off the test section side walls, these measurements are considered to be qualitative and only used to determine the general effects of configuration changes on noise.

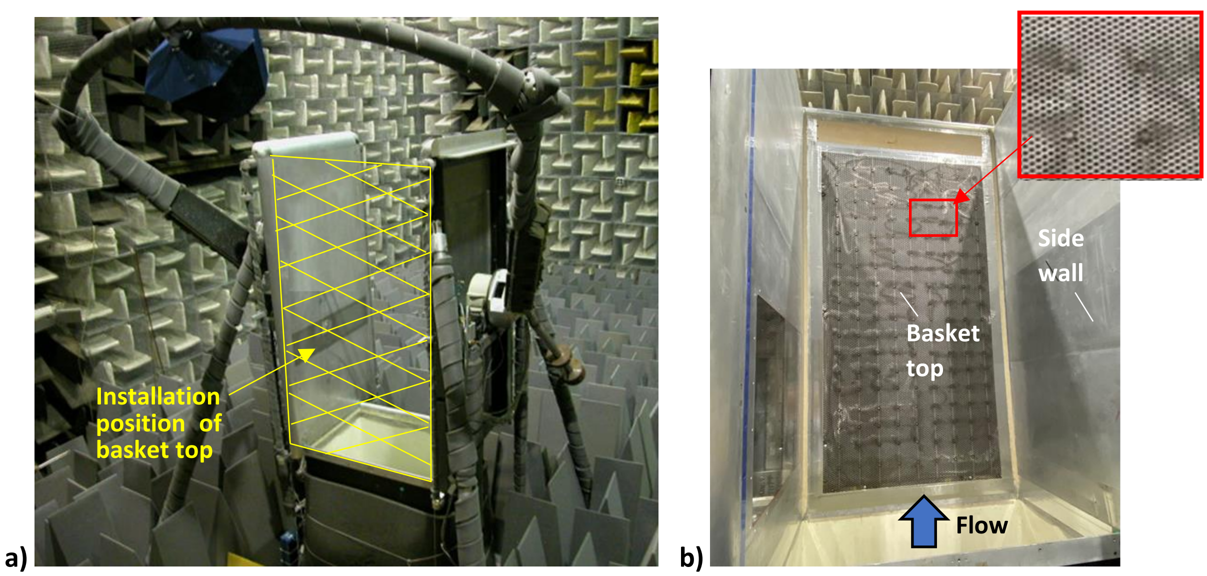

Figure 3. Quiet Flow Facility test section (a) empty and (b) with basket top installed as third wall; the red inset shows a close-up of the perforated panel.

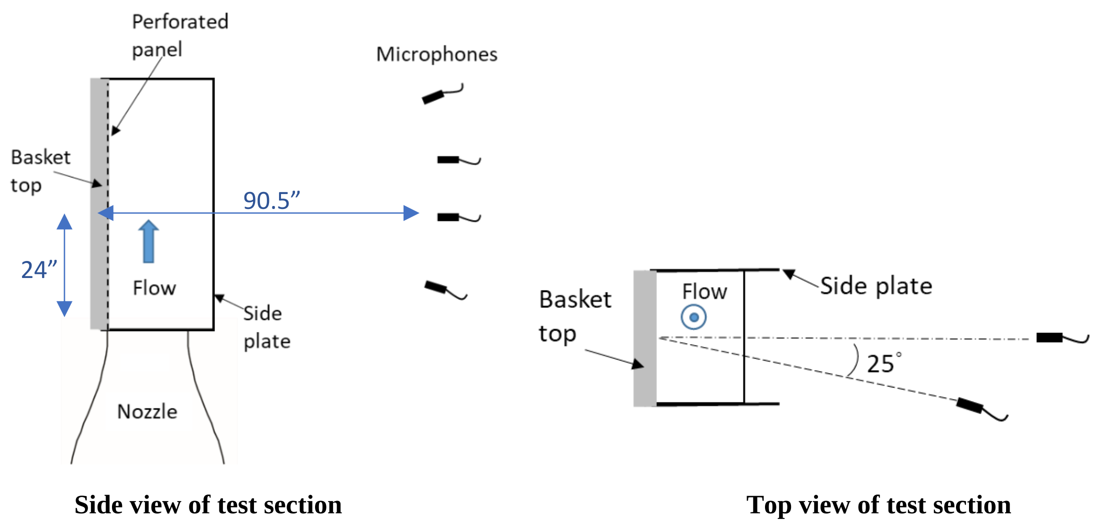

Figure 4. Microphone set up.

A cross section of the basket top as installed in the QFF test section is shown in Figure 5a. A stack of acoustically absorbent material was installed behind the basket top to form an approximately 4" thick layer. This stack comprised two 1.25" thick sheets of open cell (45 Pores Per Inch (PPI), 1.5 lb/ft^3 density) polyurethane foam pressed against the grid and back of the perforated panel and two 1" thick acoustic boards (of 7 lb/ft^3 density and composed of polyester fibers), which were somewhat rigid and were used to help keep the foam sheets evenly pressed against the back of the basket top. Finally, three angle bars positioned across the back of the acoustic boards were used to keep the acoustic treatment tightly secured (Figure 5b).

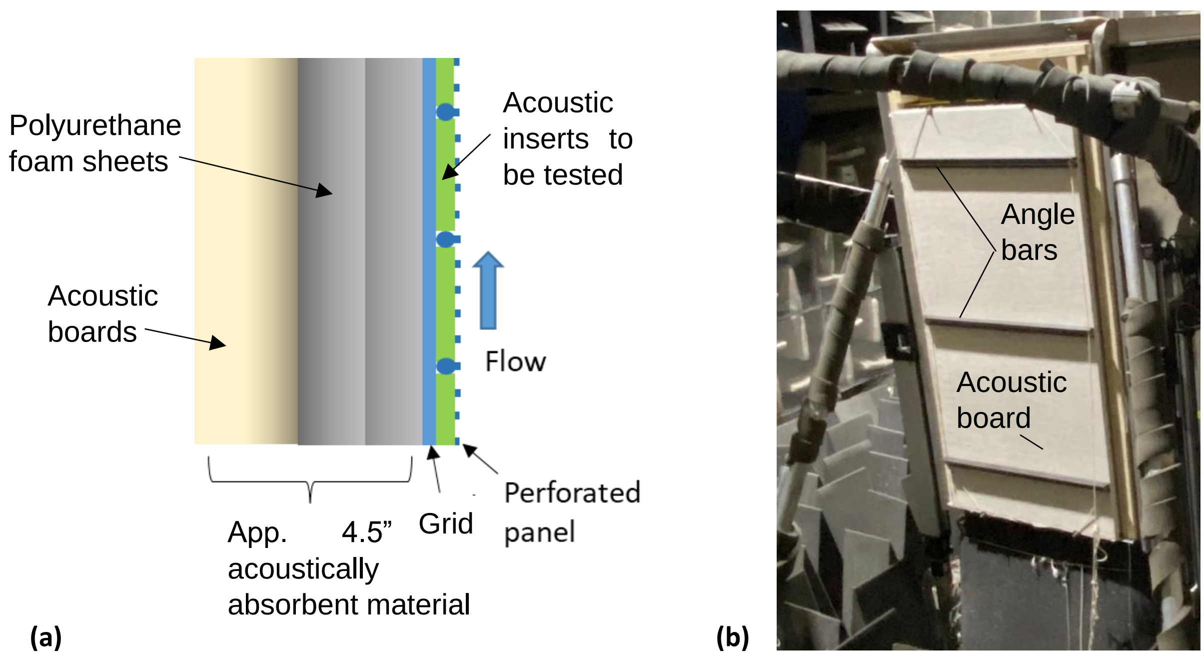

Figure 5. (a) Cross section of basket top as installed in QFF; (b) view of acoustic treatment behind basket top.

The stainless-steel perforated panel was 0.06” thick with 0.25” diameter holes staggered 0.3” apart (center to center). The holes created an open area that was approximately 54% of the total surface of the panel. Different types of acoustic materials were used to make the strips that were inserted between the perforated panel and the grid bars, and because of the quick turn-around time required from this study, only materials that were readily available were evaluated. Materials investigated were a 2 lb/ft^3, 70 PPI open cell polyurethane foam and two polyester fabrics of, respectively, 5 lb/ft^3 and 7 lb/ft^3 density. These polyester fabrics were similar to a very light felt with loose fibers. In addition to measuring scrubbing noise with and without the strips installed, acoustic measurements were acquired with the following panel covers: (a) a fine steel mesh (316L stainless steel screen, with lock crimp/plain weave, 11 gauge wire diameter and 58% open area), similar to what the reconfigured 14x22 floor treatment originally called for; (b) a Kevlar fabric (Kevlar 49, style 120, and ~6% open area); and (c) adhesive-backed polyester felt of 3 different densities (light (~ 5 lb/ft^3), medium (~ 10 lb/ft^3) and heavy (~ 20 lb/ft^3)). The felt was 1/8” thick and backed with a very thin (0.003” thick) impermeable adhesive film. The fine steel mesh and Kevlar covers were glued to the perforated panel using spray adhesive. Additional data for a smooth surface (which was simulated by installing a smooth plywood sheet in the test section) and for a foam surface (which was obtained by gluing a 1” thick foam sheet to the plywood panel) were also acquired for reference purposes. The foam surface was intended to provide an approximate representation of the scrubbing noise generated by the foam baskets prior to the installation of the perforated panels, while the smooth surface was to provide a noise measurement with minimal scrubbing noise. A sheet of 45 PPI (1.5 lb/ft^3 density) polyurethane foam was used for the foam surface configuration, as it was the type of foam that formed the top layer of acoustic treatment in the floor baskets prior to the installation of the perforated panels.

2.2 Test Results:

The data presented here were obtained from a B&K 1/8” pressure-field microphone positioned in the midspan plane of the test section, 24” above the nozzle exit plane, and 90.5” away from the perforated panel (see Figure 4). Data from the other microphone locations were used to verify the consistency of the test results. Noise measurements presented here were acquired for freestream Mach numbers ranging from 0.11 to 0.17.

Pictures of the untreated basket top (i.e., without acoustic inserts or a cover), the smooth surface, and the foam surface are shown, respectively, installed in the QFF test section in Figure 6.

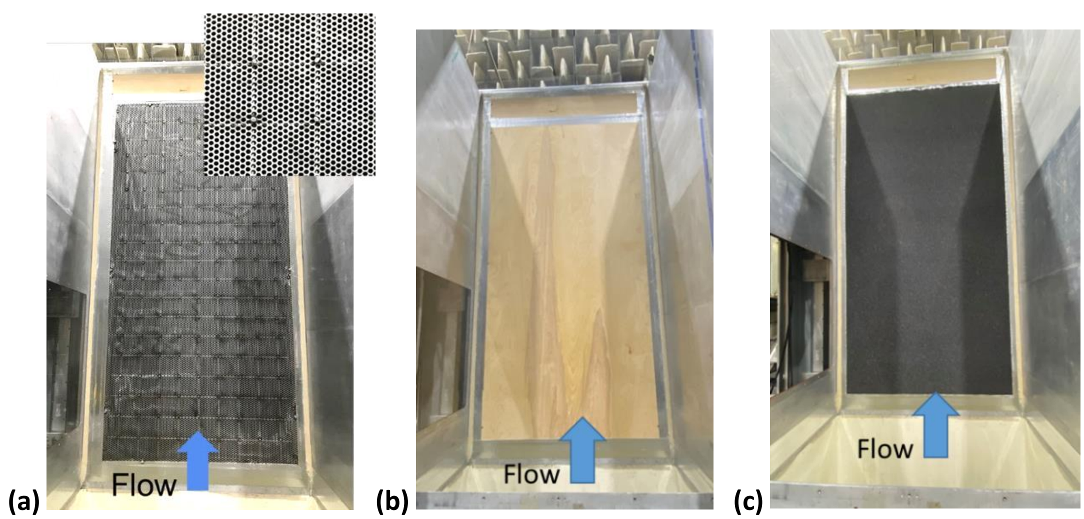

Figure 6. Photos of three configurations tested: (a) Untreated basket top (as in Figure 2a); (b) Smooth plywood panel; (c) foam surface.

The spectra obtained for these three configurations and a flow Mach number of 0.17 are displayed in Figure 7. Note that the large spikes seen in some of the spectra (notably for the smooth surface) were caused by electronic noise. The spectra obtained for the foam surface and untreated basket top configurations highlight the reduction in high frequency noise and increase in low frequency noise associated with the installation of the perforated panel. The untreated basket top configuration is louder below 20 kHz, with a large spectral peak around 3 kHz that is approximately 18 dB above the scrubbing noise generated by the foam sheet. However, it is quieter than the foam surface above 20 kHz. The low frequency peak of the untreated basket top spectra, as well as the broad hump seen in the foam surface spectra, were found to both scale with the 5th power of the freestream velocity (as shown in Figure 8). Above 10 kHz, the untreated basket top spectra followed more closely a 6th power of velocity dependence (not shown). As previously mentioned, the foam surface spectrum is intended to only provide an approximate representation of the scrubbing noise that was generated by a foam basket prior to the installation of the perforated panels, as the absence of the grid (see Figure 1) and the presence of the plywood backing used to support the foam sheet may affect the measured spectrum.

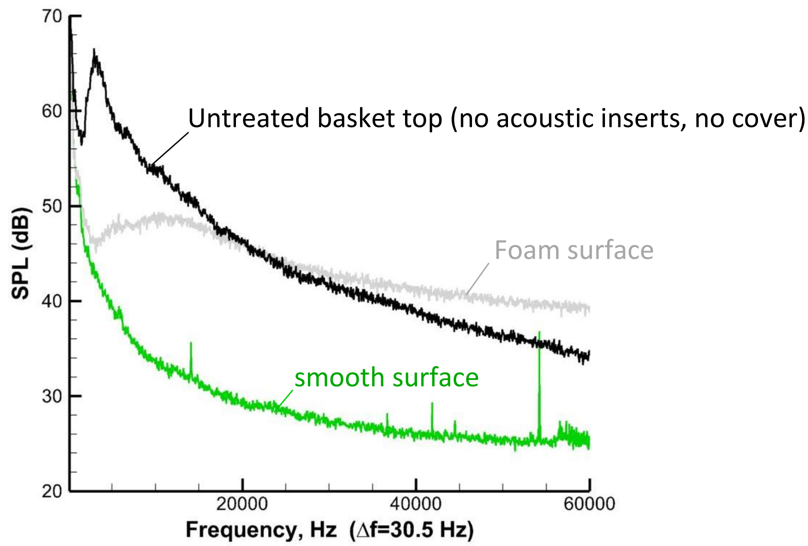

Figure 7. Scrubbing noise spectra from an untreated floor basket top (as in Figure 2a), a foam surface and a smooth surface; *Mach* = 0.17.

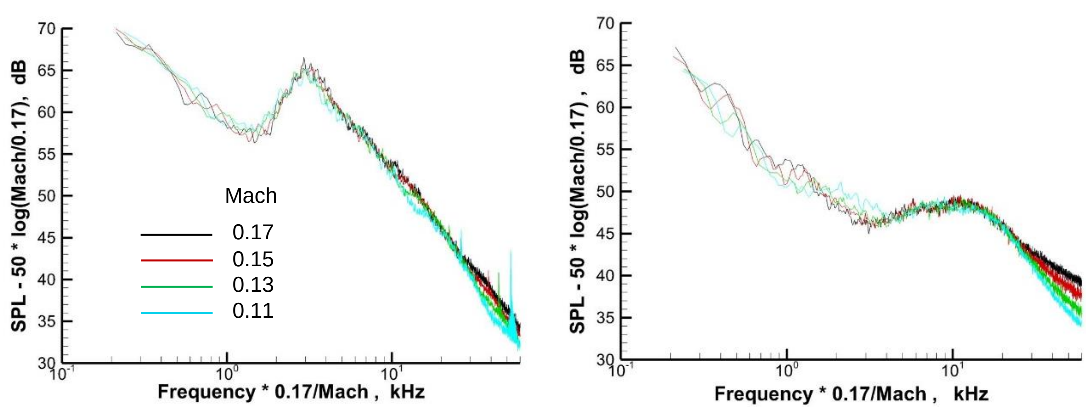

Figure 8. Fifth power of velocity scaling: (a) untreated basket top (as in Figure 2a) and (b) foam surface.

Acoustic inserts

Figure 9 displays the noise spectra that are obtained when strips of the polyurethane foam or polyester fabrics are inserted behind the perforated panel. It is seen that the low frequency spectral peak for the untreated basket top is nearly eliminated and spectral levels are also reduced over the full frequency range. Nevertheless, noise levels below 10 kHz remain greater than those measured from the foam surface. Close ups of the perforated panel with the open cell foam and polyester inserts are also shown in Figure 9. Although the polyester inserts performed best, they were not an "off the shelf" item available in the needed thickness and size, and they would have been difficult to cut to size. Conversely, the foam strips could be easily cut from 0.5" thick sheets of 70 PPI foam and were thus used to treat the top of the 14x22 foam baskets prior to their installation into the 14x22 test section for the CRM-HL test.

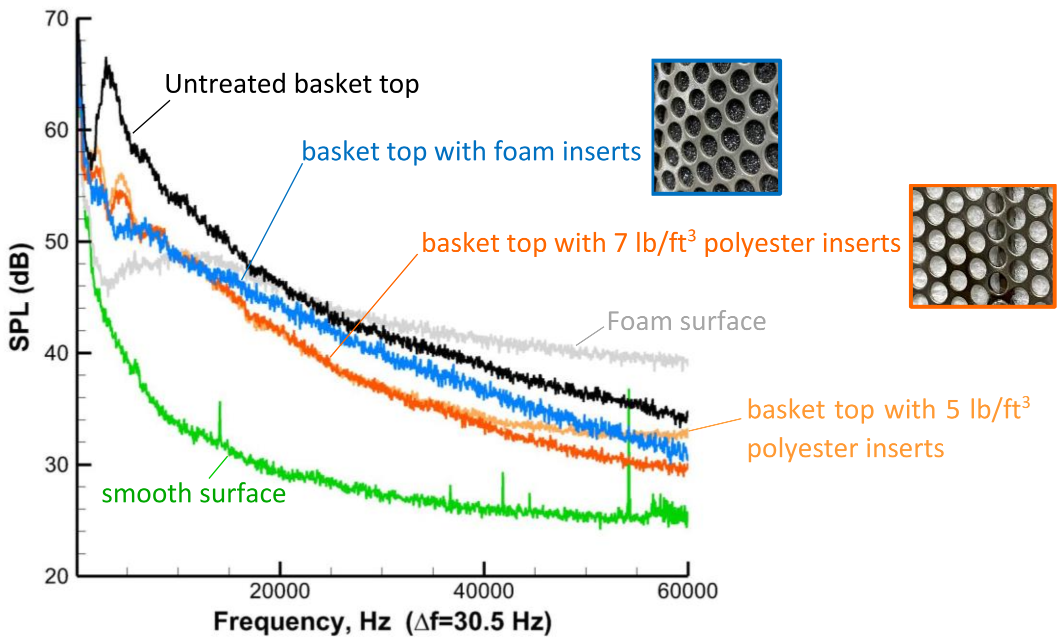

Figure 9. Scrubbing noise spectra from floor basket top treated with acoustic inserts (as in Figure 2b) and comparison with untreated basket top, foam surface and smooth surface spectra; *Mach* = 0.17.

Perforated panel covers

Figure 10 displays the spectra that are obtained when, in addition to the open cell foam acoustic inserts, the fine steel mesh or Kevlar is glued to the surface of the perforated panel. It is seen that with the addition of the fine mesh, noise levels are further reduced over the full frequency range, with a large reduction in noise above 10 kHz. Although the Kevlar cover provides the best reduction in noise below 13 kHz (despite a spectral hump at 5 kHz), it also leads to a significant increase in noise above 18 kHz with a broad spectral hump between approximately 15 and 50 kHz. The double hump spectrum observed for this Kevlar/perforated panel configuration was also noted by Alexander and Devenport and is discussed in Reference 7. They speculated that the lower-frequency hump results from the diffraction of the surface pressure fluctuations by the underlaying perforated panel, while the broad high-frequency hump may be more strongly associated with the Kevlar fabric characteristics (such as porosity and weave pattern). In a follow-on study [8], they corroborated these findings, as well as identified the effects that the perforated panel hole diameter and open area ratio have on the low- and high-frequency content of the noise spectra.

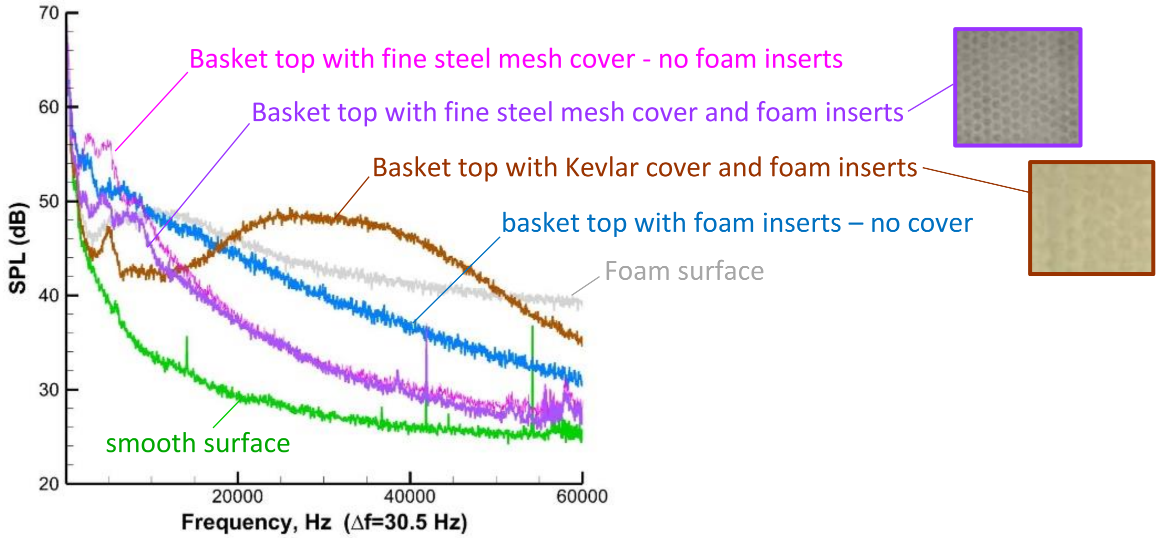

Figure 10. Effect of Kevlar and fine steel mesh cover on scrubbing noise from basket top; *Mach* = 0.17.

Figure 11 displays the velocity scaling of the spectra for the Kevlar covered basket top. The low-frequency hump is shown to follow a 5th power of the freestream velocity dependence, while the broad hump in the higher-frequency range scales with the 6th power of velocity. For the steel mesh cover, the lower-frequency hump (near 4 kHz) was also found to scale with the 5th power of velocity (result not shown), possibly indicating that it is generated by a similar mechanism.

Also added for reference in Figure 10 is the spectrum obtained when the perforated panel is covered with the fine steel mesh and the foam inserts are removed. It is seen that without the foam inserts, the large noise reduction provided by the screen above 15 kHz is maintained. However, below 15 kHz, noise levels significantly increase, surpassing those for the uncovered basket top below 7 kHz. This again stresses the importance of having the floor basket's foam filling flush to the back of the perforated panels for reduced noise in the lower frequency range.

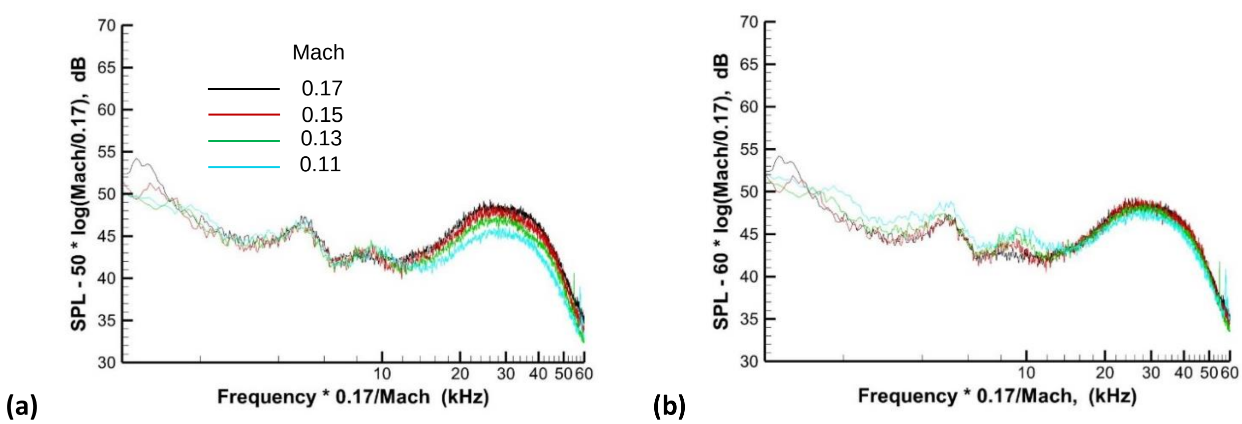

Figure 11. Scaling of noise spectra from basket top with Kevlar cover: (a) fifth power of freestream velocity and (b) sixth power of freestream velocity.

Figure 12 displays the spectra that are obtained when the light, medium and heavy felt are, respectively, adhered to the surface of the perforated panel. All 3 types of felt are significantly quieter than the fine steel mesh and Kevlar covers between 3 and 20 kHz. Below 3 kHz, the Kevlar cover is slightly quieter than the felt fabrics. Above 20 kHz, the heavy felt performs best. It remains quieter than the steel mesh up to about 35 kHz and performs approximately as well as the steel mesh at higher frequencies. The light and medium felt covers, however, are louder than the steel mesh above 35 and 45 kHz, respectively. This slight increase in noise observed at higher frequencies with the less dense felt covers may be attributed to the increased permeability of the fabric to the flow. It is important to note that the effect of the impermeable adhesive backing on the noise attenuation achieved with the felt is not known, and it could be inferred from Figure 12 that the observed decrease in low-frequency noise is associated with the decreased open area ratio of the covers (~58% for the steel mesh, ~6% for the Kevlar and 0% for the adhesive-backed felt). However, a similar noise reduction performance was reported in Reference 8 using felt without backing, leading the authors to believe that the impermeability of the adhesive film may not have played a dominant role in the noise reduction.

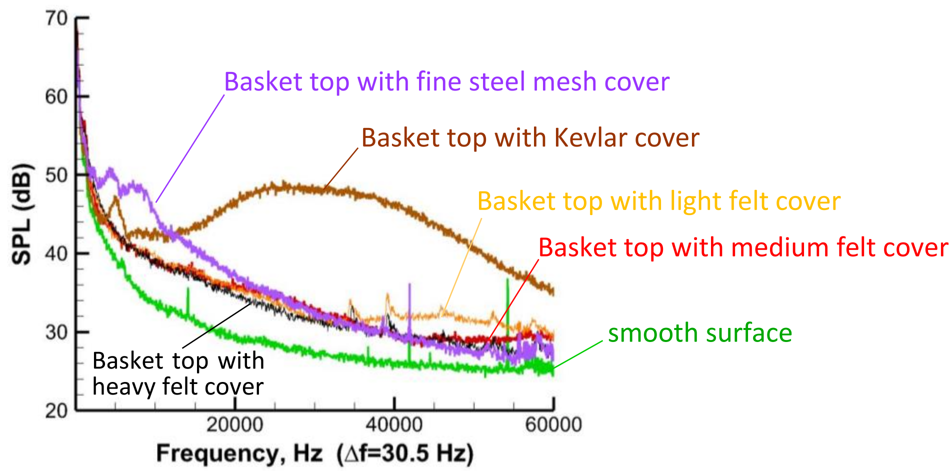

Figure 12. Noise spectra from the basket top with foam inserts and the felt, Kevlar and fine steel mesh covers; *Mach* = 0.17.

3. 14x22 Background Noise Mitigation

Figure 13 is a picture of the 14x22 test section at the beginning of the CRM-HL test entry. A microphone phased array [2] is positioned outside the test section flow, and the half-span CRM-HL model is mounted a few inches above the floor baskets with a brush seal closing the gap between the model fuselage and the floor. The floor basket tops are treated with ½" thick strips of the 70 PPI polyurethane foam, but they were left exposed because at the time of the test entry, alternative options to cover the floor baskets had not yet been explored in the QFF.

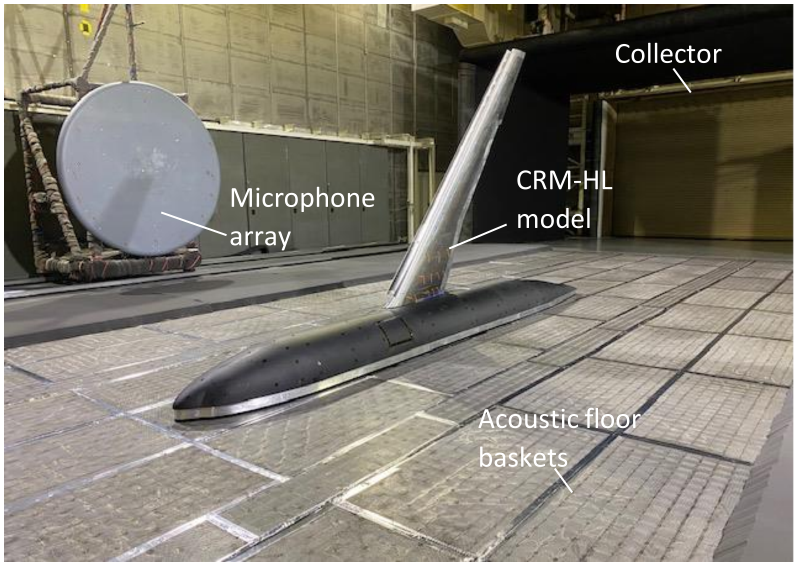

Figure 13. 14x22 test section configuration at the beginning of the CRM-HL test; acoustic floor baskets with perforated panel and foam backing; perforated collector and diffuser leading edges with fiberglass backing.

Early into the CRM-HL test, it was noted that despite the addition of the foam inserts to the floor baskets, the level of background noise measured in the test section was significantly greater than in past test entries. Noise maps obtained for different test section treatments are compared in Figures 14, 15 and 16. These noise maps in a plane cutting through the center of the test section were obtained using conventional beamforming with the microphone phased array positioned directly "below" the test model (as in Figure 13). They are shown at three sample frequencies, 7.5 kHz, 15 kHz and 25 kHz. Noise maps from data acquired at the beginning of the test (labeled as Prior to Felt Treatment in Figures 14a, 15a and 16a) revealed the presence of extraneous noise emanating from the floor as well as above the collector. The noise around the floor was mostly observed below 20 kHz, while the noise in the region of the collector was seen over a broader frequency range. After a series of troubleshooting efforts, the elevated background noise was determined to be predominantly caused by a strong interaction of the test section unsteady shear layer with the collector and diffuser leading edge surfaces, and from scrubbing noise from the test section floor.

To confirm the contribution of the floor configuration to the background noise, the perforated panels on the floor baskets were covered with a matte adhesive vinyl, effectively replacing the perforated panels with a smooth surface. The vinyl was 0.0048" thick. Part (b) of Figures 14 through 16 are noise maps obtained for this vinyl cover configuration. It is observed that the noise that was previously "seen" distributed around the floor is replaced with a strong reflection of the model's airframe noise sources. Corresponding spectra (not shown) of the noise measured with and without the vinyl cover also revealed that despite strong contamination from increased floor reflections, the application of the vinyl led to a decrease in noise below 20 kHz where scrubbing noise from the perforated panels is strongest (as was shown in Section 2.2).

To investigate the collector noise source, the path and unsteady behavior of the test-section shear layer was visualized using a smoke wand. After confirming that large, unsteady vortical structures were impacting the collector, attempts were made to stabilize the shear layer using different types of vortex generators and jet exit vanes [9]. Those attempts were, however, unsuccessful.

Following this trouble-shooting effort, the collector and diffuser, as well as the floor perforated panels, were covered with adhesive-backed felt (the same type of felt that was later tested in the QFF and is discussed in Section 2) in an attempt to attenuate the noise resulting from the interaction of these surfaces with the test section flow. Note that reflections from the adhesive film of the felt were a concern; however, the adhesive allowed for a simple and rapid installation, which was necessary to meet the test schedule. Alternative methods to secure the felt fabric without the adhesive backing were not feasible at the time.

First, the heavy felt (of 20 lb/ft^3 density and most likely to withstand severe unsteady loading from the shear layer) was installed along the leading-edge regions of the collector and diffuser, extending to about midchord along the collector wall. Figure 17(a) displays the noise spectra that are obtained before and after the application of the felt to the collector and diffuser (with the exposed perforate on the floor). It is seen that despite scrubbing noise from the floor, the felt treatment led to a small reduction in the test section noise above 4 kHz. Examination of the noise maps obtained for this configuration (such as those shown in part (c) of Figures 14 through 16) indicate that at and above 5 kHz, the noise previously seen in the upper region of the collector was no longer detected by the microphone array. Below 5 kHz, "tunnel" noise radiating from the diffuser dominated the noise maps' collector region. While the intent of the leading-edge treatment was to attenuate the pressure fluctuations on the collector and diffuser (hence, the noise scattered by these surfaces), the apparent elimination of the noise source may indicate that the flow interaction with the perforated leading-edge surfaces (prior to them being "sealed" by the impermeable adhesive film of the felt) may have been a dominant component of the measured noise.

Next, the floor perforated panels were covered with felt. The lightest felt (5 lb/ft^3) was used to cover the floor between the microphone phased array and the test model to (aside from the adhesive film) minimize reflections from the added material. The 10 lb/ft^3 density felt was used to cover the rest of the floor, as a compromise between durability and reflection mitigation. The spectra obtained prior to and after the addition of the floor cover are compared in Figure 17(a). Spectral levels are seen to be further reduced above 4 kHz with the addition of the floor cover. The corresponding noise maps (as shown in part (d) of Figures 14 through 16) reveal that the noise previously "seen" around the floor is replaced with a weak reflection of the model airframe noise sources. Comparing the floor reflection of the model's airframe noise sources in the noise maps produced for the three different floor configurations tested (namely, no cover, with vinyl cover and with felt cover) revealed that the 1/8" layer of felt material provided some acoustic absorption and reduced reflections from the perforated panels above 5 kHz. This is seen in Figures 14, 15 and 16, where the reflections produced with the felt cover appear weaker than those produced by the uncovered perforated panels and much weaker than those produced by the smooth vinyl cover. At and below 5 kHz, the reflections produced with the felt cover were observed to be stronger than those produced with the uncovered perforated panels, but they remained weaker than those produced with the smooth vinyl cover, down to 2 kHz. Below 2 kHz the floor reflections produced with the adhesive-backed felt were similar to those produced with the vinyl cover. It can be speculated that reflections could be attenuated at lower frequencies by increasing the thickness of the felt layer (e.g., down to 2.5 kHz with a doubling of the felt thickness). The increased thickness may, however, change and possibly increase scrubbing noise (self-noise) from the felt, although based on the results from the QFF experiment, this self-noise would be expected to remain relatively low.

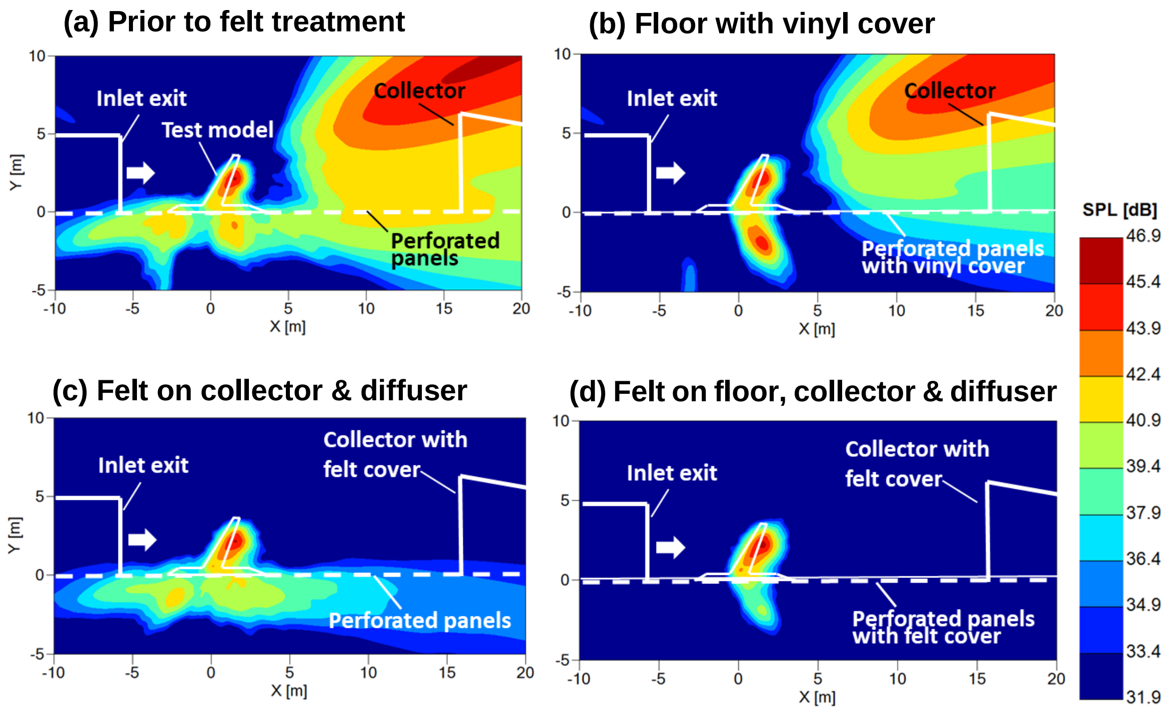

Figure 14. Noise maps of the 14x22 test section obtained using conventional beamforming of the microphone phased array data. *Mach* = 0.16; *AOA*=0˚; $f_{1/12th}$ = 7.5 kHz.

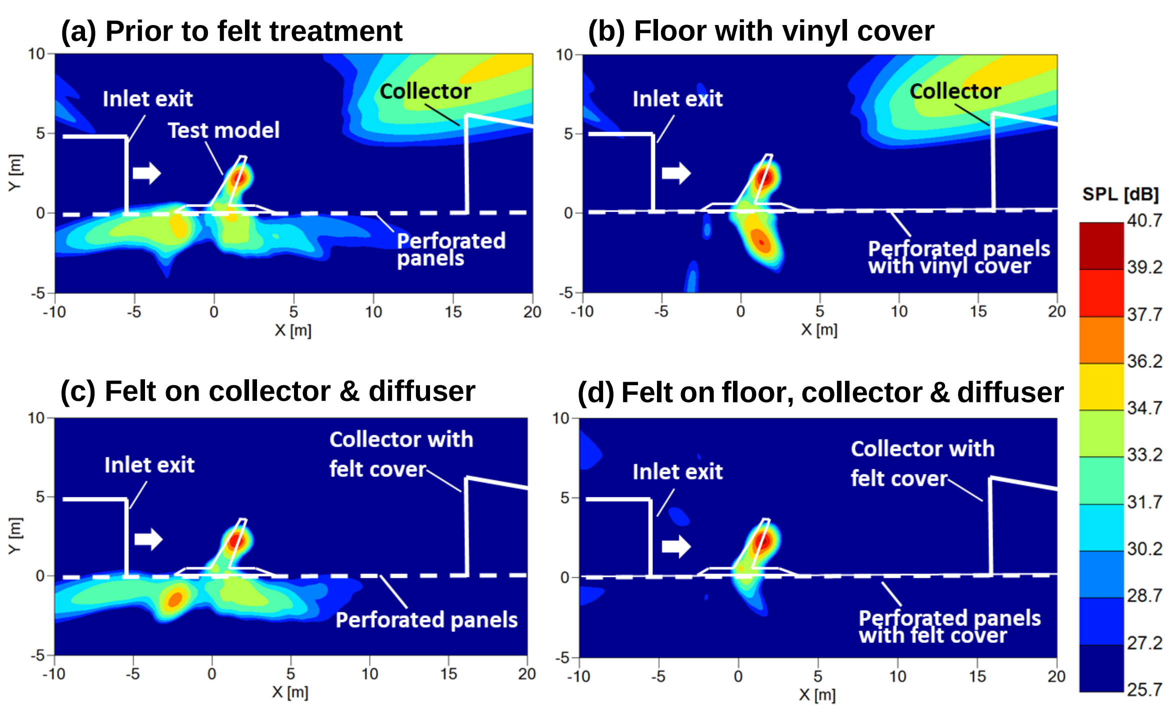

Figure 15. Noise maps of the 14x22 test section obtained using conventional beamforming of the microphone phased array data. *Mach* = 0.16; *AOA*=0˚; $f_{1/12th}$ = 15 kHz.

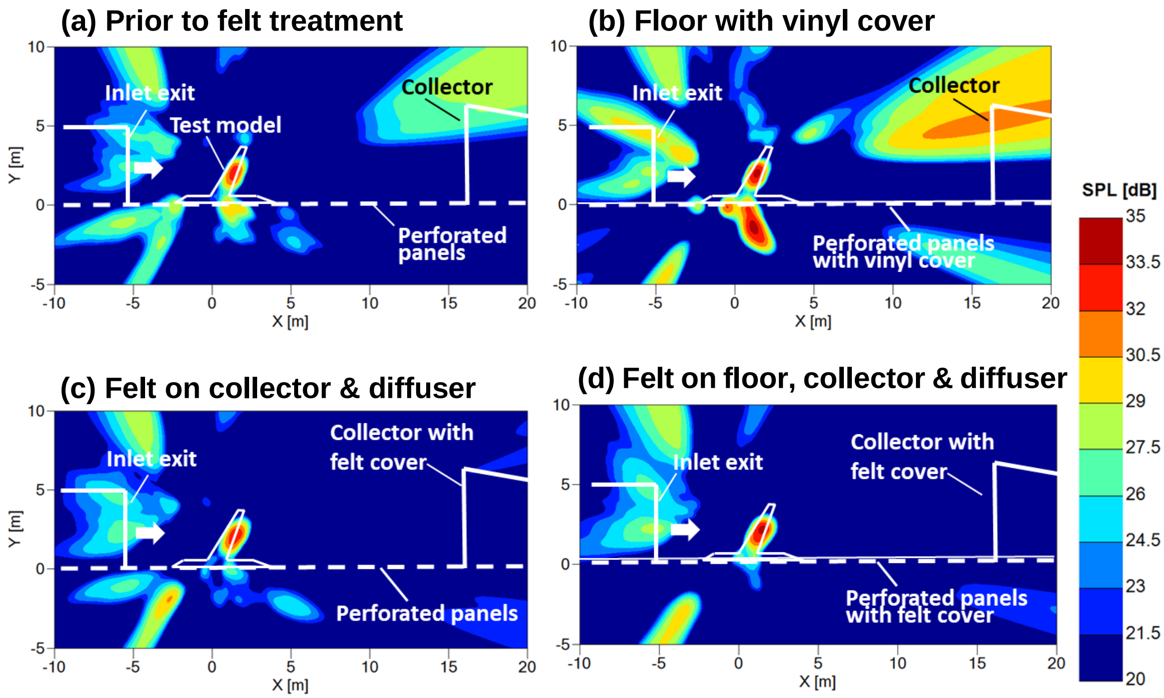

Figure 16. Noise maps of the 14x22 test section obtained using conventional beamforming of the microphone phased array data. ***Mach*** **= 0.16;** ***AOA*****=0˚;** $f_{1/12th}$ **= 25 kHz.**

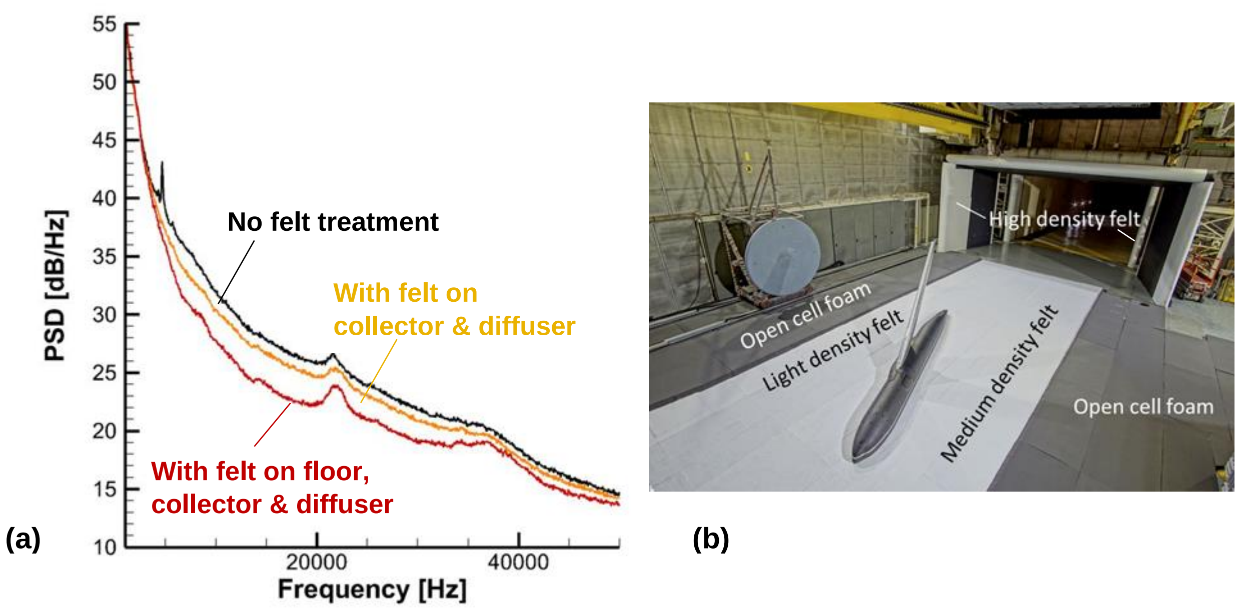

Figure 17. (a) Noise spectra from center microphone of phased array; ***Mach*** **= 0.16;** ***AOA*****=0˚ and (b) Picture of the 14x22 test section treated with felt (shown with test model at 8.5˚ AOA).**

Finally, a strip of the medium density adhesive-backed felt was applied along the bottom 6 inches of the test model fuselage to eliminate an extraneous noise source that was present near the junction of the fuselage with the floor when the model was positioned at moderate to high angles of attack (AoA) and generated significant lift. It is speculated that this noise source may be the result of the interaction of the fuselage with the horseshoe vortex that is generated near the floor when the model produces lift. The layer of felt appeared to have effectively attenuated the surface pressure fluctuations on the underlaying fuselage and hence the radiated noise. The effect of the mitigation of this extraneous noise source on the spectra obtained from the center microphone of the phased array with the model at the landing AoA is shown in Figure 18. Noise maps, not shown here, confirmed the mitigation of this source.

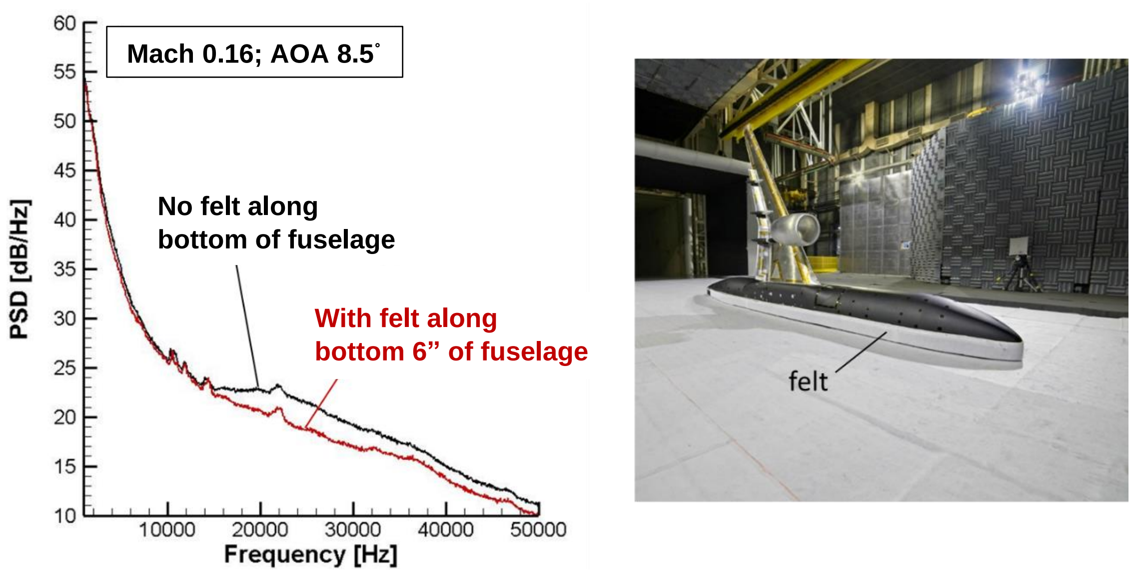

Figure 18. Noise spectra from center microphone of phased array: *Mach* = 0.16; *AOA*=8.5°.

4. Summary

Adhesive-backed felt was used in the 14x22 test section to attenuate (1) the noise resulting from the strong interaction between the test section unsteady shear layer with the perforated leading-edge surfaces of the collector and diffuser, (2) scrubbing noise from the floor perforated panels and (3) an extraneous noise source present near the fuselage junction with the floor when the model was positioned at moderate to high angles of attack. The felt was applied to the different components progressively. First, it was used to cover the leading-edge regions of the collector and diffuser. This treatment was effective and appeared to eliminate a strong noise source otherwise observed in the region of the collector. A main component of this noise source is believed to have been produced by the shear layer interaction with the perforated portions of the collector and diffuser which were “sealed” by the felt’s impermeable adhesive film once the treatment was applied.

Next, the felt was used to cover the floor perforated panels. This led to further reduction of the test-section background noise. The layer of felt also appeared to provide some acoustic absorption and reduced reflections from the perforated panels above 5 kHz. However, increased reflections (likely from the felt’s adhesive film) were observed at lower frequencies. It is speculated that reflections could be attenuated at these lower frequencies by increasing the thickness of the felt without a significant increase of the felt’s self-noise (although this is not known). Reflections may also be reduced with the felt secured to the panel without the impermeable adhesive backing, but the potential increase in low-frequency noise that could be associated with such change is not known. Associated work for a different class of aeroacoustic experiments is being pursued along these lines [10], with initial results indicating that optimal solutions are dependent on the measurement bandwidth of interest and operating conditions of a given test.

Finally, a strip of felt was applied along the bottom of the model's fuselage. It appeared to effectively eliminate the extraneous noise believed to be otherwise produced by the interaction of a horseshoe vortex with the fuselage. It is again believed that the added layer of felt helped attenuate the surface pressure fluctuations on the fuselage, resulting in the greatly attenuated noise source. Following the CRM-HL 14x22 test entry, scrubbing noise measurements from a floor basket top were acquired in the QFF to compare the performance of the felt cover with that from a steel mesh and a Kevlar cover. The felt provided the best attenuation in low-frequency noise, and while the role of its impermeable adhesive backing in the noise attenuation achieved is not known, it may not be prominent, as similar noise reduction performances were reported in another study using felt without backing. The higher-frequency content of the measured spectra (which has been shown in other studies to be more directly associated with the characteristics of the cover's fabric such as weave pattern and thread density) was significantly lower for the felt and steel mesh covers than for the Kevlar cover. Finally, the importance of having the foam backing properly flush to the back of the perforated panels for reduced low-frequency noise was shown.

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