Acoustic Improvements to the 9- by 15-Foot Low Speed Wind Tunnel

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A major refurbishment of the 9- by 15-Foot Low Speed Wind Tunnel at NASA Glenn Research Center was undertaken between 2016 and 2019 to improve the acoustic measurement capability of the facility. The principal objective was to lower the background noise in the test section so quiet aircraft propulsors could be tested with good signal-to-noise ratio. The secondary objective was to improve the anechoic quality of the facility so that the measurement uncertainty would be reduced and the data collected would be more accurate. The results of the project were a vastly improved anechoic wind tunnel, with one-third octave sound levels reduced by 8 to 18 dB in the frequency range of interest. The anechoic quality of the test section was improved substantially, reducing the effect of unwanted echoes contaminating the noise measurements, with the error in an impulse response measurement reduced from 0.8 dB to 0.2 dB. This report describes the main acoustic findings and is intended to provide guidance for other facilities requiring a low noise environment.

I. Introduction

Wind tunnels come in all shapes, depending on their intended capabilities. The subset which contains large acoustic wind tunnels was reviewed by Sverdrup Technology (now Jacobs Engineering)[1], in a survey that included automotive and aerospace facilities around the world. At NASA, the large acoustic tunnels are the 14- by 22-Foot Subsonic Tunnel at Langley Research Center[2], the National Full-Scale Aerodynamics Complex 40- by 80-Foot Wind Tunnel (NFAC 40x80) at Ames Research Center[3] and the 9- by 15-Foot Low Speed Wind Tunnel (9x15 LSWT) at NASA Glenn Research Center (GRC), which is the subject of the present report. The improvement project described here was principally to reduce the background noise of the facility without negatively impacting the other qualities of the facility, with Jacobs Engineering as the prime contractor. The focus of the present report is the acoustics, both noise of the empty test section and the acoustic quality of the facility. The report contains a brief history of the facility, a description of the supporting studies conducted as part of the improvement project, and an overview of the net results on the facility. This paper is one of four being used to report various aspects of the task.[4–6].

II. History of the 9x15 LSWT

The 9x15 LSWT is located in the return leg of the 8- by 6-Foot Supersonic Wind Tunnel (8x6 SWT) and shares the same drive system. The 8x6 SWT was built in 1949 for testing supersonic propulsion systems while the 9x15 LSWT was built for testing vertical lift systems for aircraft in 1968. The design of the 9x15 LSWT includes a hard-wall test section where 12 mm (0.5 inch) thick aluminum plates would be attached to an I-beam structure to make a 2.7- by 4.6 m (9- by 15-foot) cross section at the end of the contraction. Slots in the wall allowed for streamline expansion or exhaust of air from vertical lift systems being tested. Divergence of the side walls accounts for boundary layer growth. By the mid-1970's, the acoustics of propulsion systems was becoming a topic of interest for community noise and so acoustic treatment in the form of a 2 inch thick fiberglass mat was added[7] to enable collection of microphone measurements in the flow. In 1986, this treatment was replaced with a 13 inch deep liner as low-frequency turboprop noise became of interest. The deep liner was an unwoven Kevlar bulk absorber in two different densities, with a 40% open perforated plate on the flow surface[8]. This treatment was fit around the structural beams of the facility with a 2 inch liner on top of the beams. This created a patchwork of deep and shallow treatment. The tunnel operated in this condition for the next 30 years. The noise absorbing quality of the resulting test section modifications was discussed by Dahl and Woodward[9]. The background noise of the facility prior to the current improvement project has been reported by Woodward[10] and Stephens[11]. By 2010 it was realized that the wind tunnel background noise should be reduced to ensure good microphone measurements of future quiet aircraft engine propulsor models. In 2012 a set

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of noise measurements made throughout the tunnel loop[11] was provided to Jacobs Engineering for analysis. A noise reduction goal was developed based on expected future quiet aircraft engine fans[4]. The final construction plan was for five major modifications to the facility: acoustic turning vanes upstream and downstream of the test section, a set of parallel baffles, a new carefully shaped diffuser and a rebuilt test section with a new low-noise flow surface.

III. Supporting Studies

Replacing the tunnel flow surfaces was considered the most critical part of the tunnel improvement task. This was because noise generated by airflow over the test section walls could propagate directly to inflow microphones. By contrast, noise sources elsewhere in the tunnel loop could be expected to diminish due to distance, or be absorbed by treatment or scattered away before affecting microphone measurements. In order to better understand the implications of a new flow surface over the acoustic treatment, a number of supporting studies were conducted. Two studies are discussed in this report: a set of roughness noise measurement and tests to determine the anechoic qualities of the proposed acoustic liners. Other testing was conducted, including noise absorption studies at Riverbank Acoustic Laboratories and normal incidence tube measurements at the NASA Langley Research Center Liner Technology Facility. A full report of the supporting studies is being documented as a NASA Technical Memorandum[12]. A similarly comprehensive report on the improvement to the 9x15 LSWT acoustics is also being prepared[13].

A. Roughness Noise Testing

Analysis by Jacobs Engineering concluded that a major part of the background noise in the 9x15 LSWT was due to the airflow over the perforated plate that made up the walls, floor and ceiling of the test section[4]. This noise source is due to the turbulence in the air flow boundary layer causing unsteady forces on the rough surface of the wall, or "roughness noise" for short. Most studies of roughness noise consider something like sandpaper, but the noise mechanism is similar. Replacing the flow surface with something smoother was expected to reduce the noise source. In order to improve confidence in the magnitude of potential noise reduction modifications, NASA contracted with Virginia Polytechnic Institute and State University (Virginia Tech) to conduct a series of noise tests on various surfaces of interest. Most of the samples were a fabric or metal woven material attached to a perforated plate using spray adhesive. These tests took place over four years under several test campaigns. It had previously been established that the Virginia Tech roughness noise facility could measure the noise due to airflow over a single 3 mm cube[14], so there was little reason to doubt the capability to measure the noise due to airflow over a 30 by 60 cm (1- by 2-foot) sample of perforated plate. Measurements of flow over fabric surfaces were novel, however, and iteration in the test setup were expected. The team from Virginia Tech has prepared several papers based on these studies,[15, 16] so only the final results are presented here. A photograph of the test setup is shown in Figure 1.

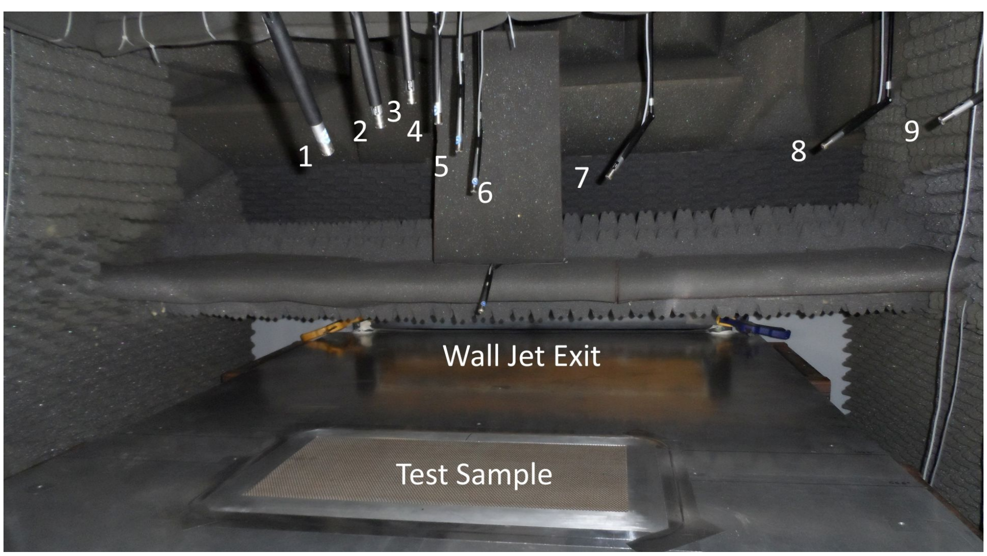

Fig. 1 Experimental setup for background noise validation measurements in test section at Virginia Tech.

The flow surface in the 9x15 LSWT from 1986 to 2016 was 16 gauge perforated plate 40% open with 3 mm (1/8 in) holes. The new design for the flow surface was 63% open with 4 mm (5/16 in) holes. The floor was a built using 16 gauge perforated plate while the walls and ceiling used 20 gauge. Most importantly, the new flow surface is covered with a 200 by 600 threads-per-inch micronic wire cloth with a flow resistance value of 8-10 MKS Rayls. This value of flow resistance was determined to give a smooth surface to the airflow passing over the panel and also be largely transparent to sound waves traveling toward the panel. The wire cloth is diffusion bonded to the perforated plate, creating a combined *diffusion bonded panel.* These panels were tested by Jacobs Engineering to document the flow resistance before acceptance. Testing at Virginia Tech determined the roughness noise was the same between the best panels made using diffusion bonding and those made using spray adhesive. A new manufacturing process ensured we did not have the same difficulty with fiber contamination of diffusion bonded panels that was experienced during the NFAC 40x80 renovation; roughness noise was not part of that design and the diffusion bonded panels were only intended to create a low-drag acoustic liner[3]. Since the NFAC 40x80 used a similar diffusion bonded panel flow surface, we were confident in the long term durability of this material in a wind tunnel. Additionally, the background noise[17] of the NFAC 40x80 was significantly lower than the 9x15 LSWT, suggesting the lower noise flow surface was possibly one reason.

The noise measured by flow over the bare perforate is compared with the new low-noise design in Figure 2. Gaps in the spectrum for the diffusion bonded panel indicate frequencies were the noise was indistinguishable from the noise of the facility with a smooth plate test sample. The measured roughness noise is reduced by more than 10 dB for frequencies above about 2 kHz when the flow is over the diffusion bonded panel. The wall jet length scales and flow velocities are substantially different in the Virginia Tech facility than the boundary layer flow in the 9x15 LSWT. Despite this, the spectral shape and peak noise frequency observed in both facilities was similar, which gave us confidence that the majority of the 9x15 LSWT background noise was due to flow over the perforated plate. Additionally, it was clear that this particular noise source would be considerably reduced by use of the new flow surface.

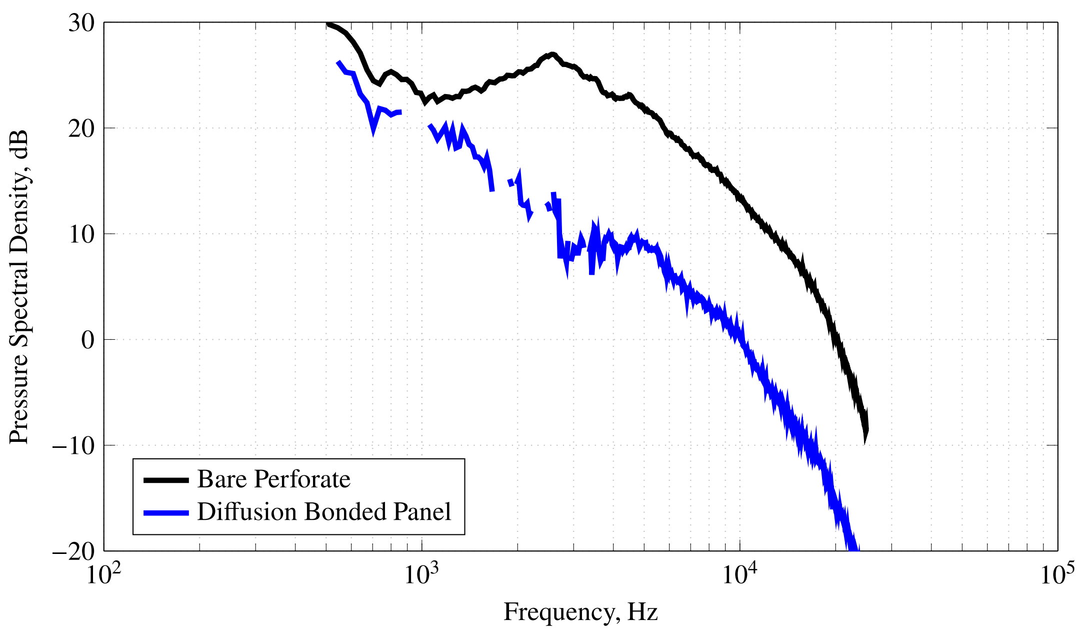

Fig. 2 Example result from Virginia Tech roughness noise facility.

B. Acoustic Box Testing

The acoustic wind tunnel should be sufficiently quiet such that microphone measurements have a good signal-to-noise ratio. The acoustic tunnel must also approximate an infinite space, with sound propagating outward only, and with minimal reverberation. Microphone measurements should be made far from the model being tested so that the source is acoustically compact. Relatively large models are tested in the 9x15 LSWT so we put the microphones relatively close to the walls. This means the direct and reflected sound paths between the source and the receiver are of the same magnitude. Thus it is very important to have walls that minimize sound reflections. A good understanding of the acoustic properties of the flow surface is required.

A convenient and useful test to measure the acoustic reflection from a panel was described in the NFAC 40x80 improvement project publications (see Figure 18 of reference [3] and supporting text), which cites a series of reports by Wilby, White and Wilby, and by Wilby and Wilby. A speaker emits a short time signal, which then reflects off of a panel and is measured by a microphone. If the incident sound on the panel is known, the reflection can be related to the acoustic qualities of the panel. These tests were conducted in the NASA GRC Acoustical Testing Laboratory (ATL)[18].

The speaker was mounted on an overhead rail near the ceiling of the ATL, about 12 feet above the floor. A set of three microphones were suspended about 4 feet from the floor. Test samples were placed on the floor, which is a steel grating above the acoustic wedges. A JBL 2426H horn driver with a Selenium HL14-25 horn was used as the sound source. This combination was chosen as it handled a wide frequency range and substantial signal levels. Typical samples were 4'x3', corresponding to the size of the individual boxes used in the 9x15 LSWT. The background noise of the ATL was excellent and is not believed to have had a negative influence on the results. The experimental setup is shown in Figure 3.

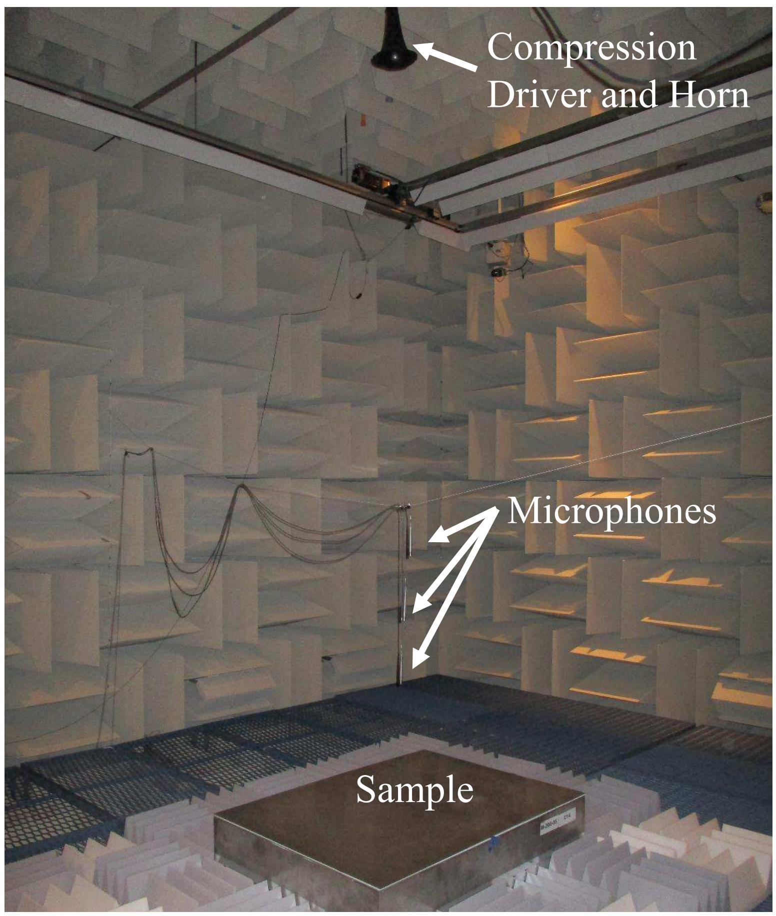

Fig. 3 Experimental setup for noise absorption test of 9x15 acoustic boxes in the ATL at GRC.

To conduct the test, the speaker emits a white noise burst approximately three milliseconds long (300 samples at 100 kHz). This creates a pressure disturbance about 1 m (3 ft) long. The noise is measured by the microphone going downward, reflects off the panel being tested and is measured again by the same microphone going upward. It is necessary for the microphone to measure a quiet gap between the outward and reflected sound waves to easily separate the incident and reflected waves. The sound reflected from a solid steel panel is compared to the sound reflected from an acoustically absorptive panel and used to calculate an absorption coefficient as,

$$C(f) = 1 - \frac{\overline{P^2(f)}_{Sample}}{\overline{P^2(f)}_{Solid}}. \tag{1}$$

In this expression, $\overline{P^2(f)}$ is a frequency-dependent power spectrum of the reflected signal. More details of the method are given in the supporting studies report[12].

The overall acoustic absorption impact of the low roughness noise surface is shown in Figure 4. For frequencies below 4 kHz, there is a penalty to the acoustic performance due to the added resistance of the micronic wire cloth. This represents a potential negative impact to the facility due to the diffusion bonded panel. Lower flow resistance cloth would have higher roughness noise, and vice versa. This was confirmed in testing a Virginia Tech and the GRC ATL[12]. The selected panel was considered the best compromise of both aspects. Above 4 kHz, the acoustic performance is improved, due to the higher percent open area of the perforate plate. The absorption coefficient at 10 kHz improved from 0.87 to 0.94. The better low-frequency properties of the 1986 design were likely appropriate for the advanced turboprop[19] testing that was expected at the time.

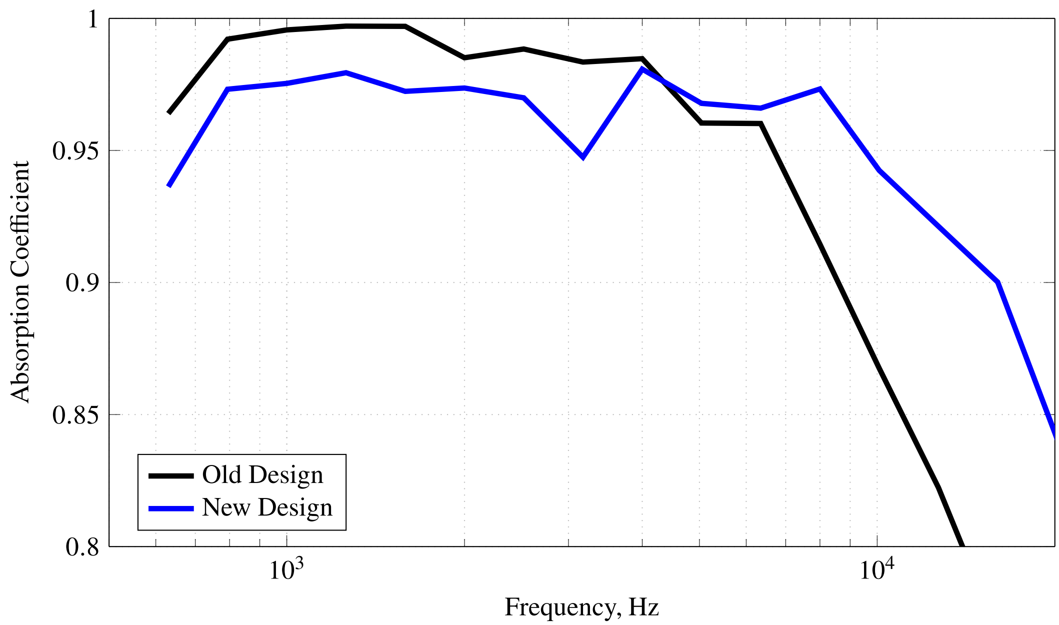

Fig. 4 Example result from absorption coefficient test.

IV. Background Noise Improvement

This section discusses the noise measured in the 9x15 LSWT before and after the renovation and the amount of noise reduction achieved. The experimental setup for the background noise reduction validation measurements was a single microphone mounted to the floor of the 9x15 LSWT, as shown in Figure 5.

The modifications to the 9x15 LSWT resulted in substantial reduction of the background noise. The focus of the improvement project were the one-third octave bands between 630 Hz and 50 kHz. Over these bands, the average noise reduction was 13 dB. The noise reduction at frequencies above 2 kHz is believed to come principally from the smoother flow surface enabled by the diffusion bonded panels. The care and attention to the manufacturing methods and assembly also contribute to the background noise reduction as the gaps and steps between panels seems to result in very little additional noise. Below 2 kHz, the noise reduction is due to the other components of the improvement project, especially the upstream baffles. The noise below 300 Hz is believed to be due to the microphone holder strut used in the tunnel. The smallest noise reduction was 7 dB, occuring at 2 kHz. This frequency was previously a local minimum and is now a local maximum.

Fig. 5 Experimental setup for background noise validation measurements in test section.

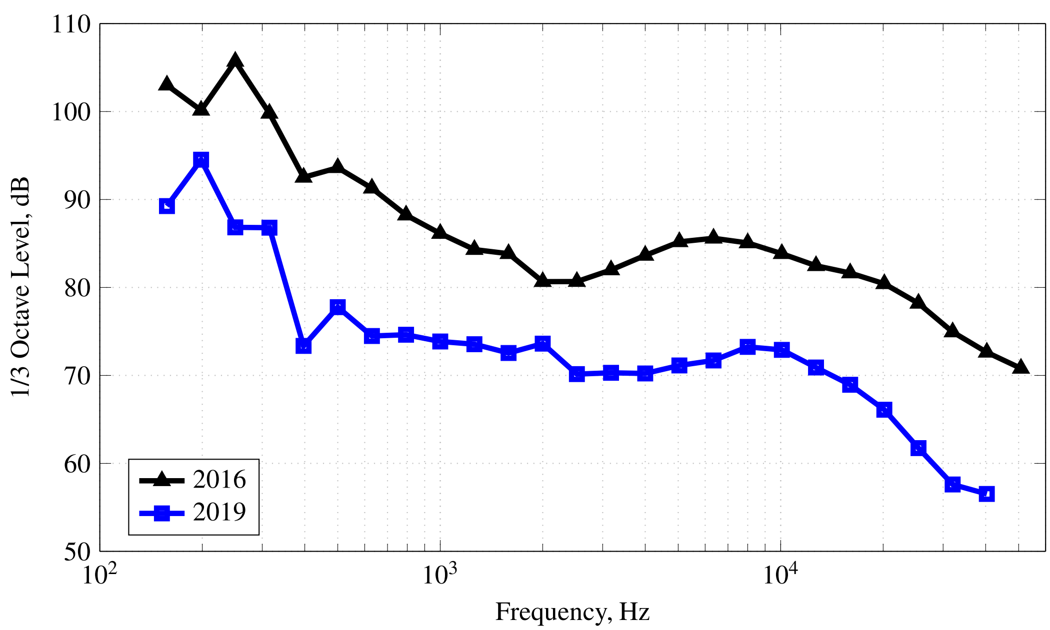

Fig. 6 Example result of background noise new vs old at Mach 0.20.

The usual method of collecting noise data in the facility utilizes a streamwise traversing microphone running the length of the test section. This gives data analogous to a model flying past an observer. A new traversing microphone probe support has been developed for operational testing, but was not available at the time of this validation testing and is not discussed in the present report.

V. Anechoic Quality Improvement

The original goal of the facility improvement project was to reduce the background noise in the test section while maintaining the existing sound-absorbing quality provided by the acoustic treatment. The test section needed a smooth flow surface, but it should also absorb a very high fraction of the sound energy incident on it. Solid walls for the test section would have low roughness noise but would have strong reflections that would make microphone measurements problematic. The usual solution for acoustic chambers is to use foam or fiberglass wedges, but this could not be used as a flow surface. After extensive testing and analysis, we determined that the two-layer bulk absorber designed for the 1986 acoustic treatment[8, 20] was excellent and could not be meaningfully improved upon with the space constraint of 33 cm (13-inch) deep boxes. The very light upper layer of unwoven Kevlar was retained while the lower layer of compressed Kevlar was replaced with a readily available fiberglass batting of the appropriate flow resistivity that did not need to be compressed. Details of the updated acoustic treatment are provided in Section 6 of [12]. The anechoic quality of the test section was measured using an impulse response method, a reverberation time analysis, and also a tone-based draw-away method. The goal of these three tests was to quantify changes to the anechoic quality of the test section.

A. Interrupted Noise

Measurements of the reverberation time in the 9x15 LSWT were made using a CESVA FP121 dodecahedron speaker system. The 12-sided speaker sends sound out in various directions to help ensure the entire space participates in the reverberation. The testing method was largely following the specifications for interrupted noise testing described in ISO 354.[21] The speaker was placed at the typical model location, as shown in Figure 7, and microphones on tripods were placed at the ends of the sideline path traced by the traversing microphone system typically used for acoustic measurements. The usual 9x15 acoustics data acquisition system was used[22], composed of B&K 4939 microphones, B&K Nexus signal conditioning amplifiers and an RC Electronics DataMAX recorder set to 90 kHz bandwith. The provided microphone gridcaps were used as there was no airflow in the test section during these tests. This test was conducted with a white noise signal generator. When the speaker was turned on, the test section was "ensonified," or filled with sound. While the recording was active, the sound source was abruptly shut off and the sound field decayed. This was repeated 10 times in order to provide some statistical averaging to smooth the results and improve interpretation.

Fig. 7 Dodecagon speaker in the 9x15 LSWT test section at the location of a typical fan model. Test conducted June 27-18, 2019. Looking upstream from diffuser ramp.

The measured time history from the microphone was passed through a digital one-third octave band filter bank, which split the signal into 18 time history signals each representing a frequency band from 315 Hz to 20 kHz. The dodecahedron speaker does not make significant noise above or below these frequencies. The time histories at each frequency were then used to compute a short time sound pressure level with a moving standard deviation window of 50 ms length. The 10 filtered samples were then averaged to give a final decibel level time history. An example measurement result from the test is given in Figure 8 where the one-third octave band centered at 1 kHz was selected as representative of the frequency range. Starting amplitude was set to 0 dB for both measurements. In the data from 2012, the sound termination results in a quick fall by 15 dB, as the reflections echoing within the test section decay away. The same initial decay is more than 30 dB in the 2019 data. Similarly, the secondary reflections occurring within the first 0.3 seconds are much steeper in the updated test section. At 0.5 seconds the level in the new test section has fallen by 54 dB compared 27 dB in the earlier measurement, although this is probably a combination of audio and electrical noise floors.

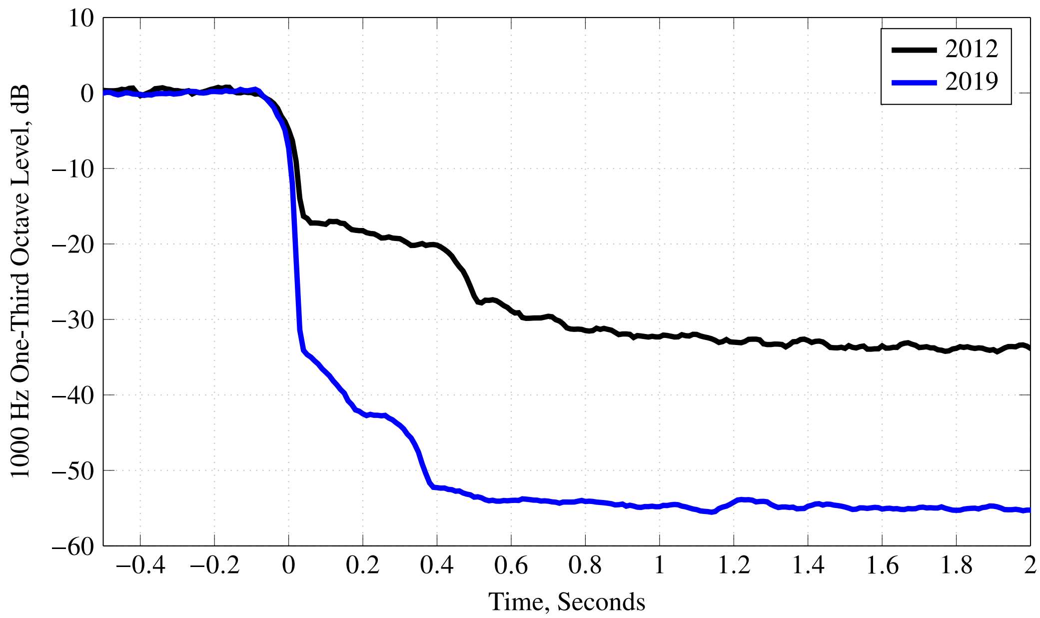

Fig. 8 Interrupted noise example measurement for 1/3 octave band center frequency of 1000 Hz.

As described in ISO 354, the resulting metric for reverberation time is typically given as RT60, the time required for the sound to decay 60 decibels. Directly measuring this would require a source that could produce more than 60 dB of noise above the noise floor of the room and measurement system. Since this is not always possible, a smaller decay is measured and the RT60 is extrapolated from that. Using this method, RT60 was calculated at all frequencies measured and is shown in Figure 9. These numbers demonstrate that RT60 measured in the test section was previously as long as 2 seconds at frequencies up to 3 kHz. This was noticeable in the test section with a simple hand clap. After the acoustic improvement project, RT60 was reduced to less than 0.5 seconds at all frequencies and the facility is perceivably anechoic.

B. Impulse Response

A relatively common technique for evaluating the acoustic properties of an interior volume is an impulse response test. The method is fast and easy with modest equipment requirements and can give useful qualitative information. The resulting measurements are not a substitute for a draw-away measurement using a tone source to give a quantifiable uncertainty for measurement accuracy, but it is a good complement to the other test methods described in this report. Reasonable effort was made to reproduce the test configuration before and after the improvement project, and the same measurement and signal processing methods were used. Under these conditions, some quantifiable conclusions can be drawn. The impulse response of the 9x15 LSWT was investigated some 20 years previously by Woodward et al.[10], with results similar to those presented here for the pre-construction facility.

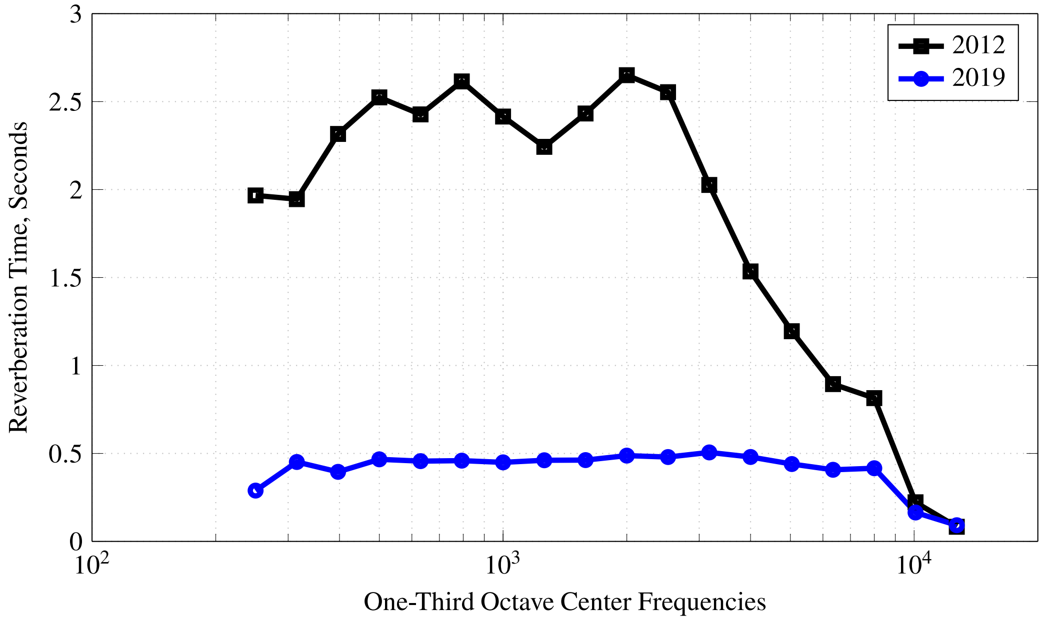

Fig. 9 Reverberation time (RT60) measurements.

The impulse for the test was generated using a hand-held starter pistol operated in the usual manner. Three test configurations were used, each with two microphones on tripods, oriented vertically to be roughly omni-directional to sounds reverberating in the horizontal plane. The microphones and pistol were all positioned at the middle of the test section height. The configuration was quite similar to that used in the reverberation time test previously discussed. A typical test is shown in Figure 10.

Fig. 10 Impulse response measurement method.

The ideal measured impulse response would be a delta function. Inside a chamber, reverberations can be reduced by never really eliminated. A summary of the impulse response measurements, pre- and post-construction is given in Figure 11. A few quantifiable metrics can be pulled from this graph. With a peak signal level of about 120 dB for both cases, it is quickly evident that the acoustic improvement project reduced the level of the peak secondary reflection from 100 dB to 85 dB. The duration of the reverberation also appears to be reduced from more than 2 seconds to less than 0.5 seconds, which is consistent with the interrupted noise result mentioned previously. A more detailed study of the reverberations and examination of the geometry of the wind tunnel is given in [13].

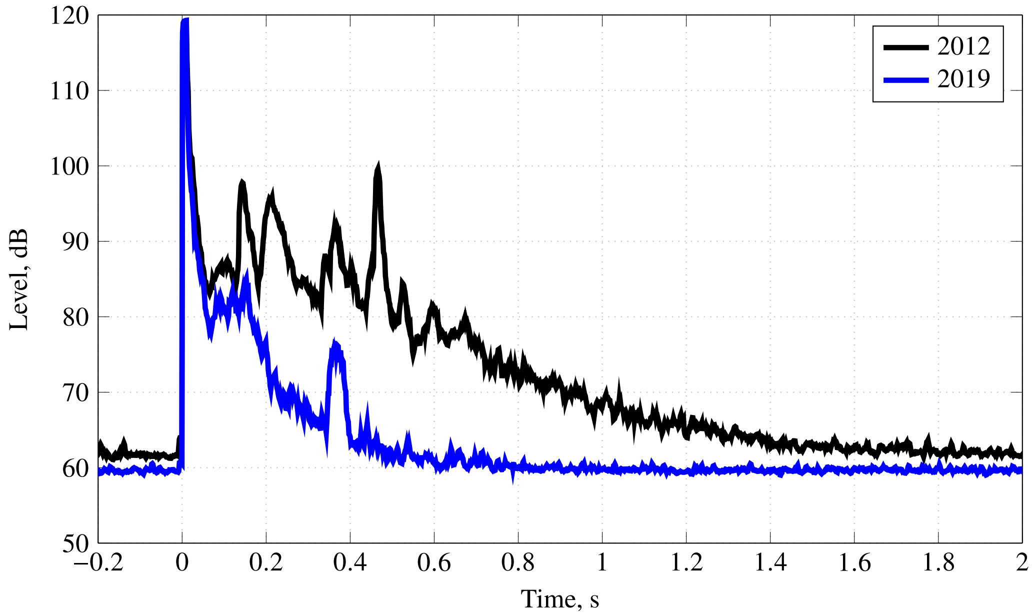

Fig. 11 Example result from impulse response test.

The impulse response test was also used to calculate the sound exposure metric L_{eq}, which is used to quantify levels of time-varying signals. This metric is given in Equation 2,

$$L_{eq} = 10 \log_{10} \left(\frac{1}{T} \int_0^T \frac{p^2(t)}{p_0^2} dt \right), \tag{2}$$

where T is the measurement duration, $p(t)$ is the sound pressure signal and p_0 is the reference pressure of 20 μ Pa. The amplitude L_{eq} was calculated twice for each curve, using an integration time of 14 ms and then 1 s. The duration T of 14 ms was chosen as representing about 20 dB down from the main peak, while the duration 1 s was chosen as capturing most of the large reverberations in the record. An error can then be calculated for each measurement as $L_{eq,1000ms} - L_{eq,14ms}$. According to this metric, the error in L_{eq} has been reduced from 0.8 dB to 0.2 dB.

C. Draw Away Tone

The most elaborate and sensitive test of the anechoic quality of a space is the draw away test. An omnidirectional sound source is placed at a location of interest in the test section. While the speaker is continuously producing a tone, a microphone measures the sound level at different locations in the test section. This is typically along a ray passing through the center of the speaker, as described by ISO 26101[23], but it could be another path of interest such as the traverse sideline. The expected "decay with distance" of the noise is an inverse square law, $1/r^2$, and deviations from this are assumed to be due to reflections from the tunnel walls which cause constructive and destructive interference. This test is extremely sensitive, but time consuming and requires specialized equipment. A photograph of the setup is shown in Figure 12.

The results from this measurement are deviations from the inverse square law, computed once the expected correction for distance is removed. Near the source, the relative amplitude of the reflections is small and so the error

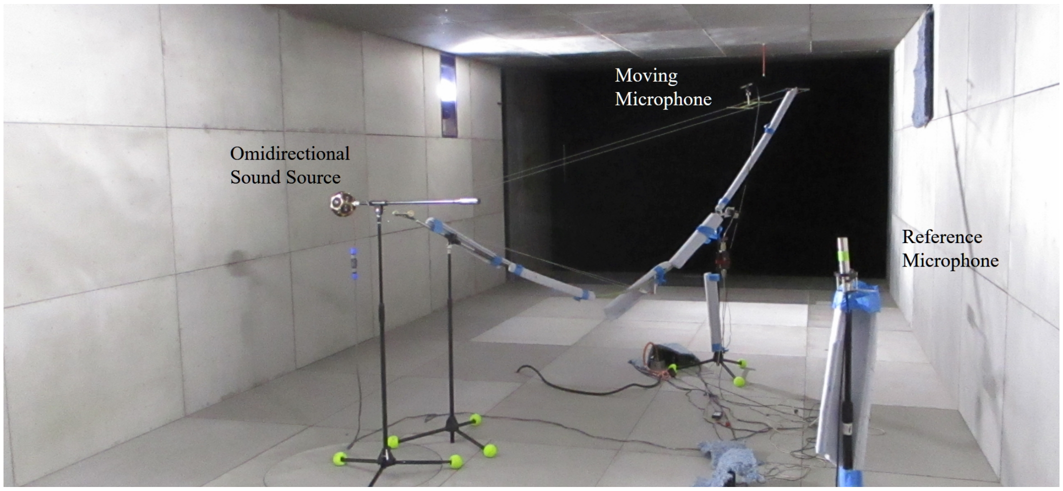

Fig. 12 Draw away testing setup used by Vi Acoustics and ETS-Lindgren in 2019.

is small. When measuring an acoustically compact source, the microphone measurements should be made as close as practical. As the microphone is moved closer to the walls, the reflections increasingly affect the measured tone amplitude. Since the test is conducted with a steady tone, a pattern of constructive and destructive interference is established in the space being tested. An example measurement is shown in Figure 13, for a draw-away line pointed towards the Northeast test section corner. It is readily apparent in this example that the deviations are significantly reduced after the tunnel improvement project. The other interpretation for this result is a distance from the source to the measurement location that is needed to give measurements with a certain accuracy. This graph shows one measurement direction and one frequency, while in total four directions and 20 frequencies were analyzed.

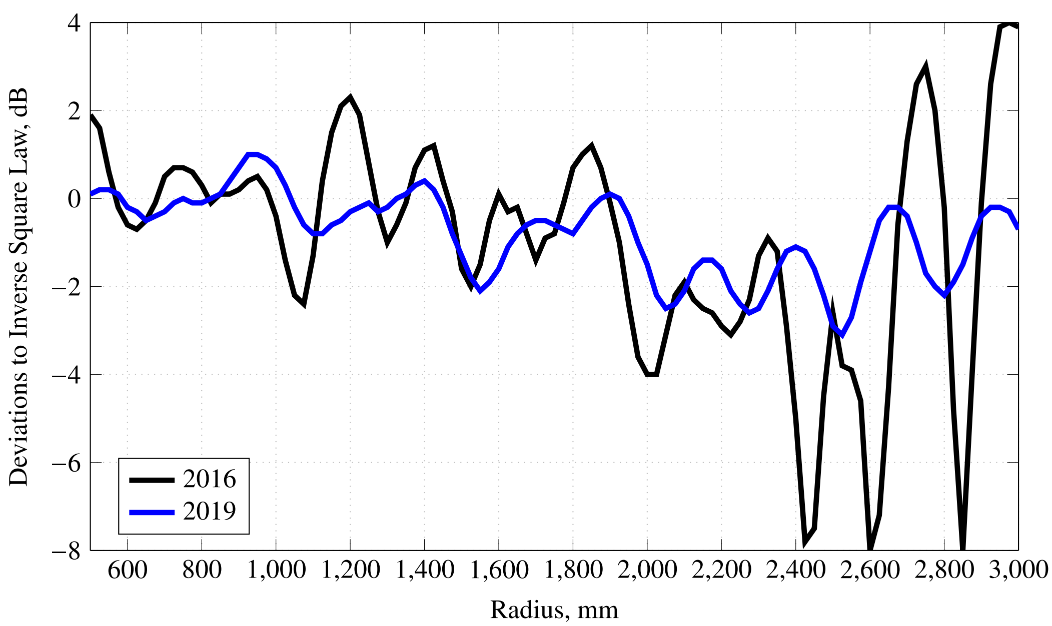

Fig. 13 Draw away deviation result for Northeast upper trihedral direction, 1000 Hz tone.

The complete results from both test campaigns is given in a pair of comprehensive reports[24, 25], so only a summary of the improvement will be reported here. As reported by Schmitt[25], the maximum deviation from the inverse square law along the sideline traverse path of the typical NASA survey was reduced at all frequencies above 500 Hz by an average of 2.5 dB. This is graphically represented in Figure 14, showing the uncertainty levels as shaded bands for different frequencies. In addition to the maximum uncertainty being reduced, the size of the band is much smaller, representing a more uniform acoustic field in the test section.

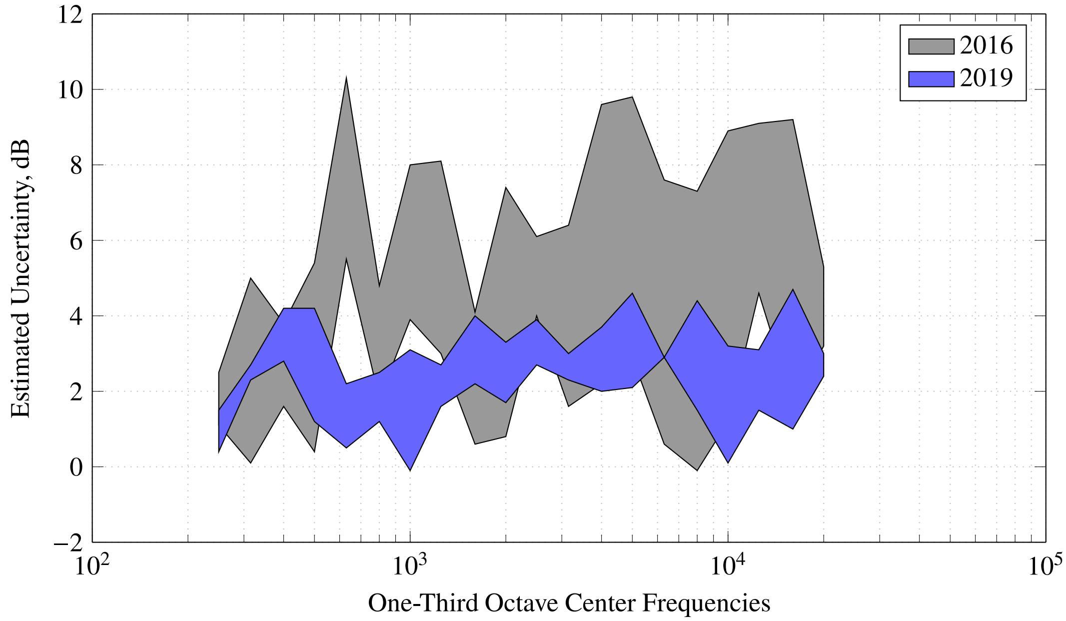

Fig. 14 Summary of new vs old draw away results, estimated error.

It should be emphasized that this study was conducted with compact sources producing steady tones without airflow. By contrast, an engine fan model producing strong tones will be slightly unsteady and turbulence in the airflow will further reduce the amplitude of interference patterns. This suggests the results presented here might be an overestimation of the tone uncertainty measured from a wind tunnel model. On the other hand, models tested in the wind tunnel are often relatively large, so it is not possible to place the microphones far enough away that they are acoustically compact, due to the limited size of the test section. Microphone placement thus becomes a compromise between trying to be far from both the model and walls. Additionally, the airflow wake of the model should not impact the microphones, or vice versa. Advanced signal processing methods for better far-field projection are being studied[26].

VI. Conclusions

The acoustic improvement to the 9x15 LSWT resulted in a much quieter background noise level and better overall acoustic quality. The use of a micronic wire cloth drastically reduced the roughness noise generated by the airflow through the test section. The flow resistance of the micronic cloth is key to the noise reduction, but it slightly decreased the acoustic absorption of the individual acoustic panels at frequencies below 3 kHz. This effect was overcome through other aspects of the construction, as a re-built test section structure, improved construction quality and acoustic improvements around the loop offset this risk and no meaningful negative impact was identified. The new test section will enable future quiet models to be tested with confidence for decades to come.

Acknowledgments

The NASA Environmentally Responsible Aviation Project funded the 9x15 LSWT background noise measurements conducted in 2012, along with the original study by Jacobs in 2012. The NASA Aeronautics Test Program and Aerosciences Evaluation Test Capabilities Portfolio funded the improvement project with support from NASA Glenn Research Center. The writing of this report was funded by the NASA Advanced Air Transport Technology project. Special thanks to Clif Horne from NASA Ames Research Center for providing a sample panel from the NFAC 40x80 for us to study. Thanks also to Nathan Alexander at Virginia Tech for leading the roughness noise experimental effort there.

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