Flight Test Methodology for NASA Advanced Inlet Liner on 737MAX-7 Test Bed (Quiet Technology Demonstrator 3)

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This paper describes the acoustic flight test results of an advanced nacelle inlet acoustic liner concept designed by NASA Langley, in a campaign called Quiet Technology Demonstrator 3 (QTD3). NASA has been developing multiple acoustic liner concepts to benefit acoustics with multiple-degrees of freedom (MDOF) honeycomb cavities, and lower the excrescence drag. Acoustic and drag performance were assessed at a lab-scale, flow duct level in 2016. Limitations of the lab-scale rig left open-ended questions regarding the in-flight acoustic performance. This led to a joint project to acquire acoustic flyover data with this new liner technology built into full scale inlet hardware containing the NASA MDOF Low Drag Liner. Boeing saw an opportunity to collect the acoustic flyover data on the 737 MAX-7 between certification tests at no impact to the overall program schedule, and successfully executed within the allotted time. The flight test methodology and the test configurations are detailed and the acoustic analysis is summarized in this paper. After the tone and broadband deltas associated with the inlet hardware were separated and evaluated, the result was a significant decrease in cumulative EPNL (Effective Perceived Noise Level).

I. Nomenclature

3DOF	=	Three degrees of freedom
AATT	=	Advanced Air Transport Technology
BCW	=	Boeing Canada Winnipeg
BFI	=	Boeing Field International Airport
BPF	=	Blade Passage Frequency
CFM	=	Engine company partnership of Safran Aircraft Engines and General Electric Aviation
CGS Rayl	=	Centimeter/Gram/Second (metric units) Rayl
EPNL	=	Effective Perceived Noise Level
G	=	Slot-to-slot Gap [in]
L	=	Slot length [in]
KCAS	=	knots calibrated airspeed
MDOF	=	Multiple Degrees-of-Freedom, interchangeable with 3DOF in this paper
MWH	=	Grant County Airport in Moses Lake, WA
N1	=	Rotation speed of the fan [rpm]
NASA	=	National Aeronautics and Space Administration
NLF	=	Non-linearity factor
P	=	Pitch between slot rows [in]
PEEK	=	Polyetheretherketone thermoplastic
POA	=	Percent Open Area [%]
QA	=	Quality Assurance

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QTD	=	Quiet Technology Demonstrator
RPM	=	Rotations per minute
t	=	Facesheet thickness [in]
T12	=	Temperature at fan inlet
W	=	Slot width [in]

II. Introduction

The overarching goal of the NASA Advanced Air Transport Technology (AATT) Project is to explore and develop technologies and concepts for improved energy efficiency and environmental compatibility for fixed wing subsonic transports, which includes improvements on community noise acoustic performance. In this particular study, the AATT Project is developing advanced acoustic liner technology to improve the broadband noise reduction and reduce the drag characteristics through multidegree-of-freedom (MDOF) nacelle treatment designs. In late 2017, a dedicated project was launched between NASA and The Boeing Company to investigate the full-scale acoustic liner benefits in flight.

The project had multiple phases spanning just over one year: design development, hardware manufacture, flight test planning and safety, flight test execution, and acoustic data analysis. The acoustic flyover test is also known as Quiet Technology Demonstrator 3 or QTD3, following full-scale acoustic test predecessors of QTD in 2001 and QTD2 in 2005, see Ref. [1], [2]. This paper documents the flight test methodology portion of the contract and summarizes key findings from the successful acoustic flyover test. The measured data coming out of this project demonstrates at full scale the benefits of an advanced acoustic liner design on the 737 MAX Inlet; these benefits can be applied to future aircraft design work and trade studies.

III. NASA Multidegree-of-Freedom Low-Drag Inlet Design

NASA led the conceptual design of the Multidegree-of-Freedom acoustic liner and supplied the acoustic requirements for the honeycomb core with dual septa and facesheet with lower drag slot perforations. The design process to optimize the acoustic liner impedance is described in Ref. [3]. The acoustic liner optimization process aims to improve broadband fan noise reduction relative to standard production liners. Working together with the Boeing Company, the design requirements were fine-tuned such that the hardware would meet manufacturability requirements and the aggressive test schedule.

The MDOF core was designed by NASA Langley and was fabricated by the Hexcel Corporation. The core design contains two layers of Polyetheretherketone (PEEK) mesh septa within each honeycomb cell. Figure 1 shows a sketch of the acoustic core design parameters, and an example cross-section of the fabricated MDOF core. The combined system of septa has a total flow resistance of 190 CGS Rayl at 105 cm/s, and a nonlinearity factor (NLF) less than 1.9.

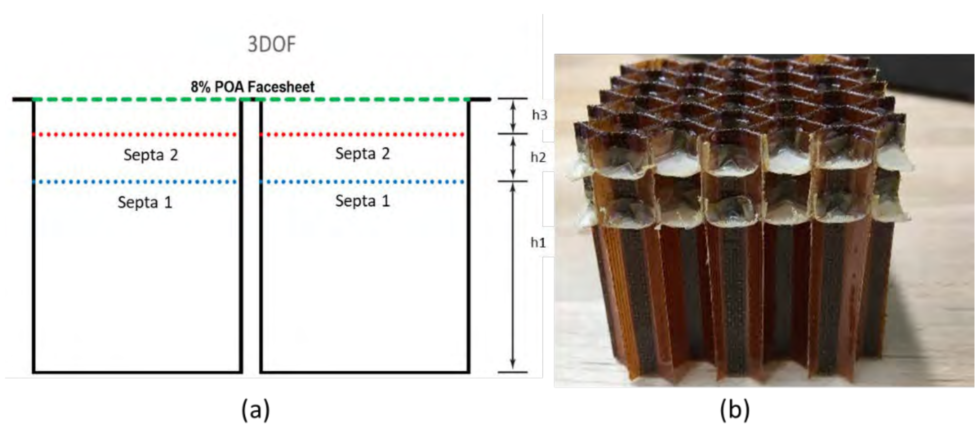

Figure 1: (a) Schematic of MDOF septa configuration, and (b) MDOF core specimen showing two layers of septa per cell.

The final facesheet definition is provided in Figure 2 and Table 1. The optimal slot width was 0.02" for the best drag performance based on previous measurements in the grazing flow impedance tube (GFIT). Boeing investigated the full-scale manufacturability of this slot width, but it proved to be quite challenging for the development time frame. As a compromise, the Boeing Canada Winnipeg (BCW) manufacturing team was capable of manufacturing 0.031" wide slots in the given time frame. NASA assessed this width and found it to still be a drag improvement relative to conventional perforations. For future low-drag liner development and production implementation, it is recommended to investigate thinner face sheets or alternate methods of creating slots that would enable thinner widths.

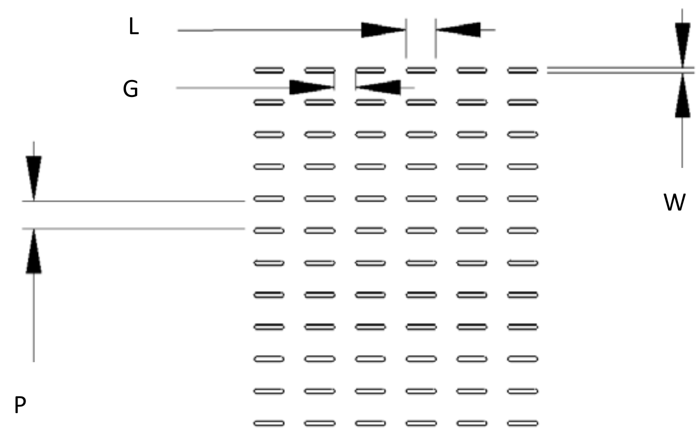

Figure 2: Parameter definition of low-drag slot perforations.

Table 1: Nominal dimensions of Low-Drag Facesheet geometry.

Nominal Low-Drag Facesheet Dimensions	
Percent Open Area [%]	8.0
Slot Length (L) [in]	0.2
Slot Width (W) [in]	0.031
Slot-to-slot Gap (G) [in]	0.142
Pitch (P) [in]	0.185
Total Thickness (t) [in]	0.055 (5 plys + adhesive)

The manufacturing of the MDOF inlet was a "One Boeing" effort involving multiple Boeing facilities and Suppliers. The MDOF core was manufactured in Casa Grande, Arizona by the Hexcel Corporation. The inlet core was then shipped to Hexcel's Burlington, WA facility to be formed and fitted into two core blankets. These blankets were then shipped to Winnipeg, Canada and installed into the acoustic inner barrel. The acoustic inner barrel was then shipped to Boeing's Propulsion South Carolina facility and fitted with the flanges and fairings necessary for flight. Finally, the completed inlet was shipped to Boeing Field in Seattle and fitted onto the 737MAX-7 aircraft for the flight test.

The acoustic impedance of the inlet was measured with a portable impedance meter after final assembly (Figure 3). Figure 4 shows the average normalized impedance components, Resistance and Reactance, for the NASA MDOF flight test inlet liner. The MDOF liner has a flattened resistance curve, and the reactance remains near zero for frequencies up to 4000 Hz. These characteristics will broaden the attenuation frequency range for improved noise reduction. The acoustic impedance of the inner barrel construction had lower variability than an early coupon, which can be attributed to the improvement in Hexcel's MDOF fabrication process with automation.

Figure 3: Post-paint portable impedance inspection of NASA MDOF inlet

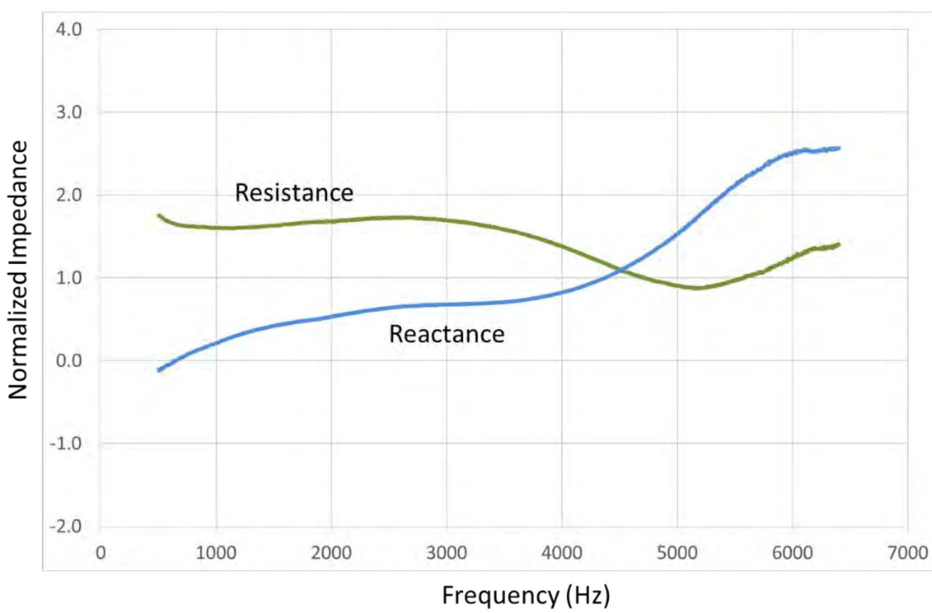

Figure 4: Average Measured MDOF inlet bond panel impedance levels with Portable Impedance Meter.

IV. Inlet Test Configurations

There were three inlet configurations tested that are of interest for this project: 737 MAX Production inlet, NASA MDOF Low Drag inlet, and a Hardwall taped inlet. All inlets were acoustically smooth and without discontinuities, except for the small fan inlet temperature (T12) probe installation.

Figure 5: List of Inlet and Forward Fan Case Hardware that were tested.

The 737 MAX inlet had been in production for about three years at the time of this test. The airplane identified for this test was provided with two production inlets. The inlets went through the typical fabrication and inspection processes. No modifications were made to the acoustic treatment. The Boeing production acoustic liner consists of circular perforations over a two-degree-of-freedom honeycomb core.

In lieu of fabricating an entire inlet without acoustic treatment, an effective and well-documented technique is to apply thick gauge speed tape to the entire acoustically treated surface. For this test, the NASA MDOF inlet was used in combination with speed tape to serve as the hardwall inlet configuration. The speed tape blocks the perforations and provides the acoustic reflective properties of a hard wall.

The application of speed tape requires careful planning and execution to ensure that no tape will detach in-flight. The MDOF flow side surface was first cleaned of any residue. The speed tape was applied in axial strips, with the terminating end wrapped around the panel when possible. The tape edges were specified to overlap such that the fan blade rotation direction will always encounter a backward-facing step. A hard plastic squeegee is used to press air bubbles out and ensure good adhesion. Furthermore, the tape was pierced at regular intervals throughout the covered surface to prevent possible bubbling up that could occur with positive pressure within the underlying liner. The forward edge was sealed down with a bead of epoxy and smoothed to minimize any step height. The end result was extremely successful, with zero bubbling or lifting detected after the hardwall acoustic conditions were completed. Figure 6c shows the speed-taped NASA inlet.

The forward fan case is part of the engine build. The production configuration of the 737 MAX has an acoustically treated forward fan case with perforations, and was supplied by Safran/CFM. For this test, Boeing and NASA wanted to isolate the effect of the inlet acoustic treatment and remove any effect of the forward fan case treatment. It was believed to be too high-risk to apply speed tape to surfaces directly in front of the fan, so Boeing requested Safran to supply a test article with the forward fan case not perforated. Safran graciously supplied the QTD3 test with the unperforated version that was used in all the acoustic flyover configurations of this project.

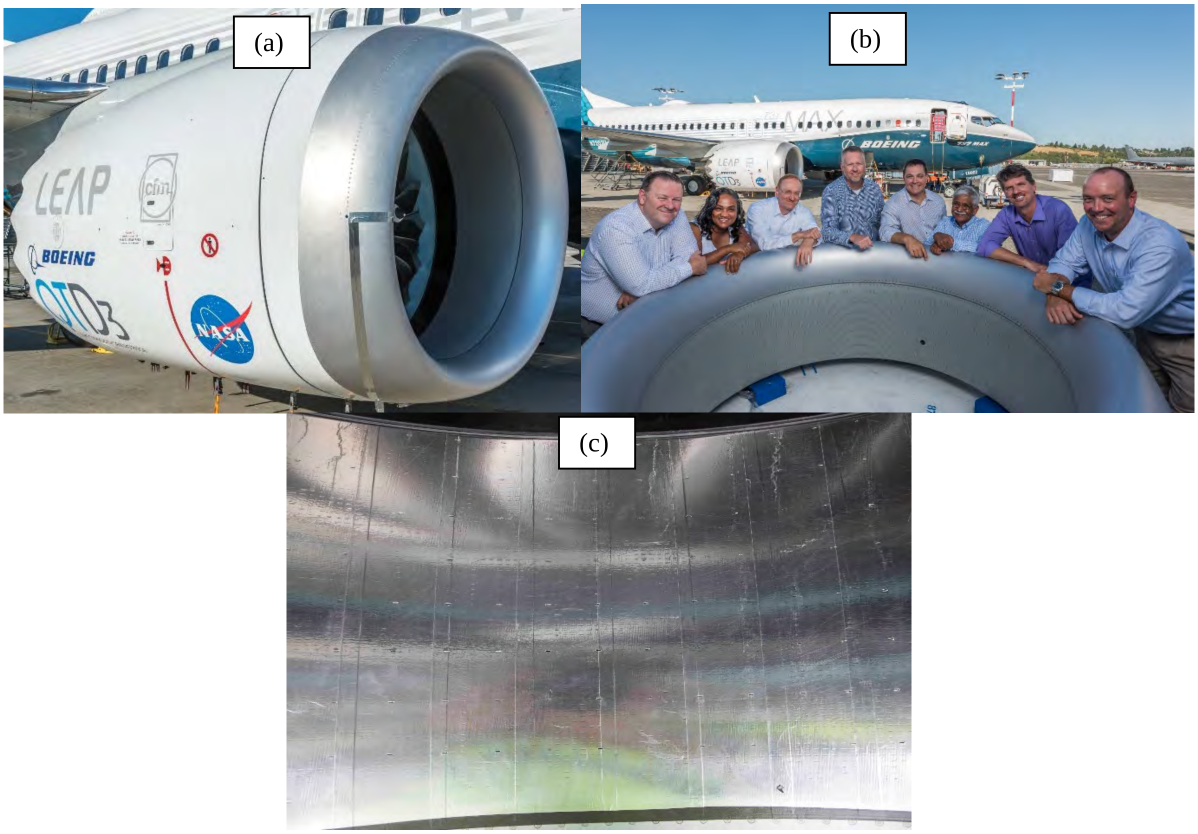

Figure 6: Photos of inlet configurations: (a) Production Baseline, (b) NASA MDOF low-drag inlet, (c) Hardwall simulated with speed tape.

V. Flight Test Set-Up

The acoustic flyover test was conducted at the Grant County International Airport (MWH) at Moses Lake, Washington. Acoustic data was acquired while the airplane performed a series of approach and takeoff flight path intercepts over the ground plane ensemble array and phased arrays for a number of inlet configurations and power settings encapsulating the operating range. The right-side engine was selected as the test engine with the experimental inlet hardware installed prior to each test day, while the left-side engine remained in the production configuration and was operated at idle for all conditions.

The airplane, aircraft crew, and ground crew were based out of Boeing Field (BFI), Washington. Test flights departed from BFI for a 30-minute ferry flight to Grant County International Airport (MWH) at Moses Lake, Washington, where specified test conditions were performed over the ground plane ensemble array and phased array instrumentation. Moses Lake was chosen as the most efficient site to conduct acoustic flyover data during the summer. The weather is typically favorable for acoustic conditions in this season, and the MWH airport is relatively close to BFI where the Boeing Flight Test organization is based.

The acoustic instrumentation was set up north of the approach end of Runway 14L as shown in Figure 7. The test conditions simulating takeoff noise were conducted by flying south-to-north over Runway 32R such that the target altitude, airspeed and engine thrust were achieved over the microphone arrays at the correct time. The test conditions simulating approach noise were conducted approaching Runway 14L flying north-to-south.

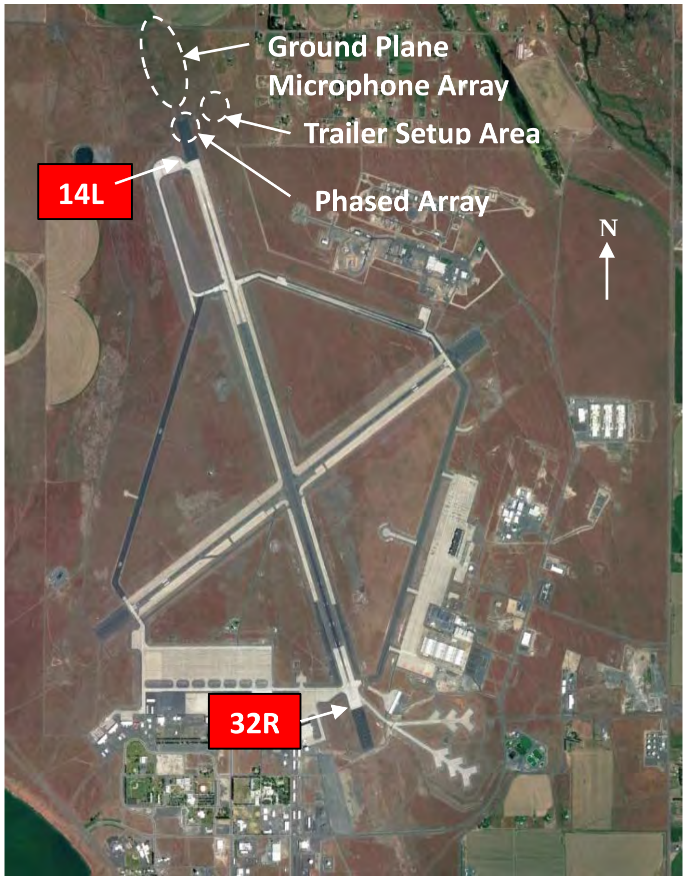

Figure 7: Grant County Airport aerial view of instrumentation setup.

Table 2 contains the daily test configuration and high-level summary of the acquired test conditions and weather description. The production inlet / production forward fan case configuration was outside of the scope of the contract, but served as a good configuration to familiarize the ground and flight crews with acoustic flyover conditions and test conduct.

Table 2: Daily Test Configurations and Notes.

Date	7/27	7/30	7/31	8/1	8/2	8/3
Day	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
Inlet	Prod	NASA	Prod	Prod	HW (taped NASA)	HW (taped NASA)
Fwd Fan Case	Prod	HW	HW	HW	HW	HW
Notes	• 22/31 accepted conditions • Data collected between 6:00am – 11:30am	• 18/29 accepted conditions • Data collected between 6:00am – 11:00am • Approach conditions at 2450 RPM, F30, gear up and down	• 8/16 accepted conditions • Data collected between 8:00am – 10:30am	• 19/30 accepted conditions • TeData collected between 5:30am – 9:45am	• 15/30 accepted conditions • Data collected between 5:00am – 9:30am	• 13/19 accepted conditions • Data collected between 5:30am – 9:00am

The approach and takeoff conditions for community noise testing consisted of a series of "racetrack" flight patterns, each with a different target corrected fan RPM (N1) set in advance to ensure that the airplane intercepted the desired altitude over the center of the microphone array. These patterns have the airplane setting up so the airplane was "on condition" as it passed over the departure end of Runway 14L, and was also recorded by the phased array and the ground plane ensemble microphone array. The nominal intercept altitude for approach conditions was 400 ft and airspeed of 140 KCAS (knots calibrated air speed). For takeoff conditions, an intercept altitude of 800 ft was flown at an airspeed of 180 KCAS. A range of engine RPMs were flown to encompass approach, cutback, and full power takeoff points for a range of airplane weights and thrust ratings. An onboard Low Speed Aero Performance engineer calculated the required parameters for airplane setup and the "rotate" or "pushover" point that would hit the mark as close as possible to target altitude, speed, and engine setting. As a safety measure, the airplane flight crew utilized an announcement of "knock it off" if the altitude ever dropped below 250 ft. Figure 8 contains a schematic of the ground plane ensemble microphone array utilized in this test as the primary absolute value data set. The phased array was used for source component separation and is discussed in detail in Ref [4].

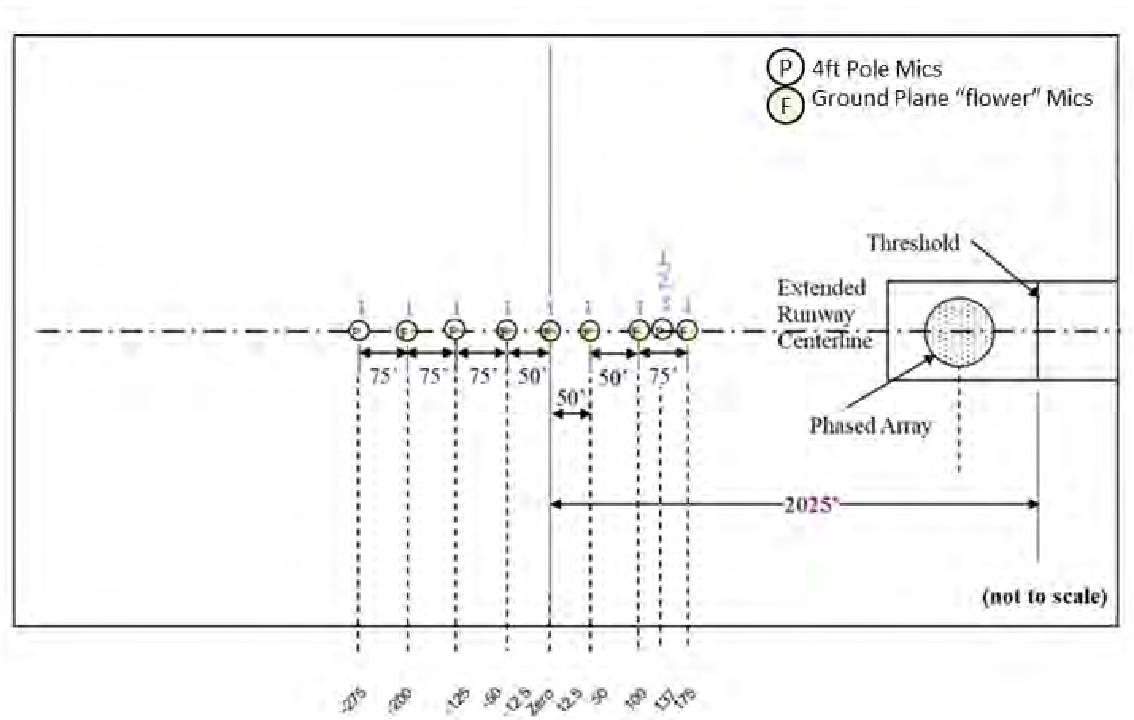

Figure 8: A layout of the microphones used for this test program (not to scale).

VI. Flight Test Results and Discussion

For standard acoustic certification flyover tests, there are defined criteria for the weather and airplane performance parameters that must be met in order to accept the condition. Since QTD3 was a technology test focused on the effects of changing hardware, it was necessary and important to make these requirements more stringent in order to gather the best possible data and be able to determine relatively small differences that might normally be within the normal certification flight test data scatter.

Regarding weather requirements, the maximum acceptable wind speed at 10 meters was set to 10 knots, with maximum gusts of 12 knots. The total crosswind allowance was reduced to less than 7 knots with maximum gusts of 10 knots. No rain, snow, or standing water in the vicinity of microphones was permitted. Figure 9 shows the collection of upper air weather measurements for the entire test. The overall weather quality was excellent and within the preferred 12 dB atmospheric attenuation window.

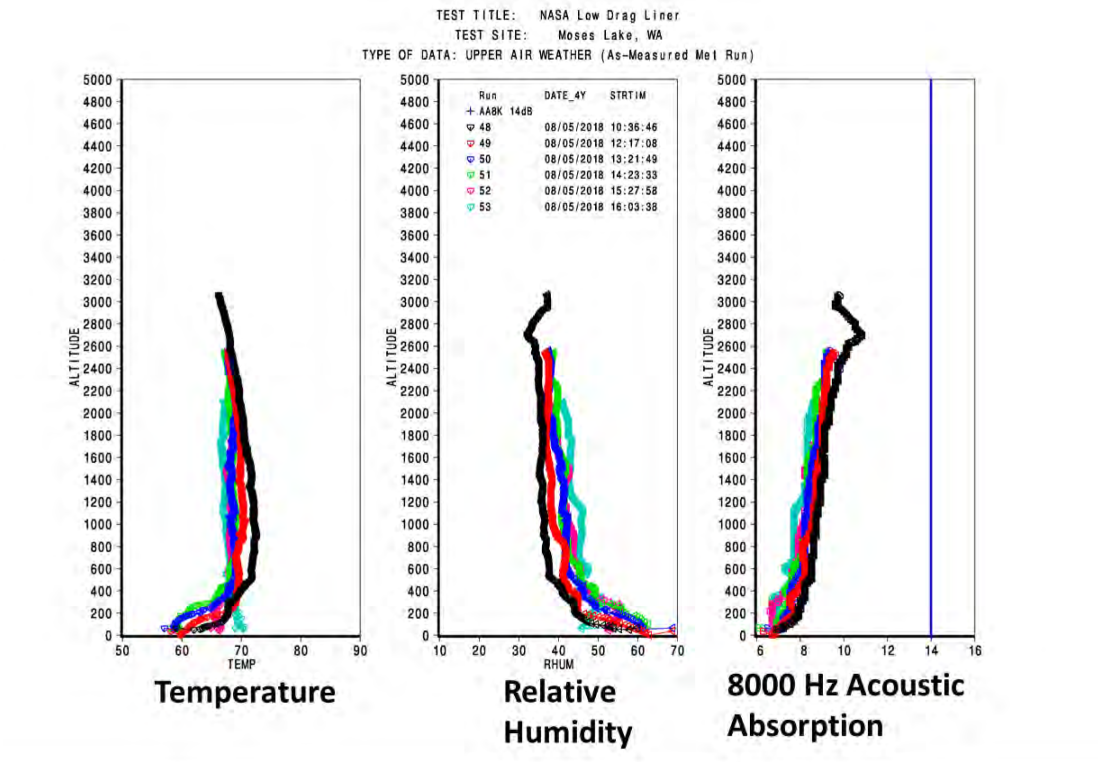

Figure 9: Temperature (TEMP), Relative Humidity (RHUM), and Atmospheric attenuation vs. altitude.

Microphone contamination screening is another important element of acoustic flyover testing that assures high quality and repeatable data. The far-field microphones are monitored from within the test trailer, with the screening focals noting when acoustic contamination occurs relative to noise recording windows. Most conditions with any contamination (e.g. birds, other aircraft, motor vehicles) were rejected and flown again. Figure 10 shows an example of acoustic contamination identified during a condition, which resulted in a rejection.

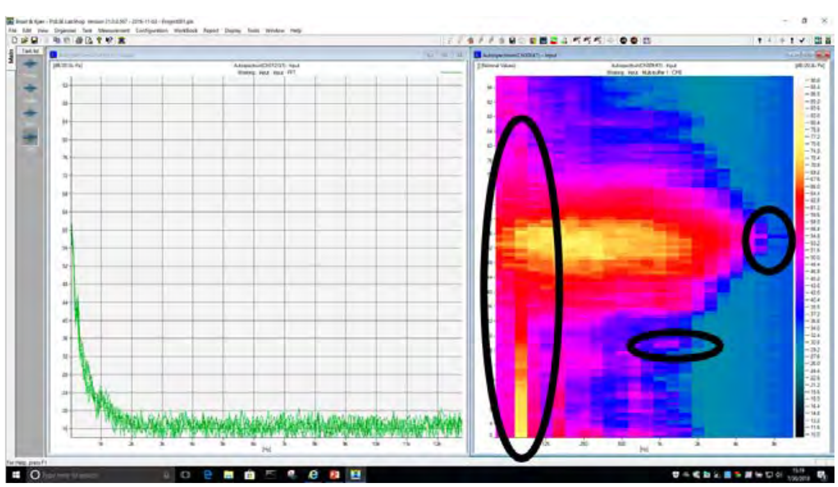

Figure 10: Example of microphone contamination screening.

The good weather quality and judicious microphone screening enabled very consistent and collapsed acoustic data capture. Figure 11 shows an example plot of 1/3 octave band normalized acoustic data monitored during the test from the ground plane ensemble microphone array. All eight flush dish microphones are tightly clustered and show very little variation, which is indicative of good data quality. Occasionally, the acoustic data will have one outlier microphone due to a localized contamination or sound variation. In these instances, the outlier microphone was omitted from the condition averaging as long as the other microphones were in good agreement.

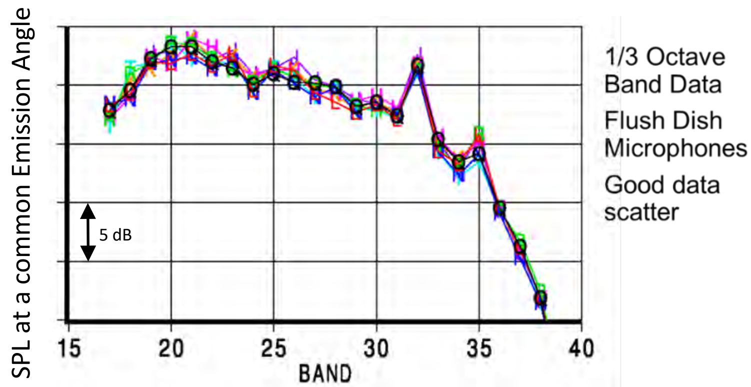

Figure 11: Example of good acoustic scatter – all eight ground microphones collapse tightly.

The measured flyover data were analyzed with a Boeing process that normalized the altitudes and velocities for each microphone, then interpolated the data to every 2 degrees of emission angle. The narrowband data were also de-Dopplerized. This normalized de-Dopplered narrowband data set was then projected to a 150-foot polar arc representing a static engine data setup, therefore enabling power levels to be calculated. The fan tones were identified and extracted using a median filter for the broadband, and a fixed width stencil for the tones whose center frequency was calculated based on the mechanical fan RPM and blade count. Figure 12 shows a sample comparison of the Blade Passage Frequency (BPF) tone noise as a function of emission angle for cutback and full power for the NASA inlet both Hardwalled and Treated. Generally, an emission angle range from 30 - 80 degrees is an appropriate span to investigate forward arc tones, and review of the phased array results in Ref [4] confirmed this was a good emission angle range for the tone power level calculations. Power levels are a better metric for looking at forward arc tone content, due to the highly directional nature of fan tones as seen in Figure 12.

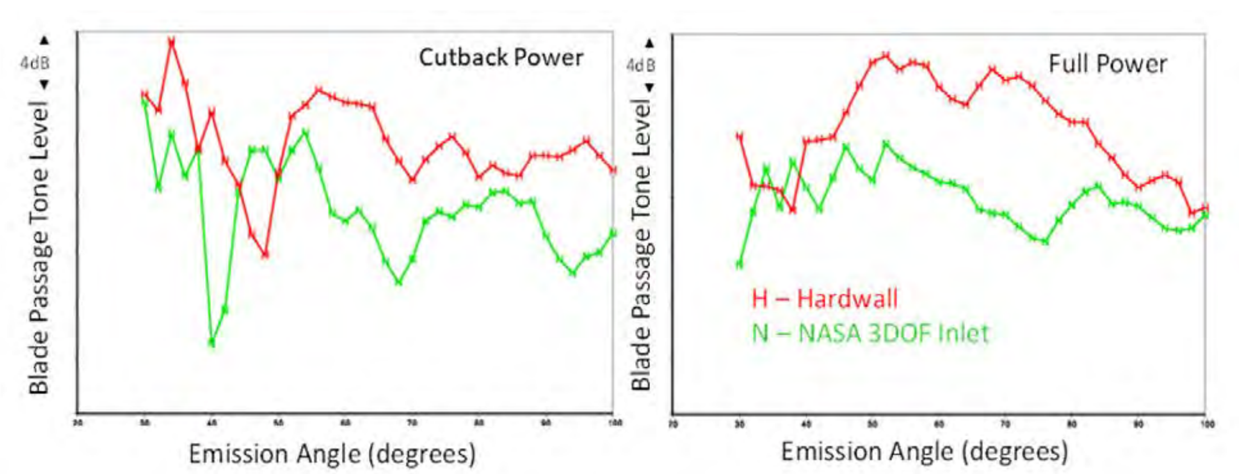

Figure 12: Blade Passage Frequency tone levels vs. emission angle for cutback power and full power takeoff.

Figure 13 shows the total forward arc fan tone power levels for takeoff power line conditions, with repeats. Between a midpower and high-power engine setting, the tone power level reduction due to the NASA MDOF inlet treatment is on the order of 12 dB. Moving to lower takeoff power settings, the attenuation decreases to about 6 dB, and the broadband noise floor begins to become a more important contributor. For the approach power settings, one good data set (with repeat at a slightly different power) was acquired for the NASA MDOF inlet configuration due to weather conditions (Figure 14). Nevertheless, the data conclusively show a good amount of fan tone power level reduction relative to the hardwall inlet, approximately 4 dB.

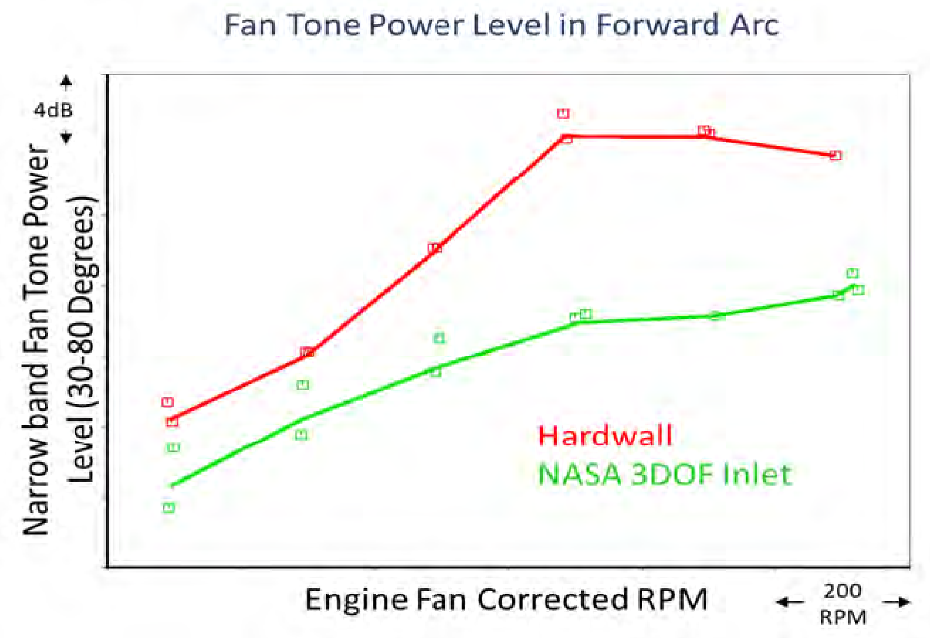

Figure 13: Total Forward Arc fan tone power level comparison between NASA Inlet and Hardwall Inlet configurations at takeoff powers.

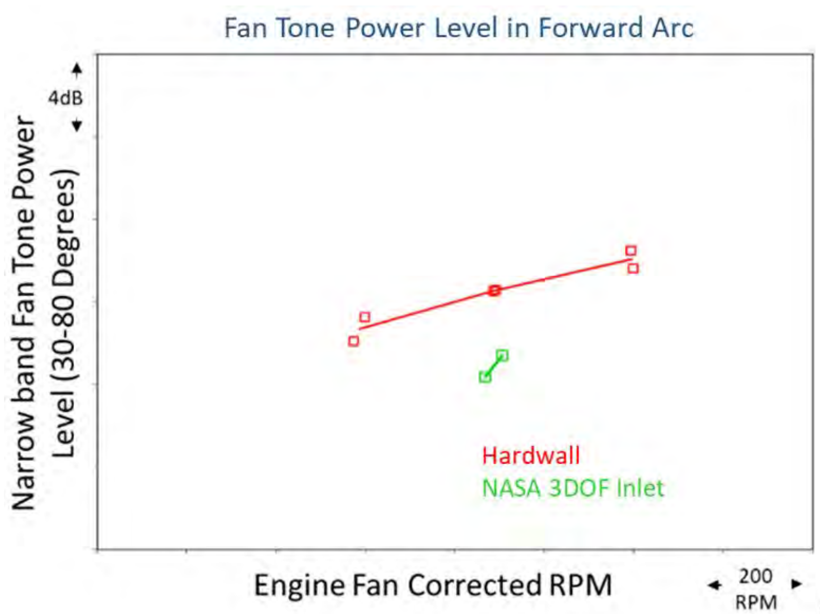

Figure 14: Fan Tone Power Level comparison between NASA Inlet and Hardwall Inlet configurations at Approach power.

The broadband attenuation required a significantly more detailed analysis and separation of other airplane noise sources. The farfield microphones were processed in a similar manner as described for the tone analysis, but the median broadband data were preserved and converted into 1/3 octave bands prior to projecting to a 150’ polar arc. The farfield microphones provided good data in the forward arc at high takeoff power settings, but it became challenging to distinguish inlet noise for one active engine at the lower takeoff power settings due to the magnitude of the airframe noise at 180 KCAS. Therefore, the lowest-power takeoff and approach conditions with the NASA MDOF acoustic inlet treatment were regarded as “Airframe” conditions, because the broadband levels did not change with the engine RPM increment. These “Airframe” spectra were then subtracted from the total broadband component from the remaining test conditions to further separate out the inlet noise.

In addition to the above component separation, the phased array data were processed with the tones extracted similarly to the method performed on the farfield microphone data. Further details on phased array processing are contained in Ref. [4]. The total phased array levels were calibrated to the farfield microphones. The phased array data were grouped into spatially-selected subcomponents. The inlet noise component for the NASA MDOF and Production hardware was subtracted from the Hardwall configuration inlet component for the phased array-derived broadband attenuation. The phased array beamformed data were used for emission angles between 60-90 degrees. The farfield and phased array analysis methods were combined, and a best-fit attenuation curve was derived, with dropouts and missing angles smoothed by engineering judgment. This process was based on prior experience that broadband noise (unlike tone noise) is fairly evenly-distributed across frequencies and emission angles, and without drastic step-changes in magnitude. Figure 15 shows resulting spectral attenuations for Approach, Cutback and Full power compared to the Boeing pre-test predictions. As shown, the data are generally showing more attenuation than predicted, particularly at the approach conditions. It should also be pointed out that the airplane noise drops below the background noise above band 37 for the approach conditions and band 35-36 for the takeoff conditions. This means that no attenuation was measurable, and does not necessarily mean that there was no attenuation.

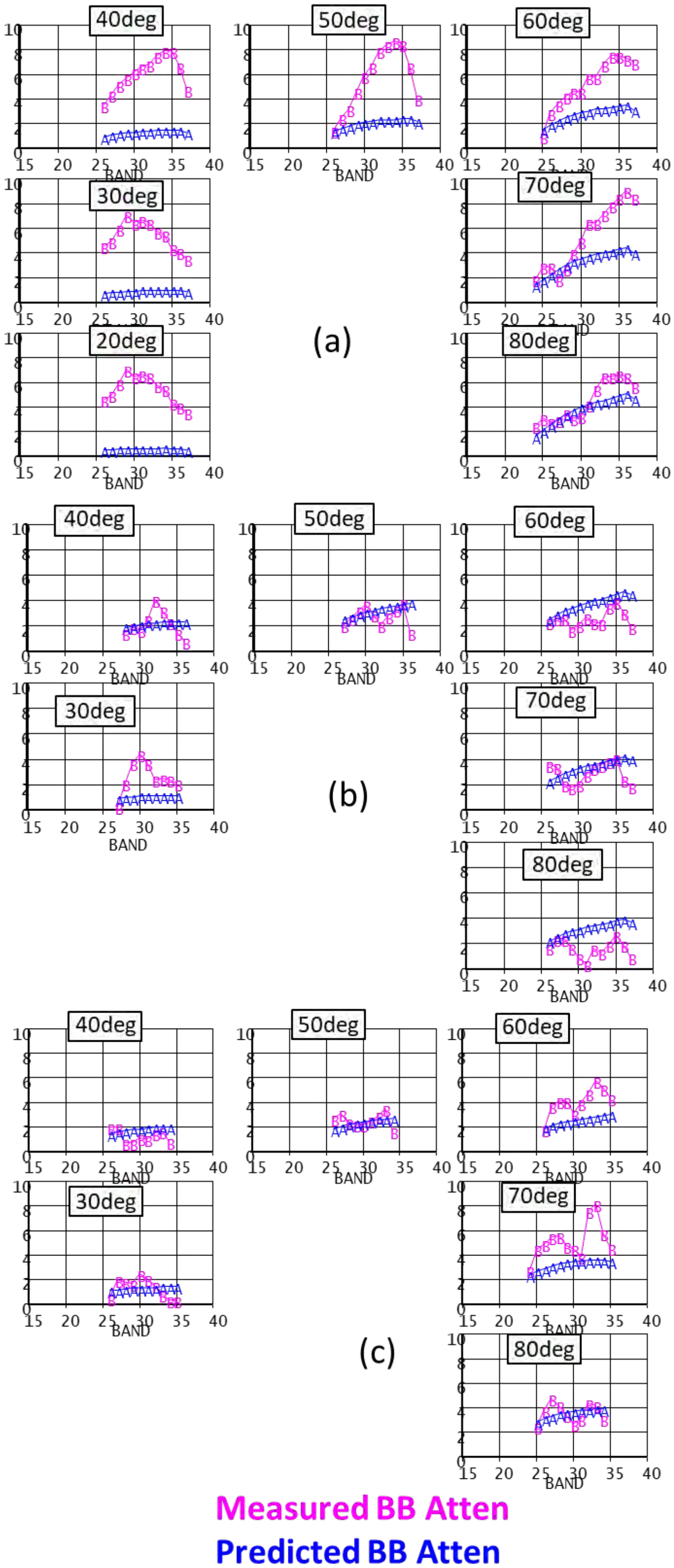

Figure 15: Broadband Attenuation Component derived from QTD3 flyover measurements and Predicted Attenuation for (a) Approach power, (b) Cutback power, and (c) Full Takeoff power.

The results from the preceding analysis were applied to a Boeing 737MAX component model. With all the other components held constant, the resulting total airplane and inlet components were projected to a nominal certification configuration. Figure 16 shows the isolated inlet component EPNL deltas along with the resultant total Airplane Level EPNL deltas. Recall that at Approach power, the broadband attenuation was significantly greater than predicted, while the tone attenuation was about 4 dB for the combined fan tone power levels. At the Cutback power setting, tone attenuation was around 6 dB for the fan tone power levels, and broadband attenuation was on-par with the prediction, with about 4.5 dB of peak attenuation. The isolated component delta rolls up to a 0.8 EPNdB reduction, but the total airplane noise level shows a smaller change in EPNL. At the Lateral power setting, the tone power levels were greatly attenuated on the MDOF inlet, while the peak broadband attenuation was between 6-8 dB. The isolated component delta is largest of the three flight conditions, as well as the total airplane noise reduction. Therefore, the largest benefit on EPNL out of the three flight conditions is at Sideline power, and is most influenced by the large reduction in tones due to the NASA MDOF inlet treatment effect.

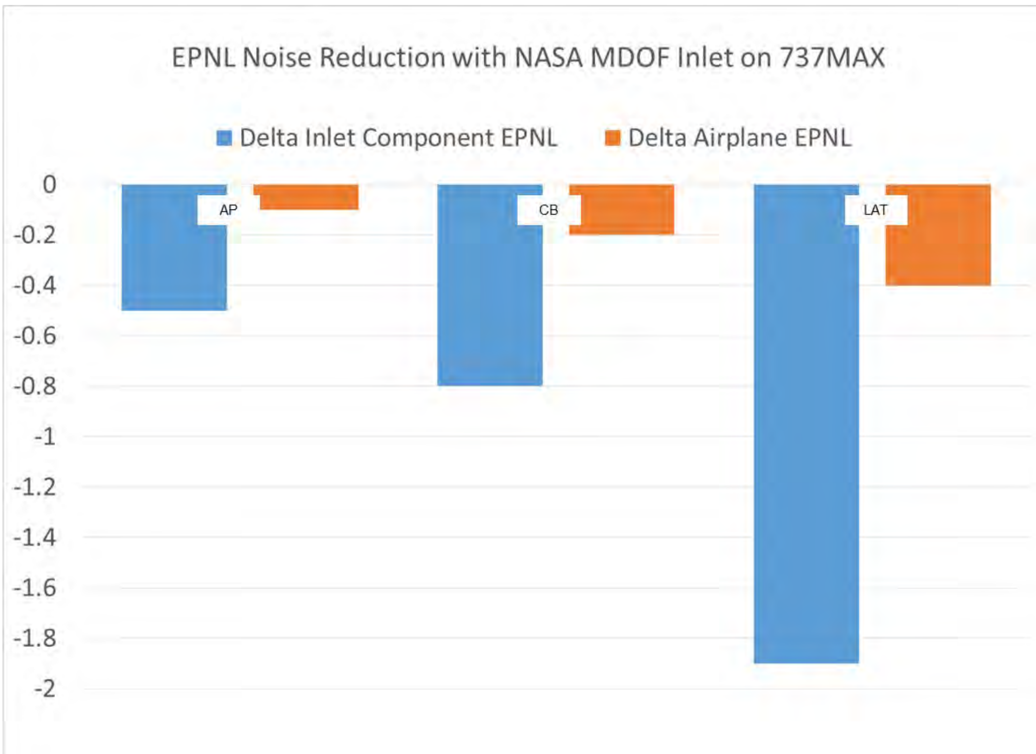

Figure 16: EPNL Noise Reduction on sample 737MAX relative to Production on an inlet component basis (blue), and a total airplane level basis (orange).

VII. Future Work

Together, NASA Langley and Boeing are pleased with the performance of the MDOF inlet hardware. The in-flight attenuation data of the inlet component provide a wealth of possibilities to apply this knowledge toward future aircraft design. Modeling and prediction capability can be improved on the liner impedance level, as well as the in-flight attenuation level. NASA and Boeing are pursuing various methodologies to predict and optimize the liner performance, and intend to use the results of QTD3 as a validation data set.

From a design standpoint, the successful validation of the MDOF low drag acoustic liner serves as a starting point for exploring the benefits of liners on other regions of the nacelle. While the inlet is a relatively small wetted area to reap any drag benefits, there may be a combined drag benefit to having an inlet and thrust reverser application with lower-drag perforations. Furthermore, the MDOF design implemented on the LEAP-1B inlet was subject to a number of geometric constraints in order to achieve the aggressive test schedule. In a future nacelle design concept, there will be fewer constraints than in this test, and advancements in manufacturing processes may provide further optimization of the liner acoustic impedance.

The physical inlet hardware is in excellent condition and could be used for follow-on testing where a reduced inlet noise component is desired on the 737 MAX LEAP-1B engine. Collaboration continues between NASA and Boeing to investigate advanced acoustic liners, with the intention of follow-up papers published covering notable discoveries.

VIII. Conclusion

The QTD3 acoustic flyover test was a positive experience for all the participants at NASA and Boeing. A substantial quantity of high quality, valuable acoustic data was acquired and will be used to improve prediction capability and influence liner technology decisions for future commercial aircraft. The design and build of the experimental MDOF low drag inlet on a short timeframe was a good challenge for the Boeing Team. The delivered inlet hardware met all requirements for acoustic quality and safety, and may be used again in future static or flight test programs if needed.

The flight test campaign was meticulously planned and smoothly executed. Many thanks are directed to the Boeing Flight Test Organization and the Boeing Noise Laboratory for their expertise and professionalism in executing an acoustic technology test with nonstandard airplane configurations. Even though the entire flight test team was split between Seattle and Moses Lake, the hardware change and test window schedule went according to plan. The excellent weather conditions gave the team confidence in the acoustic data that was acquired.

The acoustic analysis methodology to extract tone and broadband deltas utilized the ground plane ensemble microphone array and the phased array. The phased array data were paramount in identifying inlet-related broadband noise when other airplane noise sources were creating a noise floor for the ground plane ensemble microphone array. Once the tone and broadband deltas were established, Boeing applied them to a standardized airplane prediction process to isolate the hardware impact. The results of this assessment showed the NASA-designed MDOF inlet to have 0.7 EPNdB cumulative noise reduction relative to a Production inlet.

The NASA MDOF inlet tone deltas differed from the broadband deltas. This discrepancy was suspected prior to the test measurements, but there was no indication of how they might vary, as it is difficult to predict tone attenuation in flight. It was observed that the broadband attenuation was greater than predicted, and had more influence on the overall airplane noise at Approach engine power. At Lateral power, the tone deltas were significant, and resulted in the largest change to airplane noise. At Cutback power, the tone deltas were similar to production and the broadband deltas were close to what was predicted. As indicated by the difference in the inlet versus total airplane noise reduction seen, it is clear that total airplane noise can only be significantly changed if multiple noise sources are reduced.

While the NASA MDOF low-drag inlet liner flight test resulted in a measureable reduction in airplane noise on the 737 MAX, there is potential for even better acoustic performance in a future airplane design. This project had a number of constraints within the 737 MAX design envelope and the fast-paced development schedule allotted prior to the flight campaign. There is more range for optimization if the core depth, face sheet, or inlet area could be redefined, as is the case with conceptual aircraft. Furthermore, applications of this concept will likely have even greater benefit to newer airplanes with relatively lower jet, airframe, and aft fan noise sources. The Boeing team was pleased to take part in these findings of QTD3 and looks forward to future collaborations in acoustic technology.

Acknowledgments

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