THE BOEING QUIET TECHNOLOGY DEMONSTRATOR PROGRAM

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Keywords: *Airplane Noise, Acoustic Lining, Chevron Nozzle, Flight Test*

Abstract

This paper discusses the Quiet Technology Demonstrator 2 flight test program conducted by Boeing and its partners to demonstrate several airplane noise-reduction features. The testing was conducted using a Boeing 777-300ER airplane equipped with General Electric GE90-115B engines. Validated technologies such as a spliceless acoustic treatment in the inlet and chevron nozzles are making Boeing's newer airplanes significantly quieter for both passengers and the airport community.

1. Introduction

Boeing Commercial Airplanes has worked to reduce airplane noise since the commercial jet age began a half-century ago. Over the decades, dramatic gains have been made. As air travel continues to grow, however, so too do demands for further decreases in airplane noise.

These demands for lower noise levels are being addressed by the Quiet Technology Demonstrator (QTD) test program. This program encompasses both static and flight testing conducted over a number of years by Boeing Commercial Airplanes and its industry and NASA partners. The first QTD testing, referred to today as QTD1 [1], was conducted in 2001 and 2002 by Boeing in partnership with Rolls-Royce, NASA, and American Airlines. In the follow-on QTD2 flight test program, conducted in August of 2005 and described in this paper, Boeing teamed with General Electric, Goodrich Corporation, NASA, and All Nippon Airlines.

By partnering with other organizations for the QTD test programs, Boeing is able to combine its expertise with that of others, bringing together leading experts in the field of aeroacoustics. This arrangement also affords each partner the benefit of cost sharing the development of new noise-reduction technology.

The recent QTD2 flight test was conducted using a Boeing 777-300ER airplane equipped with General Electric GE90-115B engines. The test examined several airplane noise-reduction technologies: a spliceless acoustic treatment in the engine inlet, an acoustically treated nacelle inlet lip, chevron nozzles on both the fan and primary exhaust nozzles, and main landing gear fairings.

2. Inlet Technology

Engine fan noise, generated at the engine fan face, propagates in both the forward and aft directions through the nacelle inlet and exhaust ducts, where it can be attenuated by acoustic lining. The remaining noise then radiates to the community below. During takeoff conditions at supersonic fan tip speeds, the rotating shock structures from the individual blades can interact to form an irregularly spaced shock pattern. This results in multiple pure tones, known as buzzsaw noise, at engine-order frequencies.

2.1. Inlet Acoustic Barrel Design

Engine inlet acoustic treatment has typically been constructed in two or three panel segments that are joined together using splices to form a single inlet diffuser barrel. These splices have a number of detrimental effects on the generation and propagation of noise in the inlet. The splices reduce the area that is acoustically treated; they serve as a scattering mechanism that alters the structure of the noise field (mode shapes) in such a way that the lining is less effective; and they can create aerodynamic flow distortions that further increase the noise generated by the airflow entering the fan face.

The QTD2 inlet acoustic treatment was extended further aft, beyond the inlet attach flange and into the region of the engine fan case upstream of the fan. Traditionally, the forward fan case acoustic treatment, immediately upstream of the fan, is supplied by the engine company and is often composed of a series of acoustic panels. These acoustic panels in themselves introduce an additional set of axial and circumferential acoustic impedance discontinuities that can also generate modal scattering and flow distortions entering the fan. Building an integrated inlet that extends closer to the fan eliminates these unwanted axial splices while increasing inlet attenuation. Fig 1 shows the differences in the acoustically treated areas between the production inlet and the QTD2 spliceless inlet. In these photographs the acoustically treated areas have been outlined in white, which reflects the removal of splices and the aft extension.

Fig 1. Production inlet (left) and QTD2 spliceless inlet (right)

Since the elimination of the axial splices reduced the lower frequency portion of the fan noise spectrum, the acoustic treatment design was optimized to better target higher frequency broadband noise. Because lining depth scales with the targeted wavelength, this allowed for a thinner lining, which in turn provided a weight savings to the engine. Additional details on the inlet lining are presented by Yu et al. [2].

2.2. Inlet Lip Treatment

It has long been recognized that acoustically treating the inlet lip region would provide additional noise reduction. However, treating the lip is complicated by the fact that the lip needs to provide an anti- or de-icing capability. An innovative design to provide both acoustic treatment and de-icing was tested in QTD2. This design allowed the acoustic treatment to be extended further forward, beyond the inlet aerodynamic throat and into the region of the lip hilite. This area is shown as the white area in the right-hand photograph in Fig 1.

During testing the spliceless inlet barrel was tested both with the hardwall production lip, as well as with the acoustically treated lip. With the treated lip installed the total acoustically treated area of the inlet was increased by 78% relative to the baseline production inlet.

3. Chevron Technology

The jet exhaust flow is a source of noise at both takeoff and cruise conditions. At takeoff, the adjacent flow streams mix and produce relatively low-frequency broadband noise. At cruise, noise is generated when the jet flow is supersonic. Harper-Bourne and Fisher [3] have concluded that this noise - known as shockcell, or shock-associated, noise - is generated by the interaction between the downstream-propagating turbulence structures and the quasi-periodic shockcells in the jet plume. Many subsequent studies have examined this noise source [4].

Jet-mixing noise is a concern primarily at takeoff, where it affects community noise levels. Shockcell noise is a concern at cruise conditions where it is a major component of aft-cabin interior noise. Chevron nozzles have been studied in recent years as a means of reducing both jet-mixing and shockcell noise. These nozzles feature serrations, typically triangular in shape, at the nozzle exit. When immersed into the higher velocity flow stream, they produce stream-wise vorticity in the downstream shear layer. This alters the mixing action and results in reduced low-frequency mixing noise. One of the challenges of chevron design is to accomplish this low-frequency noise reduction without any corresponding increase in higher frequency noise.

3.1. Propulsion Airframe Aeroacoustics Fan Chevrons

One of the fan chevron designs for the QTD2 test resulted from extensive analytical studies and model-scale testing, described by Mengle et al. [5],[6],[7]. Whereas earlier efforts tended to consider the nozzles without the presence of struts, pylons, or wings, this QTD2 design took into account the effect of the installation of the engine on an airplane – the so-called Propulsion Airframe Aeroacoustics (PAA) effect.

Previously the individual chevron planforms of a chevron nozzle had similar shapes. Extensive wind tunnel tests, conducted at the Boeing Low Speed Aeroacoustic Facility resulted in a non-uniform nozzle design that had significantly larger chevrons near the strut and progressively smaller chevrons near the keel. Such chevron designs produce enhanced mixing near the strut due to higher immersion into the fan stream. However, since greater chevron immersion may increase engine thrust loss and high-frequency noise, chevrons with less immersion are located near the keel. This distribution, termed the PAA T-fan chevron, was chosen for QTD2 flight testing (Fig 2).

Fig 2. PAA T-fan chevrons and core chevrons

3.2. Variable Geometry Fan Chevrons

Typically, the fan chevrons are immersed into the fan stream to optimize the low-frequency mixing noise reduction. However, as mentioned above, this immersion may increase engine thrust loss and high-frequency noise. In order to balance the conflicting design objectives of maximizing noise reduction and minimizing the thrust loss, the concept of a variable geometry chevron fan nozzle was developed. This concept enables fan chevron immersion at takeoff, where community noise reduction is most critical, and allows for chevron alignment with the flow for the cruise segment of flight, which is most critical for fuel efficiency.

The variable geometry chevron (VGC) design for the QTD2 test incorporated flexures made of a shape memory alloy embedded into the chevrons [8]. These flexures (Fig 3) react to the local temperature. The shape memory alloy was trained so that the chevrons were relatively more immersed at the “hot” ambient conditions at takeoff, and relatively less immersed at the “cold” ambient conditions at cruise.

Fig 3. Variable geometry fan chevrons (inset shows individual chevron with cover removed)

Additionally, heating elements were mounted on these flexures so that the local temperature, and therefore the amount of immersion, could be controlled. Each chevron was individually controlled so that non-uniform chevron immersions could be tested. This feature is not intended for incorporation into a production version of a VGC nozzle, but provides the capability to perform parametric studies to optimize chevron immersion, particularly for shockcell noise reduction at cruise.

The final VGC design, which was flight tested in QTD2, was the result of extensive testing in the Boeing Nozzle Test Facility (NTF). The NTF testing used a single full-scale chevron that was exposed to simulated fan and ambient flows on the respective sides of the chevron. This testing was also supported by finite element modeling, which primarily addressed the development of the VGC control system.

3.3. Core Nozzle Chevrons

In addition to the two fan chevron nozzles, a core chevron nozzle was designed, built, and tested (Fig 2). The chevron nozzles and the production nozzles were tested in various combinations during the QTD2 flight test. This allowed for a better understanding of the effects of the different designs.

4. Landing Gear Technology

Airframe noise is a significant component of the total airplane noise at approach conditions where it is roughly of the same magnitude as engine noise. Landing gear noise is a major contributor, along with flap noise, to the total airframe noise.

Fig 4. Main landing gear “toboggan” fairings

Extensive wind tunnel testing at Virginia Tech on a 26% scale landing gear model examined various landing gear noise-reduction concepts. These included fairings of various widths, hubcaps, and various fillers. One of the most promising concepts was the toboggan-shaped main landing gear fairing (Fig 4). These fairings were built and flight tested.

5. Flight Test Description

The QTD2 flight test program was conducted at the Montana Aviation Research Company (MARCO) airfield in St. Marie, Montana, just outside the town of Glasgow [9]. This site is distant from any heavily populated areas and features a 13,500-ft long and 300-ft wide runway, with 1,000-ft overruns on each end. It has been the site of Boeing flight testing in the past, including QTD1 [1].

5.1. Procedure

For community noise testing, using ground microphones, the airplane flew flight-path intercepts that simulated takeoffs and approaches. For climb and cruise testing, using cabin and fuselage microphones, the airplane was flown at various specified altitudes, engine power settings, and airspeeds.

The left-hand engine was kept in the baseline production configuration, while the right-hand engine was modified in various ways. The production engine was generally set at idle power, allowing the measured noise to consist primarily of the noise from the modified test engine. To establish a reference set of data by which to evaluate the modifications, measurements were made with the right-hand engine in the production configuration and the left-hand engine set at idle power.

5.2. Acoustic Instrumentation

5.2.1. Ground Microphones

The ground-based acoustic instrumentation included ground-plane microphones and four-ft pole microphones. The ground-plane microphones were either flush-mounted in a petal-shaped structure or laid on a flat plate. The four-ft microphones were a certification-type setup. The ground microphones were placed both under the flight path and at certification sideline locations.

5.2.2. Acoustic Phased Array

Acoustic phased arrays are collections of microphones that simultaneously sample the acoustic field. By applying appropriate time delays to the output of each microphone, the resulting signals can be combined so that signals of interest are reinforced, and interfering sources and noise are attenuated. The algorithms used to calculate the time delays and combine the outputs are referred to as beamforming algorithms. The end product is a spatial map showing the locations and intensities of the various noise sources. Mosher [10] provides a general review of phased array applications for aeroacoustic testing, and Underbrink [11] provides an in-depth review.

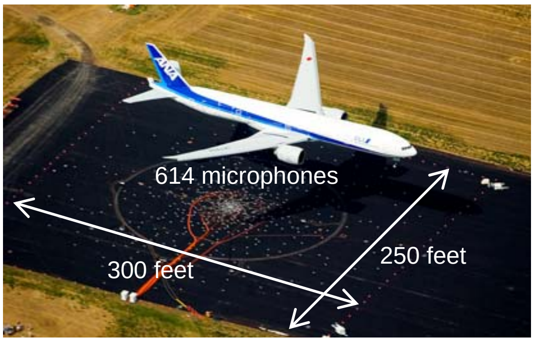


Fig 5. Test airplane flying over the acoustic phased array

For the QTD2 flight test, a total of 614 microphones, laid out in a spiral pattern that was roughly elliptical in shape and measured 300 by 250 ft, was distributed among five separate arrays [12] (Fig 5). The smallest array was 25 feet in diameter, followed by 50-, 80-, 140-, and 250-ft diameter arrays. The 250-ft diameter array is among the largest ever used for acquiring flight test data. The larger arrays allow for acquiring lower-frequency information. The range of sizes for the QTD2 arrays provided coverage of a broad range of frequencies.

5.2.3. Cabin Microphones

The cabin acoustic instrumentation consisted of seat-back microphones [13] and manikin-mounted microphones. The seat-back microphones acquired interior noise data while the manikin microphones acquired sound quality information.

5.2.4. Fuselage Microphones

Two microphone (Kulite) arrays were mounted on the exterior of the fuselage and eight Kulites were mounted in the production inlet. The fuselage arrays were on the same side of the airplane as the modified engine, and were used to acquire data at climb and cruise conditions. One of these arrays was aft of the engine and was used to acquire shockcell noise data. The other array was forward of the engine and was used to acquire buzzsaw noise data. The Kulites in the inlet were installed to measure the nonlinear propagation of the shocks at various axial positions.

Data from the side-of-body Kulites can be compared with data acquired by the interior microphones for the same configuration and condition. Such comparisons provide information on the sound transmission loss as noise propagates through the airplane sidewall.

6. Inlet Test Results

The QTD2 modified inlet was very successful in reducing both community noise at take-off and interior noise related to the buzzsaw during climb, as described in the following sections [2].

6.1. Community Noise Results for the QTD2 Inlet

The level of the fan tones at the blade passage frequency (BPF), as measured by the community noise microphones, was reduced by up to 15 dB with the spliceless acoustic barrel plus the treated lip, as shown in Fig 6. This spectral plot shows the sound pressure level (SPL) as a function of frequency at a forward radiation angle for an approach power setting. Significant reduction of higher-order fan harmonics was also achieved, as well as a reduction of the broadband noise of several dB.

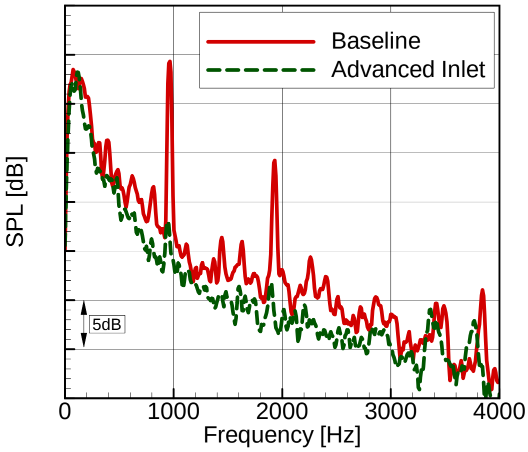


Fig 6. Community noise reduction for the QTD2 inlet

Aft-radiated tone levels were also reduced. Since this aft-radiated noise, which propagates through the aft fan duct and out the nozzle, is not subject to the advanced features of the QTD2 spliceless lining, the measured reduction is attributed to the reduction of the source levels as a result of the elimination of inlet lining splices.

The effect of the treated lip is shown in Fig 7, which shows a color contour map. In these maps the frequency is shown along the horizontal axis and the emission angle along the vertical axis (with forward radiation defined as angles less than 90 degrees and aft radiation defined as greater than 90 degrees). The noise levels are indicated by different colors. Tones are shown as colored "ridges," which typically display the familiar Doppler frequency shift, with forward-radiated tones shifting to higher frequencies.

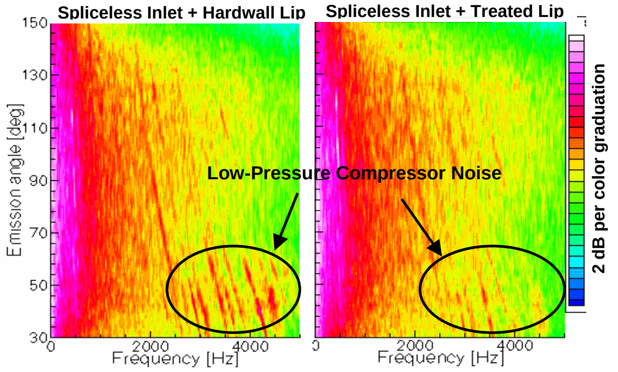


Fig 7. Benefit of lip treatment on low-pressure compressor noise

This figure compares two inlet configurations at an approach power setting. Both configurations have a spliceless inlet barrel, but one has a production hardwall lip and the other an acoustically treated lip. The lip treatment can be seen to be particularly effective in reducing the forward-radiated tones from the low-pressure compressor. The lip treatment was also shown to be effective in reducing fan tones at take-off power settings.

6.2. Interior Noise Results for the QTD2 Inlet

A spectral plot of the data from a cabin microphone is shown in Fig 8. This plot shows measurements made at a forward-cabin window seat location for a climb cruise condition. The blade-passage-frequency tone, as well as the buzzsaw noise, can be seen to have been reduced by about ten dB for the spliceless inlet barrel plus the treated lip relative to the baseline production inlet. Both the spliceless barrel and the treated inlet contributed to this total.

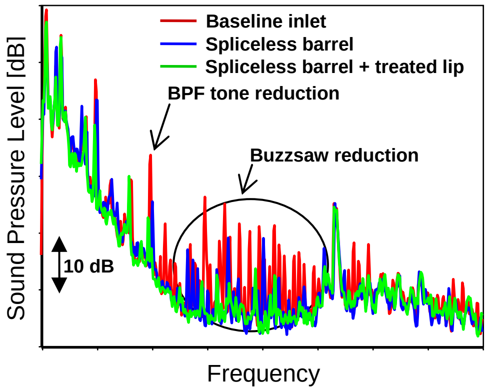


Fig 8. Interior noise reduction for the QTD2 inlet

7. Chevron Nozzle Test Results

Chevron nozzle configurations were identified that successfully reduced both community noise at take-off [8],[14] and interior noise related to the shockcell mechanism at cruise [15],[16].

7.1. Community Noise Results for the Chevron Nozzles

For the PAA T-fan chevron plus core chevron configuration, peak jet-mixing noise levels were reduced by up to two dB relative to the baseline production nozzle configuration. Fig 9 shows results measured at a community noise microphone for a high power setting at an aft angle.

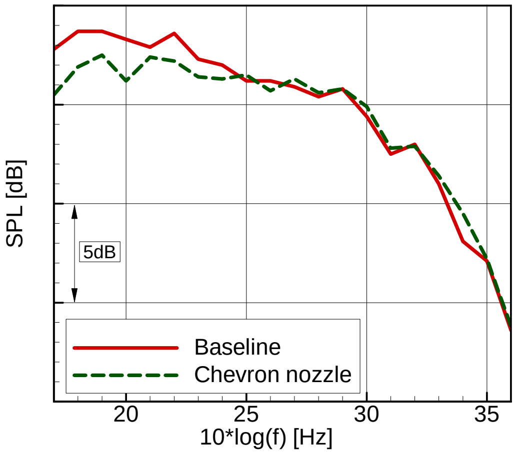


Fig 9. Spectral plot of jet noise reduction for the PAA T-fan + core chevron configuration

Earlier chevron designs often produced some increase in the higher-frequency jet-mixing noise. Certain QTD2 fan and core chevron designs showed no significant increase in this high-frequency noise at take-off. This is shown in the color contour plot in Fig 10. This plot shows that low-frequency, high-angle noise reduction is not accompanied by any significant high-frequency low- to mid-angle increase.

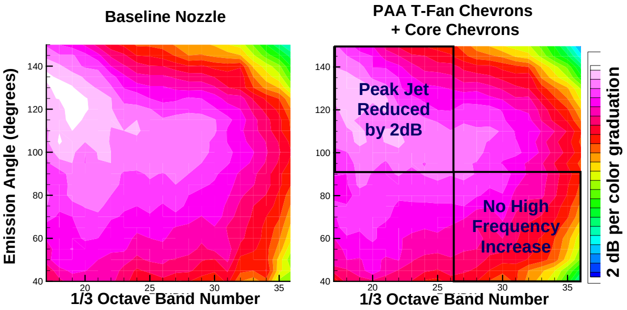


Fig 10. Sound pressure level contour map of jet noise reduction for the PAA T-fan + core chevrons

An overall sound power metric has been developed to evaluate the chevron benefit for the peak jet-mixing noise. This metric is an integration over the peak jet noise angles (90 to 150 degrees) and frequencies (50 to 400 Hertz). Fig 11 shows the results of this metric for the PAA T-fan plus core chevron configuration compared to the baseline production configuration. In this case the chevron benefit is about one dB. Similar results were seen for the VGC plus core chevron configuration, with increased immersion of the fan chevrons generally giving greater noise benefits.

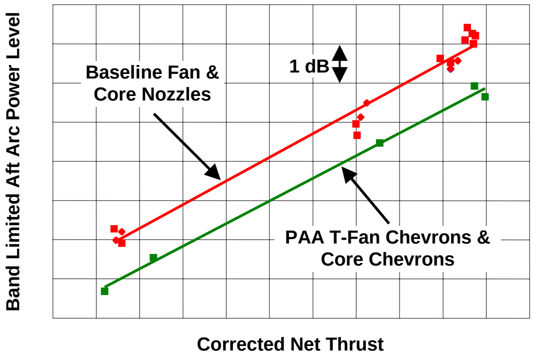


Fig 11. Overall sound power metric for jet noise reduction for the PAA T-fan + core chevron configuration

7.2. Interior Noise Results for the Chevron Nozzles

At cruise conditions, the external fuselage Kulites showed up to five dB noise reduction of the low-frequency noise for both the PAA T-fan chevrons and the VGCs relative to the baseline production nozzle configuration. More reduction in the low-frequency noise was generally observed in the VGC data for more immersed chevron configurations.

At cruise conditions, the interior noise microphones showed a reduction of both the aft-cabin low-frequency noise and the overall sound pressure level (OASPL) with the fan chevrons. Again increased low-frequency noise reduction was generally achieved with the more immersion of the VGCs. However, some high-frequency noise increases were seen for the chevron nozzles. Fig 12 shows the aft cabin spatial distribution of the OASPL reduction for the PAA T-fan chevron configuration relative to the baseline production nozzle. Recall that the test engine was on the right side of the airplane (top in the figure) and that the other engine was at idle. This explains why a noise change is seen only on the right side.

OASPL reductions of up to two dB were measured for OASPL at seat locations which are exposed to shockcell noise, and even greater reductions at certain frequencies. The PAA T-fan chevron with the baseline core nozzle generally achieved more cabin noise reduction at cruise than did the T-fan with the core chevron nozzle.

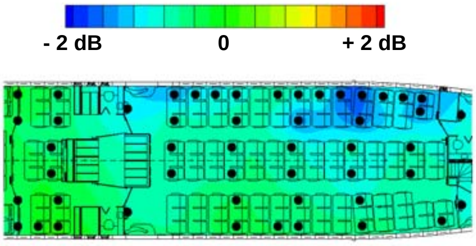


Fig 12. Aft cabin spatial distribution of interior noise OASPL reduction for PAA T-fan chevron nozzle

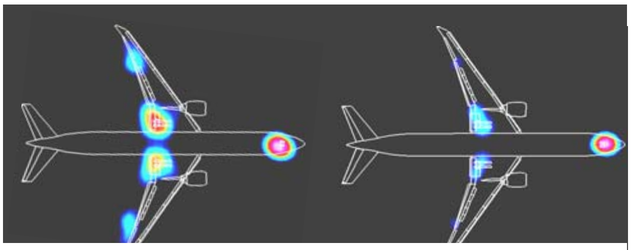
7.3. Variable Geometry Chevron Operation

The Variable Geometry Chevron system demonstrated a technique for validating different chevron designs through flight testing [8]. With shape memory alloy technology, a given component can be tested in numerous configurations during one flight test. This approach can be used to run parametric studies and optimize aircraft component design in an economical and efficient manner.

8. Landing Gear Fairing Test Results

The precise amount of noise reduction achieved by the toboggan-shaped main landing gear fairings has not been determined. The strong contribution of other airframe noise sources (e.g., the nose gear contribution) to the community noise microphone measurements at the airframe noise conditions makes it difficult to distinguish the effect of the main landing gear modifications in the ground microphone data.

However, the acoustic phased array measurements indicated some reduction of the noise at 800 Hz, which represents the higher-frequency portion of the gear noise spectra. Fig 13 shows a phased array map of the airframe noise levels for the baseline production main landing gear and for the gear with the toboggan fairings added. The engines were set at idle power for these measurements. In these maps the color range is eight dB with white being the maximum noise level measured on a particular map. Relative to the nose gear noise (which can be assumed to remain fairly constant) the main landing gear noise appears to be reduced by several dB.



Baseline Landing Gear **Toboggan Fairing**

Fig 13. Phased array map of landing gear noise at 800 Hz

9. Conclusions

The Boeing Quiet Technology Demonstrator 2 flight test program validated several airplane noise-reduction technologies. The spliceless acoustic inlet barrel and the acoustically treated inlet lip were very successful in reducing both community noise at take-off and interior buzzsaw noise during climb. Chevron nozzle configurations were identified that were successful in reducing both community noise at take-off and interior shockcell noise at cruise. The toboggan-shaped main landing gear fairing showed promise as a design that could reduce airframe noise at approach.

Boeing and its QTD2 partners are committed to developing and implementing noise-reduction technology. Technologies such as those validated in the QTD2 testing have been incorporated in various production airplanes, such as the 747-8, the 777, and the787, and are making Boeing's newer airplanes significantly quieter for both passengers and the airport community.

Acknowledgments

The success of the Quiet Technology Demonstrator 2 program was due to the efforts of the many talented and dedicated people from the partner organizations - Boeing, General Electric, Goodrich Corporation, and NASA - as well as those from various supplier organizations, particularly Spirit Aerosystems. An estimated 500 people contributed to the program and they are all gratefully acknowledged.

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