Airframe Noise Results from the QTD II Flight Test Program

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With continued growth in air travel, sensitivity to community noise intensifies and materializes in the form of increased monitoring, regulations, and restrictions. Accordingly, realization of quieter aircraft is imperative, albeit only achievable with reduction of both engine and airframe components of total aircraft noise. Model-scale airframe noise testing has aided in this pursuit; however, the results are somewhat limited due to lack of fidelity of model hardware, particularly in simulating full-scale landing gear. Moreover, simulation of true in-flight conditions is non-trivial if not infeasible. This paper reports on an investigation of full-scale landing gear noise measured as part of the 2005 Quiet Technology Demonstrator 2 (QTD2) flight test program. Conventional Boeing 777-300ER main landing gear were tested, along with two noise reduction concepts, namely a toboggan fairing and gear alignment with the local flow, both of which were down-selected from various other noise reduction devices evaluated in model-scale testing at Virginia Tech. The full-scale toboggan fairings were designed by Goodrich Aerostructures as add-on devices allowing for complete retraction of the main gear. The baseline-conventional gear, faired gear, and aligned gear were all evaluated with the high-lift system in the retracted position and deployed at various flap settings, all at engine idle power setting. Measurements were taken with flyover community noise microphones and a large aperture acoustic phased array, yielding far-field spectra, and localized sources (beamform maps). The results were utilized to evaluate qualitatively and quantitatively the merit of each noise reduction concept. Complete similarity between model-scale and full-scale noise reduction levels was not found and requires further investigation. Far-field spectra exhibited no noise reduction for both concepts across all angles and frequencies. Phased array beamform maps show inconclusive evidence of noise reduction at selective frequencies (1500 to 3000 Hz) but are otherwise in general agreement with the far-field spectra results (within measurement uncertainty).

I. Introduction

Aviation has seen great strides in aircraft technology, capability, and comfort. Likewise, the impact of aircraft noise on the environment has been greatly reduced. Notwithstanding, with continued growth in air travel, sensitivity and awareness to community noise has increased. For that reason, aircraft must now not only abide by

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governmental and FAA/JAA regulations, but also comply with escalating airport restrictions, curfews, and monitoring. The viability of the aircraft industry and commercial aviation rests on the ability and commitment to deliver quieter and more environmentally friendly aircraft.

Achieving quieter aircraft clearly implies reduction in both engine noise and airframe noise. Originally the dominant component, engine noise has been investigated extensively and has seen great advancements in physical understanding and noise reduction, both in prototype models and product implementation. Concomitantly, airframe noise has gained in importance, and is presently one of, if not the dominant component of the total noise in the approach condition. Moreover, airframe noise levels have not reduced significantly over the years, because of minimal advances in airframe noise reduction, particularly for landing gear. Without immediate focused attention, airframe noise will soon be the limiting factor for aircraft noise reduction.

Reducing airframe noise necessitates reduction of non-gear noise from flaps, slats, and other high lift surfaces, as well as noise from the main and nose gear. Through wide ranging research and model-scale testing, possible means for reduction have indeed been identified, and reduction levels have been quantified. Moreover, physical understanding has also been advanced, by means of noise source localization, level quantification, and assessment of relative prominence among airframe sources. Yet despite these achievements, the relevance to full-scale design is limited, because it is not always viable to simulate true in-flight conditions, gear-wing interactions, gear-body installation, and the wheel well cavity. Additionally, model-scale hardware rarely, if ever, simulates exactly all the details of the true full-scale geometry. This is especially true for gear noise studies, in which it is impractical to simulate the myriad of hoses, hydraulics, wires, harnesses, tubes, bolts, etc. found in the full-scale gear. To this end, full-scale flight tests must be relied upon for accuracy and fidelity in examination of the true phenomenon, and in measurement of the true noise characteristics, both in level and spectral content.

In the recent past, full-scale flight test based airframe noise investigations have been implemented both in research type testing and in non-intrusive testing during daily airport operations. In the latter scenario, phased arrays were utilized in the localization of airframe noise of single-aisle, wide-body, and regional aircraft flyovers at Frankfurt Rhein-Main international airport,[1] and at Amsterdam Airport Schiphol for single-aisle and widebody aircraft.[2] Reference 3 analyzed in detail the nose gear noise from the Frankfurt Rhein-Main airport measurements. Dedicated research testing cited in Refs. 4 and 5 entailed airframe noise measurements at prescribed flight conditions and airframe configurations, with the latter study focusing on the high lift system only. References 6 and 7 entail further detailed studies on airframe source noise localization and quantification of far-field noise. None the less, only a few studies to date have investigated noise reduction concepts in flight, especially for gear noise reduction.[8,9] Due to the high complexity, high cost and high resource demands of full-scale flight tests, limited knowledge exits on in-flight, full-scale airframe noise, and especially on full-scale noise reduction concepts.

The objective of this paper is to investigate in-flight, full-scale gear noise as well as main gear noise reduction concepts measured as part of the 2005 Quiet Technology Demonstrator 2 (QTD2) flight test program. Discussion focuses initially on test hardware, facilities, procedures and instrumentation, followed by an explanation of the analysis parameters and processing. Results will then be shown for the conventional main gear and for the main gear noise reduction concepts, utilizing far-field measurements, acoustic source localization maps, and map subregion peak spectral levels. Several flap settings will be analyzed, all at the engine-idle power condition (to minimize engine noise). Analysis of the results will aid in assessing the capability for measuring and discerning in-flight gear noise, and in evaluating qualitatively and quantitatively the merit of each noise reduction concept.

II. Test Hardware, Test Facilities, and Test Procedures & Instrumentation

Details provided below are only short summaries of the aspects of the QTD2 test relevant to this study. Further information is provided in Ref. 10, including a complete description of other aspects of the test.

A. Test Hardware

The test airplane was a Boeing 777-300ER, on loan from All Nippon Airways, which was used for studying conventional gear noise and potential gear noise reduction concepts. For the 777 series aircraft, gear and non-gear noise source spectral levels are relatively similar, yielding total airframe levels with balanced subcomponent contributions and similar weighting. In addition, the high complexity of the main gear, the main gear physical size, and the large variation in the scale of parts, collectively produce a noise source with wide ranging frequency content. Recall further that model-scale testing generally fails to capture all the details of a true gear system, in particular the main gear. Hence, from many aspects, it seemed appropriate to focus the flight test on the gear subcomponent of total airframe noise, and in particular on the main gear. The conventional main gear of the B777-300ER is depicted in Fig. 1, both in side view (a) and frontal view (b).

Several ideas were considered for potential noise reduction concepts, with choices ranging from main gear source noise alteration, to modification of noise propagation, to modification of noise-structure interaction. Potential noise benefit, system complexity, cost, operational maintenance concerns for hardware changes, and the desire for technology maturation to flight-ready status, were all used in evaluation and selection of the final noise reduction concepts by the QTD2 partners. In the end, it was determined that two of the most beneficial concepts were those which would (1) shield and (2) "hide" all of the myriad parts of the main gear from the incoming flow, thereby reducing the creation of multi-scale turbulence and acoustic-fluid/structure interactions.

For the shielding concept, a "toboggan" like fairing was envisioned which would cover the entire under surface and part of the front face of the main gear truck. Several designs were studied in model-scale testing and evaluated for noise reduction, as documented in Ref. 11. The best performing configuration then underwent extensive full-scale design reviews and analyses, detailed in Ref. 12, before materializing into the full-scale flight test toboggan fairings shown in Fig. 2. These toboggan fairings were designed by Goodrich Aerostructures as add-on devices allowing for full gear retraction and accommodating some production and safety concerns and margins.

The second envisioned concept of "hiding" the main gear details from the incoming flow was intended to alter the inclination of the gear truck from a typical "toes-up" inclination (about 13 degrees) to 0 degrees inclination with respect to the local incoming flow. The required alignment angle was derived based on CFD studies and then assessed for implementation based on hydraulic and actuation system analysis. Fortuitously, the derived angle for local flow alignment coincided with an already existing "alternate extend" angle for the 777-300ER main gear. Hence, with only minor modifications, alignment of the gear was achieved during testing. The aligned gear is shown in Fig. 3 (a), in contrast to the typical approach "toes-up" alignment in (b).

B. Test Facilities

The flight test was conducted in August of 2005 at the Montana Aviation Research Company (MARCO) airfield in St. Marie, Montana, just outside the town of Glasgow, Montana. This site features a 13,500-ft long by 300-ft wide runway, with 1,000 ft overruns on each end. The site is also distant from any heavily populated areas, thus minimizing unwanted noise contamination of test data. Boeing has conducted past flight testing at this site, including QTD1.[13]

C. Test Procedures & Instrumentation

The QTD2 test airplane flew around a "racetrack" as shown in Fig. 4, in which standard approach conditions were simulated with flight path intercepts. For all airframe measurements, both engines were set at idle-power condition to isolate the airframe only noise signature. During a fly-by, noise data were acquired with sideline and flyover (under the flight path) far-field microphones, and with an acoustic phased array system. Concerning the far-field data, this study will focus only on the flyover measurements derived from ground based flush mounted microphones. Along with acoustic measurements, ambient weather information as well airplane performance metrics such as speed, altitude, location, etc. were also recorded.

The layout of the microphones with respect to the runway is shown in Fig. 5. An aerial view of the test airplane flying over the phased array system is depicted in Fig. 6. The entire phased array system measured 300 by 250 ft, and was comprised of 614 microphones, arranged in a spiral pattern, roughly elliptical in shape. Five separate arrays were embedded within the entire array, with the smallest being 25 ft in diameter, followed by arrays of 50 ft, 80 ft, 140 ft, and 250 ft diameter. These arrays were denoted as arrays *a*, *b*, *c*, *d*, and *e*, respectively. The large variation in array size enabled measurements of a broad range of frequencies. Additional details on the acoustics instrumentation, as well as the weather, airplane performance instrumentation, and measurement procedures are provided in Ref. 10.

III. Analysis Parameters & Processes

A. Analysis Parameters

As noted earlier, airframe noise measurements were recorded with both engines at idle power. Airplane climb and pitch angle and weight were allowed to vary to control airspeed and altitude over the microphone array. The target flyover altitude was set to 600 feet, with target airspeed varying with configuration. Actual altitude, speed, and flight path were recorded on-board, and telemetered down to the ground station where it was combined with ground weather data. Time accurate positioning of the airplane in relation to the array center was also recorded. Based on these measurements, a decision was made on the acceptability of the completed test condition in meeting the weather and flight performance constraints. Out of all the airframe configurations tested, 40 flights were deemed satisfactory. These flights entail configurations with independent or simultaneous deployment and retraction of the high-lift system and landing gear. This study focused only on a subset of these flights.

The baseline gear was flown a few times and with gear retracted and deployed, in order to assess repeatability and the capability of measuring and discerning in-flight gear noise. Comparative flights at flap detent 30 and 0 were flown with the baseline gear, aligned gear and toboggan faired gear in order to compare and evaluate the noise reduction concepts. The purpose of the flap 0 configurations was to isolate the gear noise.

B. Analysis Processes

As noted earlier, concerning far-field measurements, focus herein is only on data from under-the-flight-path, ground-based, flush-mounted microphones. Final processed results were obtained, as described in Ref. 14, by ensemble averaging, and conversion to 1/3rd octave bands. Corrections were applied for pressure doubling (-6 dB), atmospheric absorption and spherical divergence. Results have all been normalized to a nominal flight altitude of 374 feet, and standard day temperature and relative humidity of 77°F, and 70%, respectively. A U^5 velocity correction was applied to normalize to a nominal 165 knots velocity. In this analysis, ground reflections were not applied.

The phased array data were analyzed using narrowband conventional time domain delay-and-sum beamforming. Corrections were then applied for altitude, velocity, and atmospheric absorption. Final results were normalized to an altitude of 400 feet, and a velocity of 170 knots.[15] For enhanced clarity in visualization of the results, the dynamic range in the beamform contour maps was restricted to 8 dB below the peak level for each frequency. Further restrictions were imposed, in which an optimal frequency range was defined for each array, based on guidance provided in Ref. 15, in which side-lobe interference was minimized and noise source resolution was maximized. These frequency ranges are denoted in Table 1. Within these ranges, "search areas" (square subregions) were defined in the beamform maps, as shown in Fig. 7, about the nose gear (NG), left main gear (MGL), and right main gear (MGR), in which peak spectral levels were extracted and tabulated for each configuration of interest. The valid spectral ranges from each subarray were then merged into a complete spectral data set for each configuration. Further details on the acoustic phased array instrumentation, beamforming analysis algorithms, and issues related to spatial resolution, filtering, among others, are discussed in Ref. 15. Similar issues are also discussed in Ref. 16.

IV. Results & Discussion

Attention will first be given to the issue of data repeatability. Baseline configuration far-field results will be presented as well as phased array beamform map subregion peak spectral levels. The ability to measure and discern the effect of gear deployment will then be discussed, utilizing only the far-field results for the baseline configuration. The subsequent sections will be subdivided into Flap Detent 30 results, followed by Flap Detent 0 results. In each flap section, comparisons will be shown between the baseline, aligned, and toboggan faired gear, utilizing far-field noise results and beamform noise results. When presenting far-field noise results, spectra of SPL vs. 1/3rd octave band number will be shown for a forward arc angle (60 degress), overhead (90 degrees), and in the aft arc (140 degress), with the angular measurement defined with respect to the engine inlet axis. The following beamforming results will be shown: subregion peak spectra (SPL vs. narrow band frequency), associated delta peak spectra (configuration peak spectra minus baseline peak spectra, i.e. delta SPL vs. narrow band frequency), and beamform noise source maps at select frequencies. All beamforming results will be based on analysis of the 90 degrees overhead position.

A. Data Repeatability

Given the inherent variability in full-scale flight testing (atmospheric conditions, position relative to microphones, speed, glide path, etc.), several baseline configuration flights were flown, spanning several days, in order to assess data repeatability. Far-field results for a subset of these configurations (4 flights at Flaps 30 and gear down) are depicted in Fig. 8 (a), (b), and (c) at emission angles of 60 degrees, 90 degrees and 140 degrees, respectively. The data for flights 1-4 in Fig. 8 are presented in black, blue, red, and green, respectively. Velocity normalization has already been applied to the results. Overall, repeatability looks very good, especially in the aft-arc. Due to noise floor contamination and atmospheric effects, data from Band 37 and above should be disregarded. It is unknown why the second flight does not fully normalize in the forward arc. Through further examination of flights 3 and 4, repeatability is illustrated with the subregion peak spectra for the nose gear (NG), left main gear (MGL), and right main gear (MGR), in Fig. 9 (a), (b), and (c), respectively. For all three regions, peak spectral levels repeat fairly consistently, although discrepancies do occur, and are on the order of approximately 2 dB. Based on these results it can be deduced that: (a) a U^5 velocity correction normalizes the data fairly well, (b) far-field noise repeats within about 0.5 dB, and (c) beamforming results repeat within roughly 2 dB. There is a noticeable tone at 3,000 Hz that is attributed to the nose gear as it is only evident in that subregion. This tone persisted for flap deployment 25 and 20 but vanished at flap 0. The origin of the tone is unknown at present.

B. Measuring & Discerning Gear Noise

Important to airframe noise measurements is the ability to discern the effect of gear deployment on the total noise spectra. This is especially true when trying to assess the relative importance of gear versus non-gear noise, and also the effect of gear noise reduction concepts. A comparison between gear down and gear up spectra, both at flap detent 30, is shown in Fig. 10 (a), (b), and (c), for the same three emission angles. The effect of gear deployment is clearly evident. Moreover, in the forward arc, the gear down spectra is about 3 dB higher than the gear up spectra, implying that the gear and non-gear subcomponents are about equal in level. The difference in level diminishes overhead and essentially vanishes in the aft arc, potentially due to the dominance of jet noise, even at idle power.

C. Flap Detent 30 Results

1. Far-Field Noise

A spectral comparison between the baseline (conventional) main gear and aligned main gear is depicted in Fig. 11 (a), (b), and (c), respectively, for 60, 90, and 140 degrees emission angle. There is clearly no evidence of noise reduction associated with alignment of the gear. Once again, due to noise floor contamination and atmospheric effects, data from Band 37 and above should be disregarded. Very similar results are observed in comparison of the baseline gear with the toboggan faired gear, as illustrated in Fig. 12 (a), (b), and (c) for the three emission angles. There is also some evidence of noise increase at the low frequencies. These results, both for aligned and toboggan faired gear are puzzling. Figure 10 clearly indicates the ability to measure gear noise deployment and its effect on the total noise. Hence, any changes in gear noise levels should have been detectable in the total far-field noise. Assuming a main gear component source noise reduction of 3 to 4 dB occurred, as deduced from Ref. 11 for the toboggan or alignment configurations, the total airframe noise should have been reduced by about 1.0 to 1.5 dB, yet no reductions are evident.

Currently, this study can only offer suggestions for these puzzling findings. There are two issues of importance: model-scale versus full-scale results not matching, and full-scale results not showing any noise reduction. Concerning the first issue, it is important to note the differences between the two tests. First, the gear was isolated in model-scale testing; whereas in the flight test the gear was beneath the wing, which is known to have a strong effect on gear noise. At high flap deflections the wing downwash slows the flow underneath the wing to the extent that the local flow speed around the gear truck is reduced substantially. Another difference not accounted for in model-scale testing is the existence of nose gear noise and its relation to main gear absolute and reduced levels. It is also possible that near-field effects measured by the phased array in the wind tunnel tests of Ref. 11 do not materialize or are altered in the far-field (i.e., the model scale measurements were taken with the phased array within a few tire diameters of the wheel bogey versus the flight test where the array was hundreds of diameters away).

Concerning the second issue of full-scale results not showing any noise reduction, both the toboggan and alignment physically reduce the fluid-structure interactions; hence, logic dictates there should be a local source noise reduction. Perhaps the reduction occurred, but was masked by other dominating noise sources. The phased array results shown next, provide some supporting evidence for the masking effect, and how it materialized in the far-field measurements.

2. Subregion Peak Spectra

A spectral comparison between the baseline, aligned and toboggan faired gears is depicted in Fig. 13 (a), (b), and (c), respectively, for the nose gear (NG), left main gear (MGL), and right main gear (MGR). The nose gear results are similar for all cases, as expected, since only the main gear was modified. Ideally all three NG results would be perfect matches of each other. Concerning the MGL and MGR, there is no clear indication of noise reduction for either concept. This is more clearly seen in the delta spectra plots shown in Fig. 14 (a) and (b) for the MGL and MGR subregions for both the aligned and toboggan gear. The MGL region delta is similar for both toboggan and aligned gear, and oscillates from +1 to -1 dB, with a mean level of about 0 dB, suggesting a roughly 0 dB noise reduction. The MGR delta is also similar for toboggan and aligned gear, and oscillates initially, but then begins to diverge. Ideally, MGR and MGL results would match, but influences such as centerline offset and yaw angle differences can affect the symmetry. The use of peak levels from the main gear regions can also be of issue since noise sources other than just the main gear may exist within the defined subregions. Therefore, the extracted peak may not be from the gear source. A more appropriate measure would be an integration of the subcomponent noise levels; however, reliable integration methods are presently lacking.

Perhaps the issue of not finding noise reduction in these results can be linked back to the possibility of masking of the noise reduction. Based on prior experience, the main gear sources in the baseline configuration would be expected to be at least as loud as the nose gear noise source due to the high complexity of the former. Interestingly, Fig. 15 depicts the opposite, in which the nose gear subregion peak spectral level is louder by as much as 3 to 5 dB in the 500-2000 Hz range. If so, then further reductions of the main gear noise would have little bearing on the total gear noise. Therefore, the total airframe noise would be unchanged as well, as observed in Fig. 11 and 12. However, reductions in peak levels can also be offset by growth in spatial extent of the noise source. In these instances, accurate integrated noise levels over the defined region may result in significantly different subcomponent spectra than those obtained based on peak noise levels.

It is also important to note that due to computing limitations, the grid size and/or density was limited and perhaps increases in either parameter would have enabled finer resolution of the sources. At approach flaps, the high-lift system noise sources and gear noise sources are not fully discernible as separate sources, thus determining separate peak spectral levels is difficult. This will become apparent when the beamform maps are shown next. In order to increase source resolution fidelity, a deconvolution type analysis method may help.

3. *Beamform Contour Maps*

Based on Fig. 14, results will be shown for 2 frequencies for which the aligned and toboggan faired gear exhibited similar performance. At 1269 Hz, utilizing array *b* measurements, the beamform maps are shown in Fig. 16 (a), (b), and (c) for the three configurations. Figure 16 (a) depicts the baseline configuration source map. The computed peak NG, MGR, and MGL subregion levels displayed in this figure were assumed to be the reference levels for the respective subregions. Subtracting the baseline NG, MGR, and MGL values from their corresponding values for the aligned gear and the toboggan faired gear, the subregions' relative levels for the two modified gears were obtained. Figures 16 (b) and 16(c) display the source localization maps (with the relative levels given numerically beside each subregion) for the aligned gear and the faired gear, respectively. Examining the NG relative values for the aligned and toboggan gear, it is noteworthy that the differences are similar, and they are both within about 0.5 dB of the baseline NG level. The similarities imply that the flight test conditions were matched quite closely. The MGR peak spectral levels are all within measurement uncertainty of 2 dB (see Fig. 9), and only show minor differences of about -0.5 dB from the baseline levels. The MGL levels for the aligned and toboggan gear exhibit differences of -1.2 and -2.1 dB. The discrepancies between MGR and MGL results may be due to variability in yaw and centerline offset. Moreover, overlap of the gear and flap sources is evident. Hence, within the defined zones of interest, it is possible that the peak level might not be from the gear source. At 2148 Hz, utilizing array *a* measurements, beamform maps are shown in Fig. 17 (a), (b), and (c), for the three configurations. In this instance, the nose gear relative levels for the aligned and toboggan configurations are self similar but not as similar to the baseline configuration (up to 1.0 dB different). The MGR levels are once more within tolerances, and hardly exhibit any differences from baseline levels. The MGL levels exhibit close to 2 dB increases. However, close examination reveals these increases to be from non-gear sources, such as flap or strut noise. Again, discrepancies between MGR and MGL results may be due to variability in the yaw and centerline offset. A higher level of spatial resolution is required in order to distinguish more clearly between these various noise sources.

4. *Summary of Flap 30 Results*

Far-field results dot not exhibit any noise reduction for both the aligned gear and toboggan faired gear across all frequencies and angles. Subregion peak spectra for MGL and MGR also exhibit no noise reduction, and they are also not equivalent. The aligned and toboggan gear exhibit essentially equivalent results. NG levels dominate the main gear levels across a wide frequency range and seem to render the reductions ineffective (mask the reductions). Fully discerning the gear noise sources on the contour maps and evaluating the effects of the noise reduction concepts is quite difficult since the flap sources are convolved with the gear sources and affect the analysis. A subcomponent integration or deconvolution method is needed for higher fidelity subcomponent quantification. However, installation effects may be responsible for the observed dissimilarity between full-scale and model-scale results.

D. Flap Detent 0 Results

The purpose of studying flap 0 configurations is to isolate the gear source noise and exclude the high lift system airframe noise that would generally be present and "interfere/influence" gear noise measurements and analysis. Moreover, with isolation of the gear noise, the subcomponent nose gear source and subcomponent main gear sources can be further isolated and evaluated for relative importance. In this configuration, the likelihood of detecting and possibly quantifying changes in baseline levels brought about by the noise reduction concepts is enhanced. Additionally, with retracted flaps, the flight test configuration moves closer to simulating the isolated main landing gear tested in model-scale testing.

1. *Far-Field Noise*

A spectral comparison between the baseline main gear and aligned main gear is depicted in Fig. 18 (a), (b), and (c) for 60, 90, and 140 degree emission angle, respectively. Clearly for flap 0 as well, there is no evidence of noise reduction associated with alignment of the gear. We reiterate again that due to noise floor contamination and atmospheric effects, data from band 37 and above should be disregarded. Very similar results are observed in the comparison of the baseline gear with the toboggan faired gear, as illustrated in Fig. 19 (a), (b), and (c) for the three emission angles. In both instances, the noise increases in the low frequencies have amplified from that observed at flap 30. Perhaps this is due to the gear acting like a bluff body source, in which the local flow velocities have increased as a result of the flaps being retracted (no downwash effect). Not observing any noise reduction is puzzling, especially with the gear now being the only deployed component. These flight measurements are the closest to matching the model-scale environment, yet there is no reduction. Again the only explanation that can be offered is an inference that the reduction is masked by the nose gear. The peak spectra and beamform maps will be examined again for any supporting evidence.

2. *Subregion Peak Spectra*

A comparison between the baseline, aligned and toboggan faired gear is depicted in Fig. 20 (a), (b), and (c), respectively for the nose gear (NG), left main gear (MGL), and right main gear (MGR). The nose gear results are similar, but not as closely matched as for the flap 30 results. Ideally all three NG results would be perfect matches of each other. Differences from baseline levels for the MGR results are not clearly apparent. The MGL results exhibit differences from baseline levels centered around 2,000 Hz. The differences are more easily viewed in the delta spectra plots depicted in Fig. 21 (a), and (b) for the MGL and MGR subregions for both the aligned and toboggan gear. The MGL deltas for the aligned and toboggan gear are similar, and seem to reach a maximum difference from baseline levels on the order of -3 to -4 dB at 2000 Hz. They average about -2 dB between 1500 Hz and 3000 Hz. The noise increases in the low frequencies may be attributable, as noted earlier, to bluff body behavior. The MGR deltas are in general more erratic and dissimilar for the aligned and toboggan gear. The toboggan gear exhibits increases from baseline levels on the order of 2 dB. The aligned gear deltas average about -3 dB from baseline levels with differences reaching about -5 dB for a few frequencies. Given 2 dB measurement uncertainty, the MGL toboggan and aligned gear differences could be as small as -1 to -2 dB from baseline levels. The MGR aligned gear differences would reduce to -1 to -3 dB. The consistency between the MGL and MGR levels for the aligned gear may be regarded as noise reduction of about 1 to 2 dB between 1500 Hz to 3000 Hz. It is important to keep in mind that this is only local noise reduction, and the far-field results do not exhibit reductions but rather increases in noise. Also, whenever inconsistencies between the MGL and MGR results exist, it implies inconclusive evidence for noise reduction. Recall that differences between MGR and MGL results might be affected by variability in the yaw and/or centerline offset.

Assuming that conclusive evidence was found for gear source noise reduction, the total noise should have been reduced. Figure 22 compares the peak spectra (used as a measure of the relative ranking/importance to each other) of NG, MGL and MGR at flaps 0 for the baseline configuration. Up to about 2000 Hz, all three components are relatively equal, which itself requires further investigation. Beyond 2000 Hz, the main gear levels increase above the nose gear levels by about 2 to 3 dB. Suppose then if the main gear levels would be reduced by roughly the same amount, the nose and main gear levels would be equal. This is evidenced in Fig. 23 which shows the baseline MGL levels, the aligned MGL levels and the NG levels, all at flap detent 0. It is plainly visible that the aligned gear reduces the local gear noise to the extent that it generally matches the nose gear in level. In this scenario the new total gear noise (original NG + reduced MG) would still be lower than the original total (original NG + original MG). Hence, even if the MG levels are just reduced to the NG levels and not reduced even further (as is occurring based on beamforming results), the total noise should have been reduced (which is not observed in far-field results). This contradiction has yet to be resolved.

3. *Beamform Contour Maps*

At 732 Hz, utilizing array *c* measurements, beamform maps are shown in Fig. 24 (a), (b), and (c), for the three configurations. The difference in the NG subregion peak levels from the aligned and toboggan gear cases are similar to each other, about 0.7 dB different from the baseline level. In general though, these small differences imply close matching of flight conditions. At this frequency, the toboggan exhibits a very small difference for the MGL source, and an increase of 1.9 dB for the MGR source which is still within uncertainty measurements. The aligned gear exhibits a difference from baseline levels of -1.7 dB for the MGL source and a -1.5 dB difference in the MGR source. Since the MGL and MGR differences are fairly consistent, perhaps true noise reduction occurred. Larger reductions may have been obtained if the integrated levels had been utilized rather than the peak levels, because the noise contour spatial extent was also reduced. At 1757 Hz, using array *b* measurements, beamform maps are shown in Fig. 25 (a), (b), and (c) for the three configurations. In this instance as well, the nose gear levels are close in value (within 0.4 dB from baseline level). The toboggan exhibits a 3.1 dB increase for the MGR source and a -2.0 dB difference for the MGL source. The aligned gear exhibits a very small difference in the MGR source level, and a -1.3 dB difference in the MGL source. It is evident that MGL and MGR differences are inconsistent for both aligned and toboggan gear. Therefore, it is inconclusive if reduction occurred. Using array *a* measurements, beamform maps for 2099 Hz are shown in Fig. 26 (a), (b), and (c) for the three configurations. Again, the nose gear levels are close in value (within 0.5 dB from baseline level). The toboggan exhibits a -1.6 dB difference from baseline level in the MGR source, and a -2 dB difference in the MGL source. The aligned gear exhibits a -3.6 dB difference in the MGR source and a -1.5 dB difference in the MGL source. At this frequency the MGL and MGR differences are inconsistent for both aligned and toboggan gear. Hence, it is inconclusive if reduction occurred. Recall that differences in MGR and MGL levels could be due to the yaw and centerline offset.

4. *Summary of Flap 0 Results*

Far-field results dot not exhibit any noise reduction for both the aligned and toboggan gear across all frequencies and angles. Noise increases are evident in the low frequencies, possibly due to enhanced bluff body behavior. Isolation of the gear from the rest of the high-lift system allows for higher accuracy assessments of changes in gear source levels. Aligned and toboggan gear exhibit essentially equivalent MGL results but not MGR results. From about 1500 to 3000 Hz, MGL differences are on the order of -1 to -2 dB for the aligned and toboggan gears. MGR differences are about -1 to -3 db for aligned gear, and about +2 dB for the toboggan. With increases in the MGR levels of the toboggan, there is inconsistency with MGL results. Thus, there is no conclusive indication of noise reduction. In contrast, the aligned gear MGL and MGR results are similar, perhaps indicating real noise reduction. The source noise analysis indicated that the aligned gear MGL levels reduced to about the NG levels.

V. Additional Processing & Data Sets

It is important to note that several other configurations were flight tested besides Flaps 0 and Flaps 30. Variations in flight speed, flap settings, and gear deployment scenarios were tested. Concerning this study, flap detent 20, flap detent 25, and repeat flap detent 30 measurements were also analyzed for the baseline, toboggan and aligned gear configurations. These additional data sets did not impart any further insight; hence, for brevity they were not included.

In perfectly controlled environments, the nose gear source noise would be constant and equal across other test configurations. Additionally the MGR and MGL levels would be identical. One of the additional processes tried was to assume the nose gear source noise should be exactly the same for all flight test configurations. For each frequency any peak spectra delta between the nose gear sources for each configuration was then used to adjust all the noise levels of that configuration in the beamform map. Comparisons were then made between baseline gear, and the adjusted toboggan and adjusted aligned gear. This process helped in the visualization of the results, and surprisingly the final deltas were not affected much by the alterations. The drawback was that the spectral scatter was increased in the original measurements. Hence, it was decided to continue analyzing the unmodified data, and focus on configurations in which the nose gear sources were inherently +0.5 or -0.5 dB different from the baseline nose gear levels, as depicted in Fig. 16, Fig. 25 and Fig. 26.

VI. Summary & Conclusions

Due to high complexity, high cost, and high resource requirements, flight testing is not a common occurrence for airframe noise investigations. In particular, full-scale add-on noise reduction concepts tested in-flight have only begun to be realized, and little is known on their merit or the correspondence of results with model-scale findings.

This study attempted to investigate in-flight, full-scale gear noise as well as main gear noise reduction concepts, measured as part of the 2005 Quiet Technology Demonstrator 2 flight test program (QTD2). A Boeing 777-300ER was utilized as the test plane. Both flyover far-field microphone measurements and acoustic phased array measurements were utilized in the analysis. The baseline conventional main gear, aligned main gear, and toboggan faired main gear were investigated at Flap 0 and Flap 30 detents, all with engine-idle power setting. The specific analysis objectives were to assess capability of measuring and discerning in-flight gear noise, and to evaluate qualitatively and quantitatively the merit of each noise reduction concept.

Data repeatability for far-field noise measurements was within about 0.5 dB. Repeatability for the beamforming results in terms of subregion peak spectra was within about 2 dB. The difference between gear up and gear down was about 3 dB, indicating that the gear and non-gear noise sources were about equal in importance and level.

At flaps 30 and flaps 0, far-field results did not exhibit any noise reduction for both the aligned gear and the toboggan faired gear across all frequencies and angles. In the latter flap configuration, low frequency noise increases on the order of 2 to 3 dB occurred with the toboggan and aligned gear, possibly due to enhanced bluff body characteristics. At flaps 30, the toboggan and aligned gears exhibited essentially equivalent beamforming results, in which peak spectra for the MGL and MGR subregions displayed no noise reduction. It seems that any reduction was masked since the nose gear levels dominate the main gear levels across a wide frequency range and render expected noise reductions undetectable. However, at flaps 30 it is quite difficult to fully discern gear noise sources and evaluate the noise reduction concepts since the flap sources spatially overlap the gear sources and affect the analysis. At flaps 0, the toboggan and aligned gear yield differing MGR regional spectral results, but essentially equivalent MGL results. Differences in MGR subregion spectra from baseline levels are about -1 to -3 dB for aligned gear, and about +2 dB for the toboggan. The MGL differences are on the order of -1 to -2 dB for aligned and toboggan gear from about 1500 to 3000 Hz. There is inconclusive evidence for noise reduction due to the toboggan since the MGL and MGR results are inconsistent. In contrast, aligned gear MGL and MGR results are similar, perhaps indicating real noise reduction of about -1 to -3 dB within the 1500 to 3000 Hz range. Differences between MGR and MGL levels could be due to variability in airplane yaw and centerline offset.

Complete similarity between model-scale and full-scale noise reduction levels was not found and requires further investigation. Installation effects may be responsible for the dissimilarity between full-scale and model-scale results. Significant differences were also observed between the two acoustic measurement techniques. Discrepancies exist at certain frequencies between potential noise reduction levels measured by the phased array, but not confirmed by far-field measurements. Further investigation is needed to address why these discrepancies exist.

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Table 1. Optimal frequency ranges for the various sized arrays

Array	Minimum Frequency (Hz)	Maximum Frequency (Hz)
e	146	244
d	292	341
c	390	830
b	878	1855
a	1904	3906

(a) Sideview **(b) Front view**

Figure 1. B777-300ER conventional main gear.

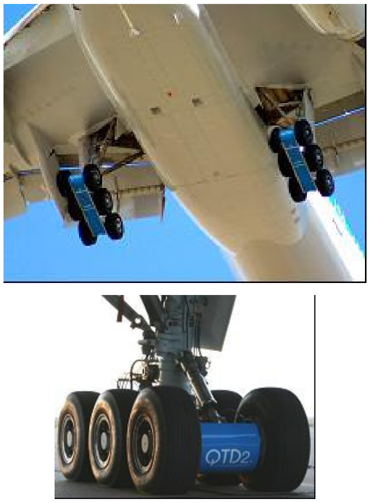


Figure 2. Full-scale toboggan fairings.

(a) Aligned

(b) "toes-up"

Figure 3. Aligned main gear (a), and baseline "toes-up" alignment (b).

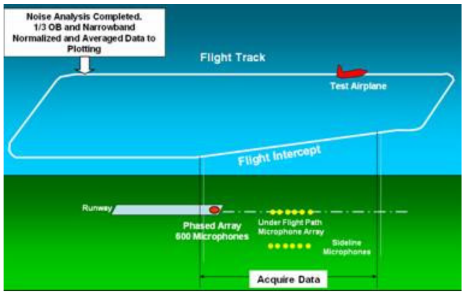


Figure 4. Flight test racetrack.

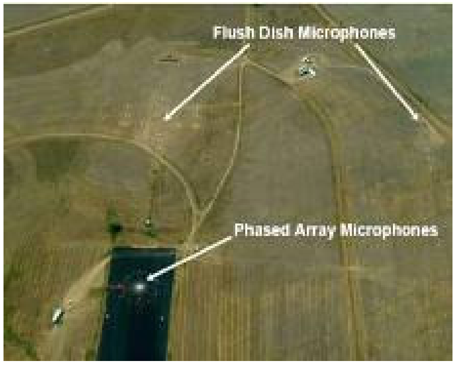


Figure 5. Layout of microphones with respect to the runway.

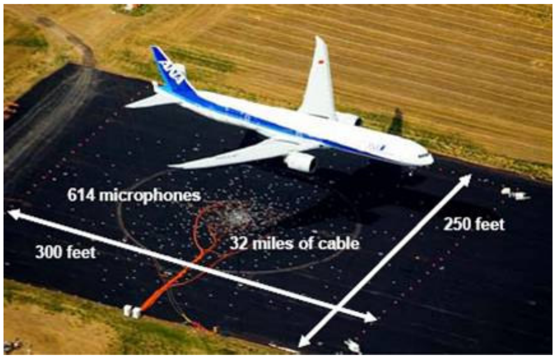


Figure 6. Aerial view of test airplane flying over phased array system.

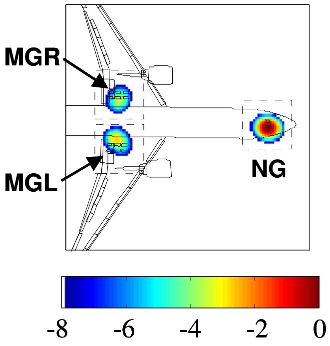
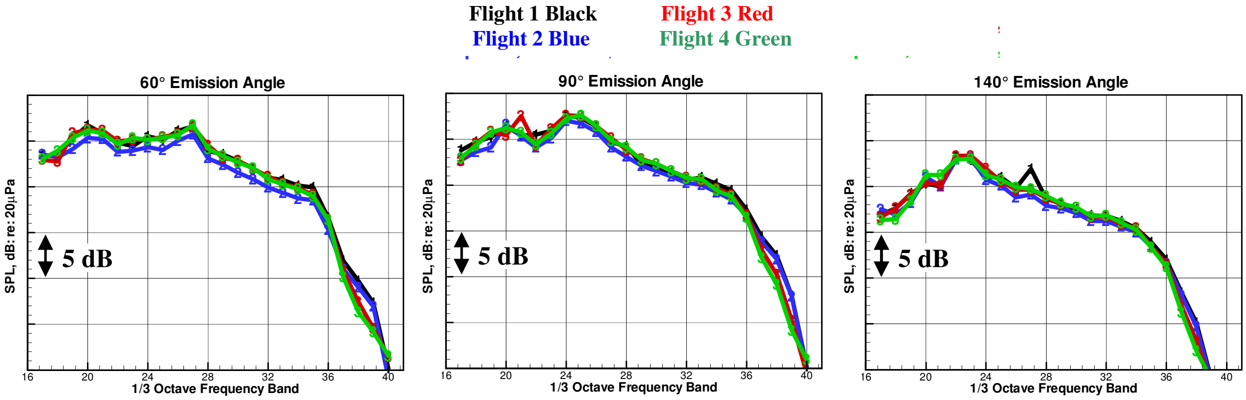
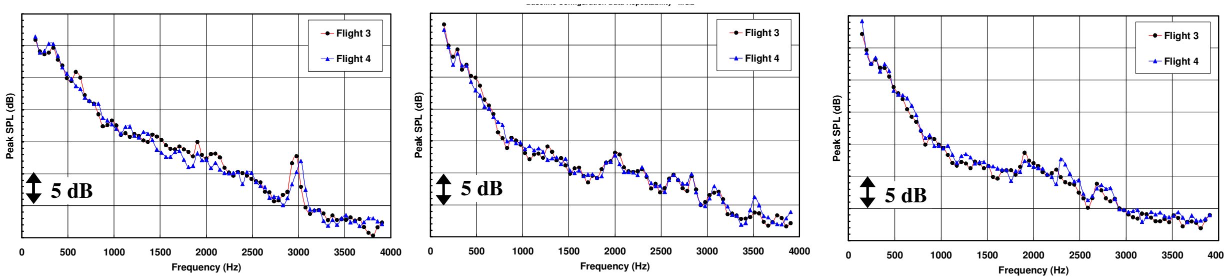


Figure 7. Sample beamform results image illustrating defined subregions and nomenclature.



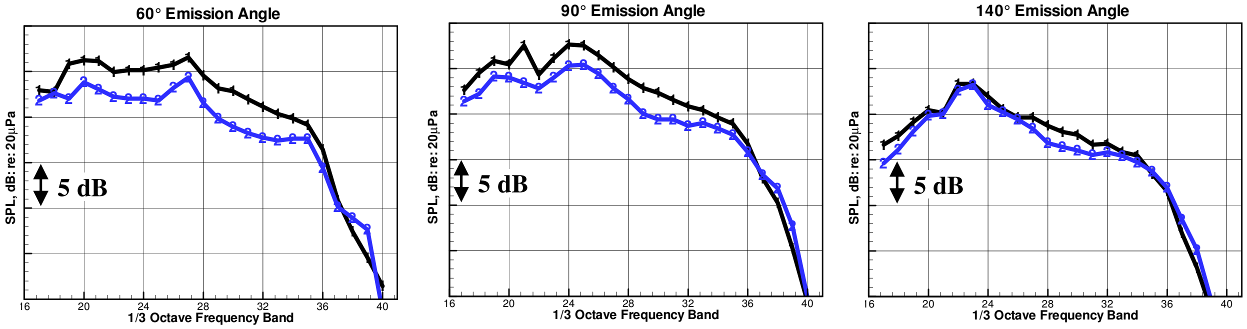
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 8. Baseline configuration far-field noise data repeatability.



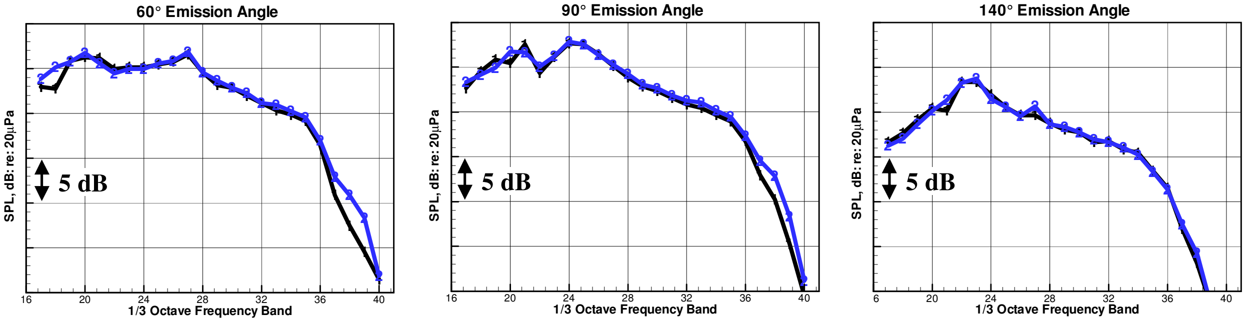
(a) NG (b) MGL (c) MGR

Figure 9. Baseline configuration subregion peak spectra data repeatability.



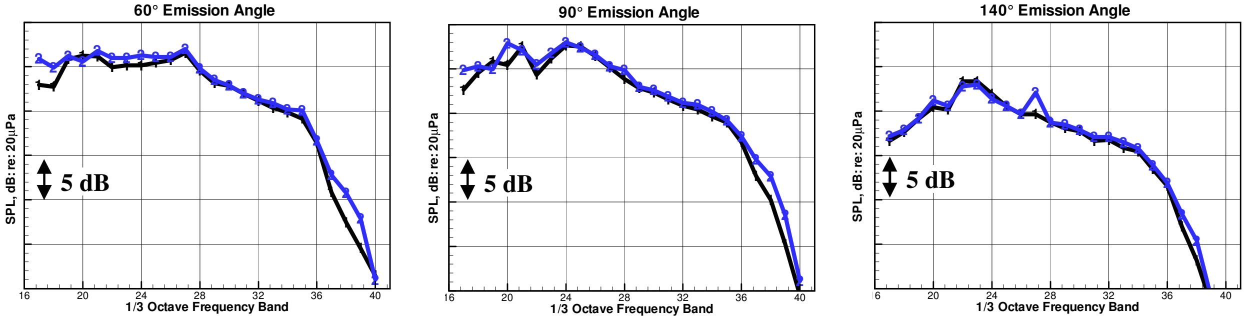
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 10. Comparison of gear down (black) versus gear up (blue) configurations at Flap 30 detent.



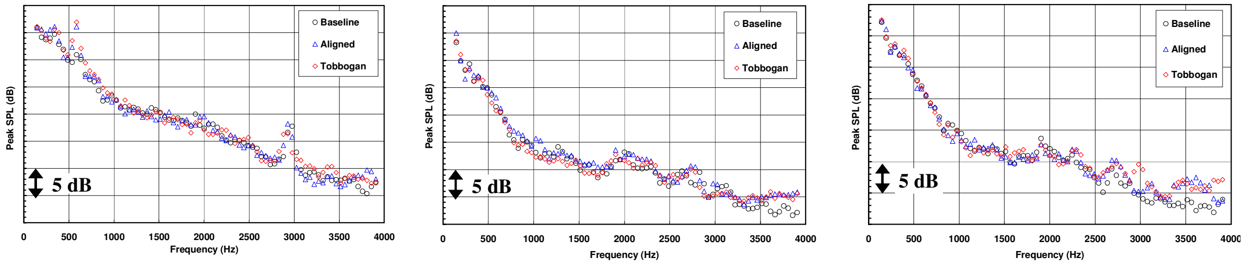
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 11. Comparison of baseline conventional gear (black) vs. aligned gear (blue) at Flap 30 detent.



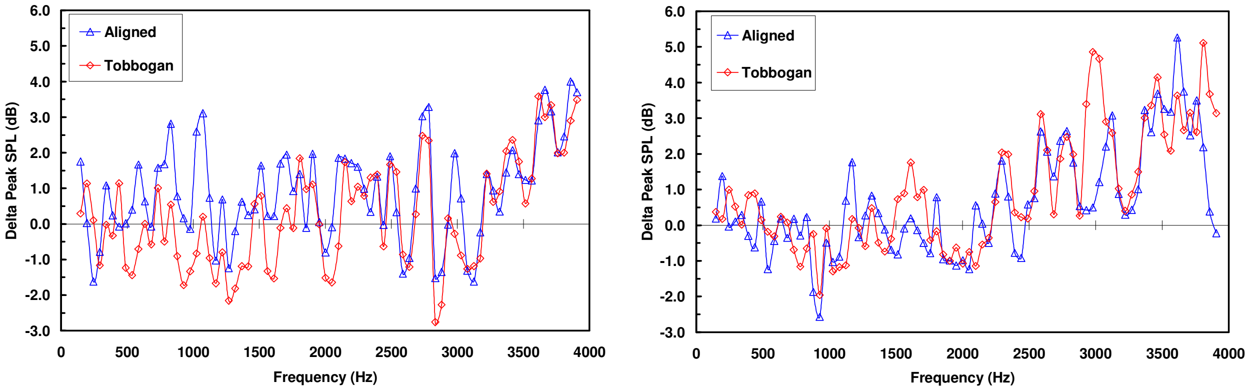
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 12. Comparison of baseline conventional gear (black) vs. toboggan faired gear (blue) at Flap 30 detent.



(a) NG (b) MGL (c) MGR

Figure 13. Comparison of baseline gear vs. aligned gear vs. toboggan faired gear at Flap Detent 30.



(a) MGL (b) MGR

Figure 14. Comparison of aligned gear differences from baseline vs. toboggan faired gear differences from baseline at F30.

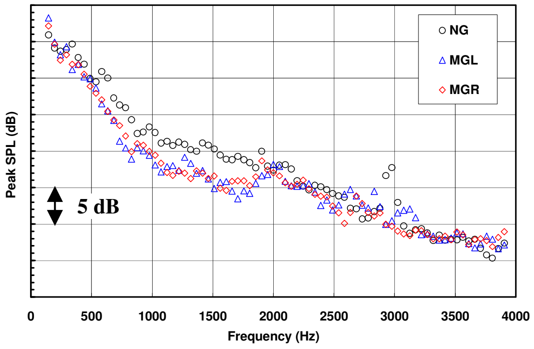
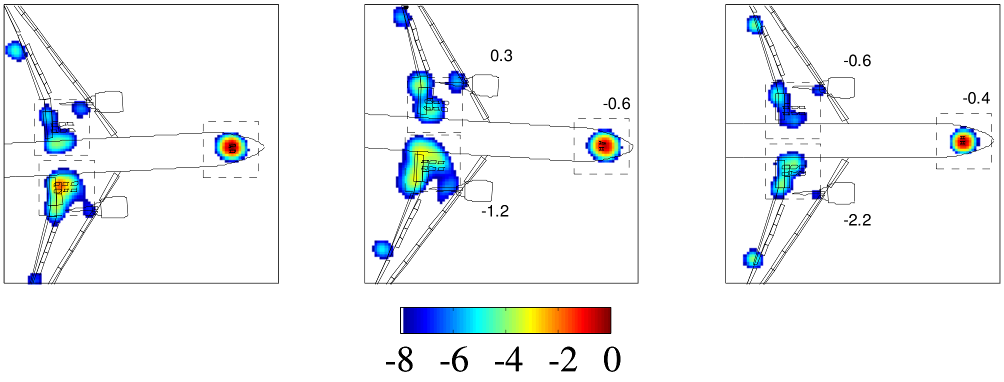
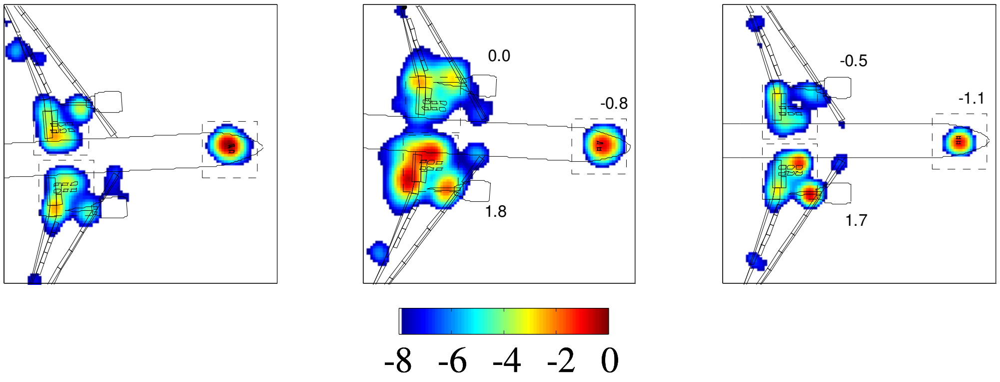


Figure 15. Comparison of peak spectral levels of NG vs. MGL vs. MGR for baseline configuration at Flap Detent 30.



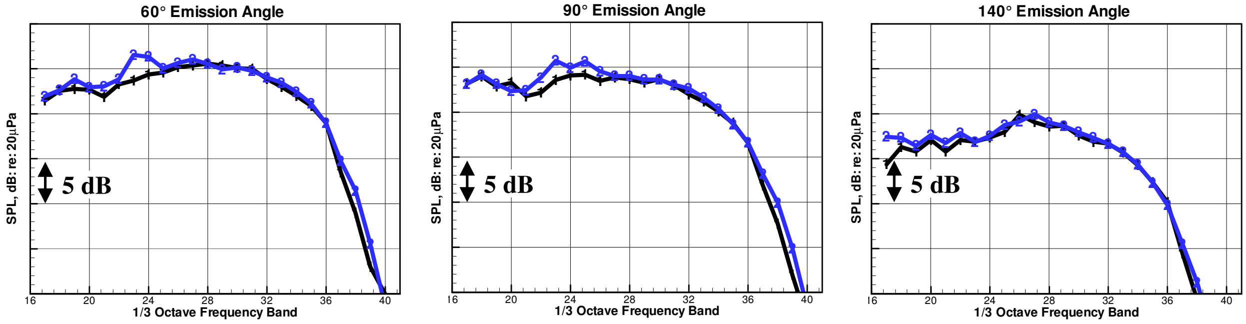
(a) Baseline (b) Aligned (c) Faired

Figure 16. Beamform contour maps for (a) baseline gear (b) aligned gear (c) toboggan faired gear. Flap detent 30 and 1269 Hz.



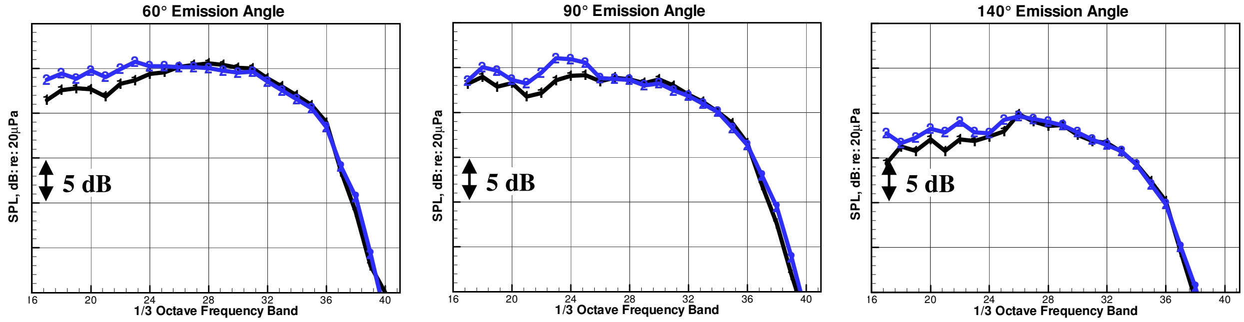
(a) Baseline (b) Aligned (c) Faired

Figure 17. Beamform contour maps for (a) baseline gear (b) aligned gear (c) toboggan faired gear. Flap detent 30 and 2148 Hz.



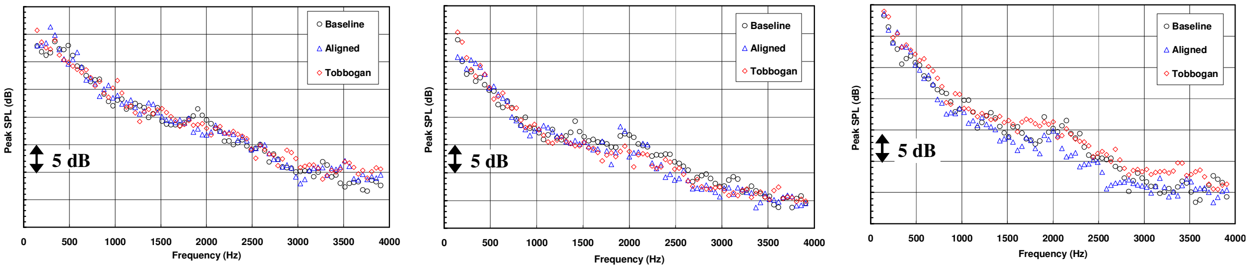
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 18. Comparison of baseline conventional gear (black) vs. aligned gear (blue) at Flap 0 detent.



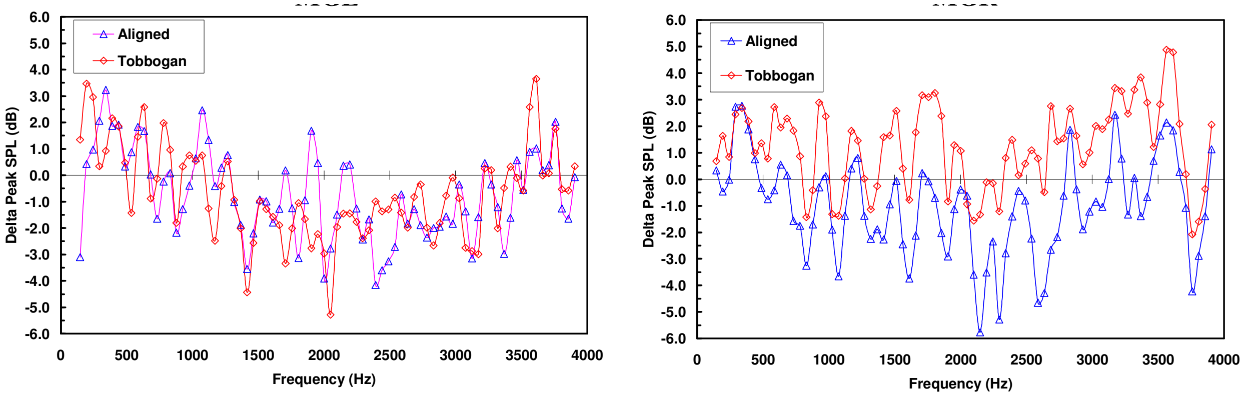
(a) Forward arc (60 deg.) (b) Overhead (90 deg.) (c) Aft arc (140 deg.)

Figure 19. Comparison of baseline conventional gear (black) vs. toboggan faired gear (blue) at Flap 0 detent.



(a) NG (b) MGL (c) MGR

Figure 20. Comparison of baseline gear vs. aligned gear vs. toboggan faired gear at Flap Detent 0.



(a) MGL (b) MGR

Figure 21. Comparison of aligned gear differences from baseline vs. toboggan faired gear differences from baseline at F0.

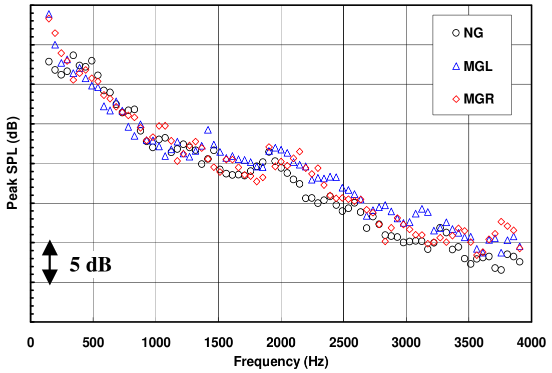


Figure 22. **Comparison of peak baseline configuration spectral levels of NG vs. MGL vs. MGR at Flap 0.**

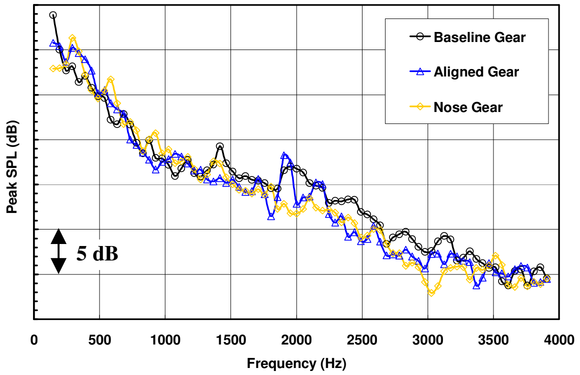
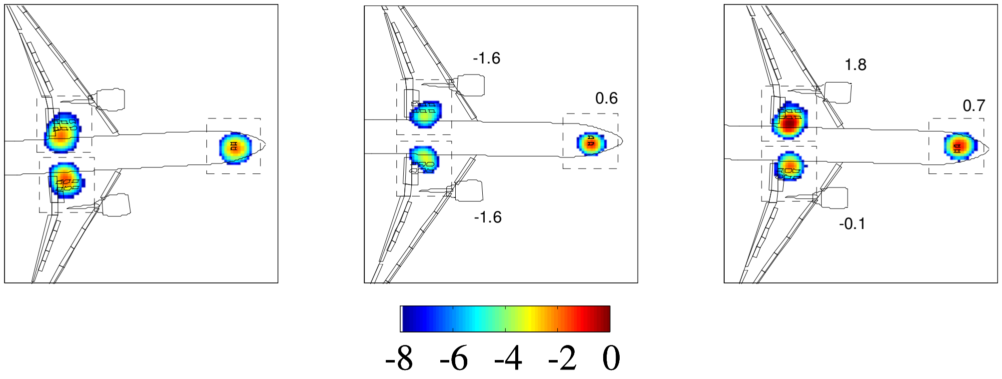
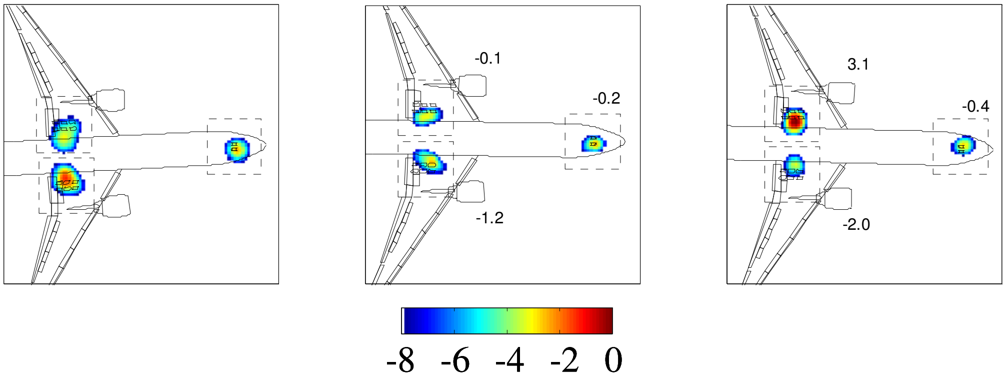


Figure 23. **Comparison of peak spectral levels of MGL vs. aligned MGL vs. NG at Flap 0**



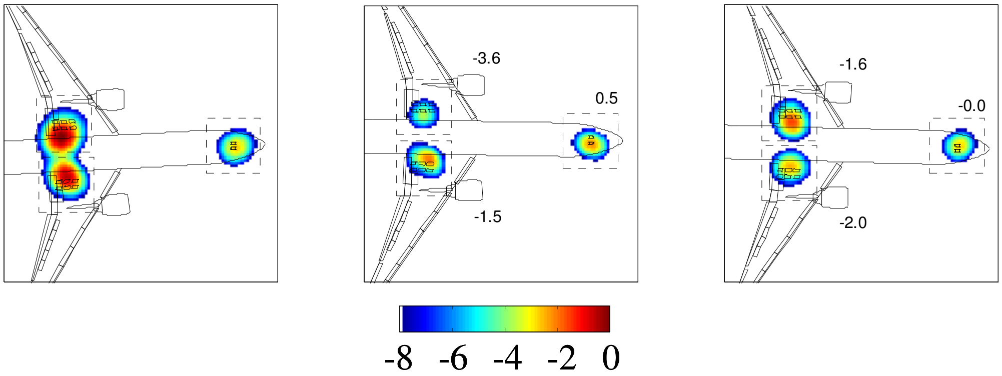
(a) Baseline (b) Aligned (c) Faired

Figure 24. **Beamform contour maps for (a) baseline gear (b) aligned gear (c) toboggan faired gear. Flap detent 0 and 732 Hz.**



(a) Baseline (b) Aligned (c) Faired

Figure 25. Beamform contour maps for (a) baseline gear (b) aligned gear (c) toboggan faired gear. Flap detent 0 and 1757 Hz.



(a) Baseline (b) Aligned (c) Faired

Figure 26. Beamform contour maps for (a) baseline gear (b) aligned gear (c) toboggan faired gear. Flap detent 0 and 2099 Hz.