DAMAS2 VALIDATION FOR FLIGHT TEST AIRFRAME NOISE MEASUREMENTS

Leon Brusniak

Boeing Commercial Airplanes
P.O. Box 3707, MC 67-ML Seattle, WA, USA, 98124
leon.brusniak@boeing.com

ABSTRACT

The DAMAS2 algorithm is a deconvolution method which can be used to quantify aircraft noise subcomponent spectral levels obtained using phased array measurements. This paper examines the effectiveness of the DAMAS2 algorithm for accurately determining flight test aircraft noise subcomponent spectral levels. First, the DAMAS2 subcomponent spectral levels are shown to be qualitatively correct through comparison with the expected behavior as seen in the phased array beamform maps. The DAMAS2 spectra are then compared to sample output from the original DAMAS algorithm and are seen to be generally within 0.1 dB of DAMAS algorithm spectral levels. Lastly, the shape of the cumulative DAMAS2 spectral levels are compared with single microphone spectra and are seen to be in very good agreement. The DAMAS2 algorithm is seen to be an effective tool for flight test aircraft noise subcomponent spectral measurement.

Copyright © 2008 The Boeing Company. All rights reserved.

1 INTRODUCTION

Acoustic phased arrays are composed of a set of spatially distributed microphones which, through the process of beamforming, act cumulatively as a spatial noise filter. These arrays are used both to determine the locations of the various aircraft noise sources and to (ideally) quantify the spectral levels of each separate noise source region. The sample flight test conventional beamforming map shown in Fig. 1 highlights some of the typical aircraft noise sources. Features include leading edge slat noise, inboard slat edge noise (near the wing/body junction), and flap edge noise. The engine exhaust noise is also visible.

A goal of flight test aircraft noise data analysis is quantification of the spectral levels of the various airframe noise components (flaps, slats, landing gear, etc.). The relative importance of each noise source can then be determined so that candidate regions for noise reduction treatment can be identified, all with the goal of designing quieter airplanes.

The breakthrough deconvolution method for aeroacoustic analysis was developed by Brooks and Humphreys (Ref. 1) and termed DAMAS (Deconvolution Approach for the Mapping of Acoustic Sources). One drawback of the method is the time required to process the data, since the array response (or, point spread function, *psf*) must be calculated at each point on the beamform map grid. Dougherty (Ref. 2) approached this issue by developing the DAMAS2 method which assumes that the array response is invariant over the beamforming grid, therefore, the *psf* is only calculated once. The objective of this study is to validate the effectiveness and accuracy of the DAMAS2 algorithm for determining flight test aircraft noise subcomponent spectral levels.

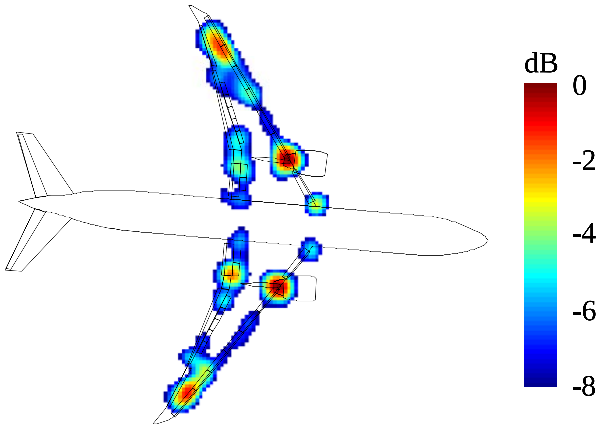

Fig. 1. Typical flight test aircraft noise sources, including airframe and engine related sources.

2 BACKGROUND

2.1 Experiment description

In August 2005, Boeing and partners NASA, Goodrich, ANA and GE conducted the Quiet Technology Demonstrator 2 (QTD2) flight test program in which phased array noise measurements were an integral part. Two independent phased array systems were used for the

Copyright © 2008 The Boeing Company. All rights reserved.

acoustic measurements. The origins of all five subarrays (i.e., from both the low and high frequency array systems) were co-located. The high frequency array system was composed of two subarrays, both arranged in multi-arm logarithmic spiral configurations. The microphone spatial distributions are shown in Fig. 2 (i.e., arrays *a* and *b*). Selected microphones were shared between subarrays. The low frequency array system was composed of three subarrays, also arranged in multi-arm logarithmic spiral configurations as shown in the figure (arrays *c*, *d* and *e*; similarly, selected microphones were shared between subarrays). Reference 3 contains an extensive description of the phased array configuration and implementation.

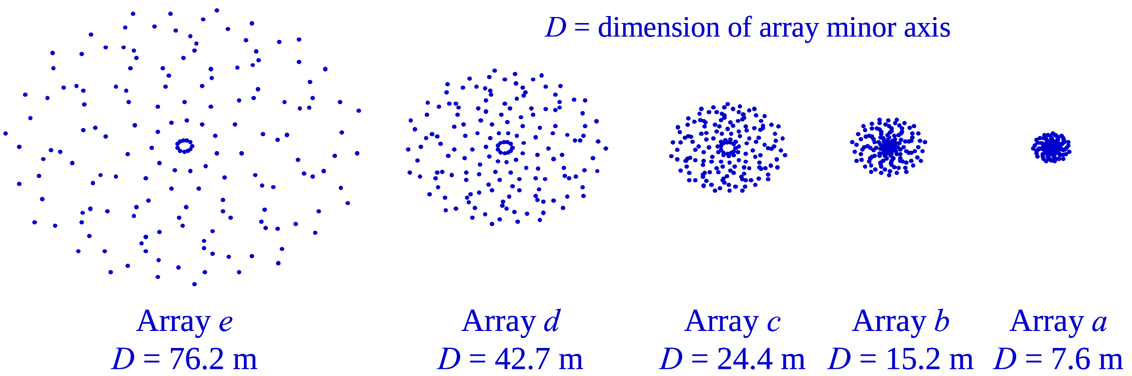

Fig. 2. QTD2 phased array microphone distributions (high frequency arrays a, b; low frequency arrays c, d, e).

The test aircraft was a Boeing 777-300ER on loan from ANA airlines. Fig. 3 shows details of the QTD2 flight test geometry, including the aircraft bearing angle, θ, and the emission angle, ε. The phased arrays could generally resolve noise sources which were within about 8 dB to 10 dB of the peak noise source in the beamform map.

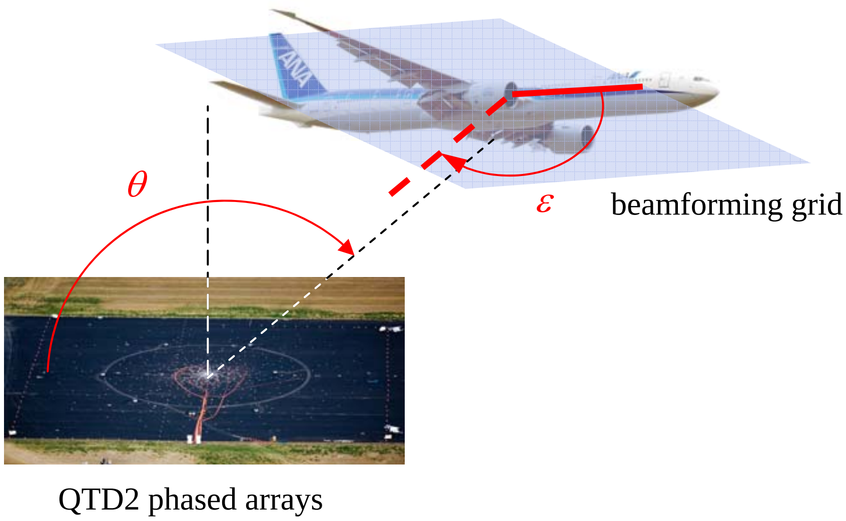

Fig. 3. QTD2 flight test geometry (aircraft bearing angle, θ, and emission angle, ε).

Copyright © 2008 The Boeing Company. All rights reserved.

2.2 Data analysis methods

A two-dimensional 81.4 m by 81.4 m (267 ft by 267 ft) region consisting of 151x151 grid points was used for the beamforming. The center of the beamforming grid was located 3.05 m (10 ft) above the aircraft reference point and was oriented parallel to the base of the aircraft (i.e., aircraft pitch was accounted for in the grid orientation). The aircraft reference point was defined as the point in space centered between the main landing gear trucks when in the deployed position.

Beamforming was accomplished using a traditional delay-and-sum approach (i.e., time-domain beamforming) with Doppler shifts removed from the data. After beamforming, the data were Fourier Transformed using a 512 point transform. The narrowband (approximately 48 Hz bin separation) beamform map data were used for the subcomponent analyses. For the results shown below, 500 iteration steps were used for the DAMAS algorithm processing and 10,000 steps were used for the DAMAS2 processing.

3 RESULTS

3.1 Source subcomponent level measurements

For the noise source subcomponent extractions, twenty-nine non-overlapping subcomponent noise regions were defined as illustrated in the bottom left hand image of Fig. 4. The subcomponent noise spectra shown at the top of the figure are based on the integration regions shown in the latter. In particular, the DAMAS2 solution levels within the green subcomponent regions (encompassing the inlets and exhaust regions of both engines) are cumulatively summed to provide a measure of the engine-related noise spectra. Representative airframe noise spectra are similarly provided by summing the flap edge/fuselage junction DAMAS2 solution levels within the blue subcomponent regions. The red line in the figure is the cumulative sum of the DAMAS2 energy levels within all twenty-nine subcomponent regions. The colors used in the noise subregion definition image correspond to the line colors used in the spectral plot.

Note first the narrowband engine-related tone near 2000 Hz. According to the DAMAS2 spectra, the cumulative engine-related noise source contribution is larger than the airframe noise-related noise source contribution at this frequency. The bottom left hand figure shows the conventional beamform map at this frequency. It is clear from the image that, owing to the engine tonal, the cumulative noise contribution from the engine will be larger than from the flap edge contributions, in qualitative agreement with the DAMAS2 spectral levels.

Consider now the spectral levels at 2148 Hz. At this frequency, the engine-related spectral levels are clearly lower than the flap edge levels. The expectation is that the cumulative energy contributions from the flap edge regions will be larger than from the engine regions in the beamform map image. This is indeed the case as shown in the corresponding 2148 Hz conventional beamform map. Note that there are significant energy contributions from both the flap edges and from the engine exhaust (all with similar peak levels), but that the noise region associated with the flap edges is spatially larger (i.e., a larger integrated energy sum).

One key feature to note about the engine and flap edge spectra is the difference in spectral shape, especially between 500 Hz and 1000 Hz. The point is that the shape of the total

Copyright © 2008 The Boeing Company. All rights reserved.

cumulative noise spectra (red line) is formed by the summation of the various subcomponent spectra, each of which can have a different shape.

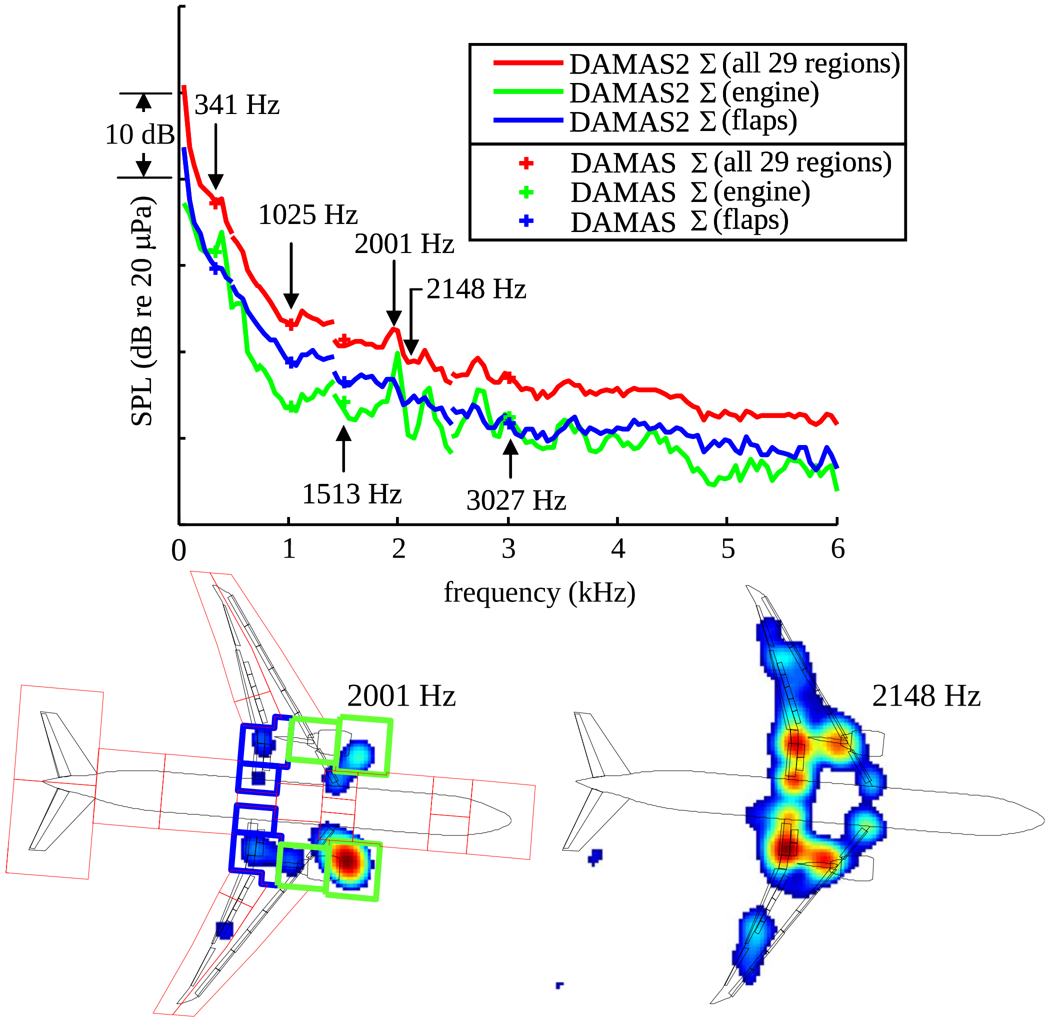

Fig. 4. Noise subcomponent spectra and sample conventional beamforming maps (beamform map colorbar same as in Fig. 1).

The DAMAS2 algorithm clearly provides qualitatively correct noise subcomponent spectral levels, but the issue of solution accuracy still needs to be addressed. One approach is to compute subcomponent spectra levels using the original DAMAS algorithm (for which no assumptions regarding *psf* shape are made) and compare the results with the DAMAS2 levels. That is, the DAMAS algorithm is treated as the "gold standard" with respect to the correct solution.

For this analysis, four frequencies were processed using the DAMAS algorithm. This small number of frequencies was processed owing to the extremely long processing times required. The resulting DAMAS spectral levels are shown in Fig. 4 as '+' marks. As seen, there is very good agreement between the DAMAS and DAMAS2 spectral levels.

Copyright © 2008 The Boeing Company. All rights reserved.

Table 1 summarizes the accuracy of the DAMAS2 algorithm in terms of the differences between the DAMAS and DAMAS2 spectral levels at each of the four selected analysis frequencies. Differences of approximately 0.1 dB or less are highlighted in green in the table. As seen, except for the results at 1025 Hz, the DAMAS2 solutions are quite accurate. In fact, these accuracies are well within the flight test data repeatability uncertainty which is estimated to be on the order of ±2 dB.

Table 1. Source level differences (dB) between DAMAS and DAMAS2 algorithms.

frequency (Hz)	All sources	Engine sources	Flap sources	array
341	0.10	-0.05	0.10	*e*
1025	-0.63	-0.86	-0.32	*c*
1513	-0.07	-0.12	0.08	*b*
3027	0.3	-0.03	0.12	*a*

3.2 Comparisons with single microphone data

Spectra from the *a* array are shown in Fig. 5a. The red line indicates the average of the spectra from all 133 of the microphones in the array. In order to provide an indication of the variation in the spectral levels from the individual microphones, the black lines show the 10th and 90th percentile microphone spectral levels. Last, the green line indicates the spectrum obtained by summing the DAMAS2 spectral levels over all of the subcomponent regions. The amplitude of the cumulative DAMAS2 spectral levels have been reduced by exactly 6 dB in order to provide a better comparison of the spectral shapes (this 6 dB value may be a result of microphone pressure doubling effects not being accounted for in the processing).

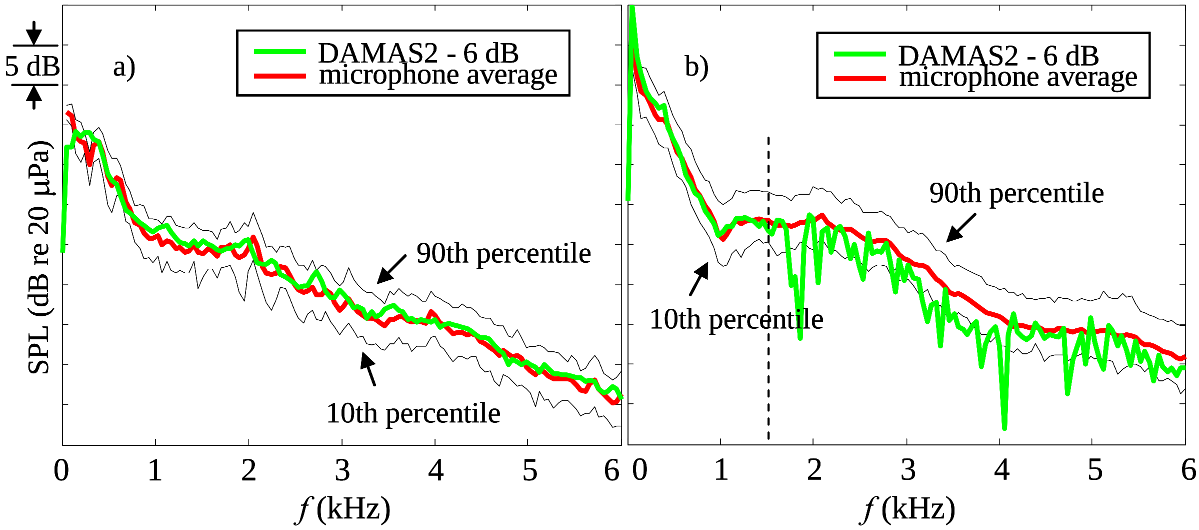

Fig. 5. a) High frequency array DAMAS2 comparison with microphone spectra – 7.6 m array a; b) Low frequency array DAMAS2 comparison with microphone spectra – 76 m array e.

Recall the earlier note that significant differences can exist between the shapes of the individual subcomponent spectra over various frequency bands and that the shape of the total

Copyright © 2008 The Boeing Company. All rights reserved.

cumulative noise spectra is formed by the summation of these various subcomponent spectra of varying shape. With this in mind, the agreement in shape between the cumulative DAMAS2 spectra and the averaged microphone spectra is seen to be quite good.

The corresponding array *e* spectra (166 microphones total) are shown in Fig. 5b. From about 300 Hz to 1000 Hz there is excellent agreement between the microphone and DAMAS2 spectral shapes. The agreement is very good between 1000 Hz and 1500 Hz. Beyond 1500 Hz there is a rapid breakdown in the quality of the DAMAS2 solutions (attributed to array decorrelation effects). However, note how the averaged microphone spectra apparently indicate an "envelope" of DAMAS2 levels beyond 1500 Hz.

The excellent quality of the above results have several implications. First, the capability of the DAMAS2 deconvolution algorithm to accurately decompose (and correctly reassemble) the noise field establishes the reliability of the method. Second, these results suggest that the modeling of the noise sources as incoherent monopoles is a very good engineering approximation of the character of the noise sources in this application. A third point is that the above type of comparison can be used to provide a measure of the range of frequencies over which the DAMAS2 spectral measurements can be considered to be reliable. Together, these results provide a high level of confidence in the capability of the DAMAS2 algorithm for providing accurate aircraft subcomponent noise level spectra from flight test measurements.

4 CONCLUSIONS

This report has established the effectiveness of the DAMAS2 algorithm for determining aircraft noise subcomponent spectral levels and characterized the accuracy of the measurements for the application shown. First, the DAMAS2 subcomponent spectral levels were shown to be qualitatively correct through comparison with the expected behavior as inferred from the phased array beamform maps. The DAMAS2 spectra were then compared to sample output from the original DAMAS algorithm and were seen to be generally within 0.1 dB of the DAMAS algorithm spectral levels. Lastly, the shapes of the cumulative DAMAS2 spectral levels were compared with single microphone spectra and were seen to be in very good agreement. The DAMAS2 algorithm is seen to be an effective and accurate tool for flight test noise subcomponent spectral measurement.

REFERENCES

[1] Brooks, T. F., and Humphreys, W. M., Jr., "A Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) Determined from Phased Microphone Arrays," *Journal of Sound and Vibration*, Vol. 294, 2006, pp. 856-879.

[2] Dougherty, R. P., "Extensions of DAMAS and Benefits and Limitations of Deconvolution in Beamforming," AIAA Paper 2005-2961, 2005.

[3] Brusniak, L., Underbrink, J. R., and Stoker, R. W., "Acoustic Imaging of Aircraft Noise Sources Using Large Aperture Phased Arrays," AIAA Paper 2006-2715, 2006.

Copyright © 2008 The Boeing Company. All rights reserved.