

Sideglass Turbulence and Wind Noise Sources Measured with a High Resolution Surface Pressure Array

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ABSTRACT

The authors report on the design and application of a high resolution micro-electro-mechanical (MEMS) microphone array for automotive wind noise engineering. The array integrates both sensors and random access memory (RAM) chips on a flexible circuit board that eliminates high channel count wiring and allows the array to be deployed on automobile surfaces in a convenient "stick-on/peel-off" configuration.

These arrays have potential application to the quantitative evaluation of interior wind noise from measurements on a clay model in the wind tunnel, when used in conjunction with a body vibro-acoustic model. The array also provides a high resolution turbulence measurement tool, suitable for validation of computation fluid dynamics (CFD) simulations for wind noise.

The authors' report on the wavenumber-frequency structure of flow turbulence measured in different flow regions on a side glass and the corresponding contributions to interior wind noise.

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INTRODUCTION

It is now well documented [1],[2],[5],[8],[9] that automobile interior wind noise is transmitted from two low wavenumber aero-acoustic source components in the exterior wind pressure loading. The two components are convecting turbulence (unsteady, incompressible aero-dynamics) and propagating acoustic waves (compressible fluid dynamics). As shown schematically in Figure 1, the amplitude of these low wavenumber components (around $k_0 = \omega/c_0$, where c_0 is speed of sound) is typically a small percentage of the total fluctuating surface pressure, which is concentrated at the much higher turbulence convection wavenumber (around $k = \omega/U_c$, where U_c is convection velocity).

The vehicle body structural-acoustic system is a very strong spatial filter [2] that preferentially transmits these low wavenumber components. The glass vibration responds strongest at its resonant mode shape wavenumbers in the range $k \approx \pm \omega/c_B$ (where c_B is bending wave speed) and the interior acoustics responds strongest at its resonant mode shape wavenumbers, in the range $k \approx \pm \omega/c_0$

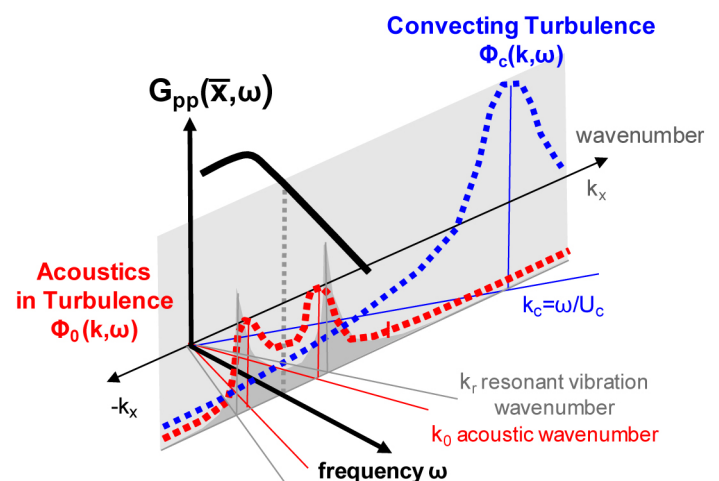


Figure 1. Streamwise wavenumber decomposition of a typical boundary layer surface pressure spectrum, showing both turbulence (blue) and acoustic components (red) at low wavenumber, with wavenumber content of a corresponding structural resonances (grey) superimposed.

If the power spectral density of these two separate surface pressure components can be quantified, it is possible to predict the interior wind noise transmitted by glass vibration [1],[6],[8] - and the wind noise transmitted by seals [10] - using a vibro-acoustic model.

DeJong [1] and Peng [5] describe semi-empirical approaches to estimating these aero and acoustic loads for a statistical energy analysis (SEA) wind noise model, from on-road testing and from wind tunnel testing. Bremner and Zhu [2] proposed the use of wavenumber analysis of an array of surface pressures, to more explicitly quantify both the low wavenumber pressure components and the corresponding spatial correlation coupling terms (modal joint acceptances) required by the vibro-acoustic model, to predict interior wind noise. Arguillat and Ricot [4] successfully built a pinhole microphone array on a rotating platform that enabled two-dimensional (2D) wavenumber analysis to quantitatively separate acoustics from convecting hydrodynamic pressure components, in the wind tunnel.

Subsequently, transient compressible CFD studies began producing some of the first credible wind noise surface pressure spectrum results for automobile configurations of interest [6],[7],[8],[9]. Moron and Powell [6] demonstrated that DeJong's semi-empirical approach to quantify acoustics in turbulence could be applied to Lattice Boltzman CFD results. They successfully applied a CFD-derived exterior acoustic source to an SEA model to correctly predict changes in interior wind noise corresponding to different side mirror configurations.

Since the CFD surface pressure simulations are generated on a fine scale spatial mesh of 1-3mm, it was also straightforward to apply the more explicit wavenumber analysis approach. The first step was to confirm that the CFD model correctly reproduced the spatial correlation characteristics of convecting turbulence observed in wind tunnel tests [8]. A number of researchers then successfully used wavenumber analysis to quantify acoustics in CFD turbulence results [7], [8]. Bremner has further demonstrated that acoustic loading which is wavenumber-filtered from CFD results can be used with an SEA model to predict interior noise [8],[14].

While the results of wavenumber analysis of CFD are encouraging, recurring instances of "artificial acoustics" in CFD numerical solutions [9] has generated renewed interest in high resolution array measurements in the wind tunnel that could validate the CFD models. A further motivation was the potential to directly measure the low wavenumber surface pressure loading that can be used in a vibro-acoustics model to predict interior wind noise, quite independent of CFD. For a new vehicle program, measuring low wavenumber loading on a clay model in an aeroacoustic wind tunnel to directly evaluate interior wind noise sensitivity to aerodynamic design changes (eg different mirrors) may be faster or more cost effective than multiple time accurate, compressible CFD simulations.

This paper summarizes progress in development of a high resolution surface pressure array configuration that is designed to facilitate *quantitative* interior wind noise design evaluation on a clay model in the wind tunnel.

REQUIREMENTS FOR WIND NOISE ARRAY

The essential performance requirements for a surface pressure array that could be integrated into the wind noise engineering process were defined as:

- i. Microphone sensing diameter small enough to measure convecting turbulence up to 6,000 Hz with less than 1dB spatial integration error (for validation of CFD results)
- ii. Microphone linearity up to at least 130 dB RMS SPL for wind noise at 90 mph (140 kph)
- iii. Microphones and data recording electronics must each have a signal-to-noise ratio of at least 65dB (to resolve small amplitude acoustics in turbulence)
- iv. Microphones should be closely spaced - preferably at 2.0 mm centers (but not more than 3.5 mm centers) - to minimize convecting turbulence "aliasing" into the acoustic wavenumber range up to 5,000 Hz at 90 mph
- v. Microphone-to-microphone gain and phase variation within an array must be small enough to ensure that RMS level of wavenumber-filtered acoustics is accurate within ± 1 dB
- vi. Array and all immediately adjacent data recording electronics and wiring must be very low aerodynamic profile and present a smooth surface to the flow to avoid package-induced perturbation to the boundary layer turbulence
- vii. Microphone array and direct-coupled electronics must be flexible enough to conform to the radius of curvature of the automotive body panel, to avoid local perturbation to the boundary layer turbulence
- viii. Array should preferably be packaged in a "Stick-on/Peel-off" configuration - ie. non-intrusive to the body surface - for efficiency of use in the production wind noise engineering process.

STICK-ON/PEEL-OFF ARRAY DESIGN

The authors have developed a novel Stick-on/Peel-off array design that meets these requirements. The commercially available ADMP621 MEMS microphone [12] widely used in mobile phones was selected to meet requirements i. - iii. The ADMP621 provides a pulse-density modulated (PDM) digital output. The very small microphone packaging shown in Figure 2 facilitates requirements iv. and vi.

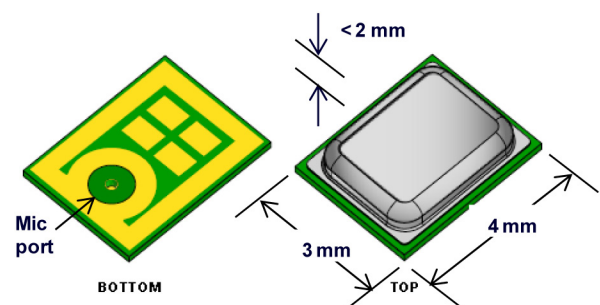


Figure 2. Packaging and dimensions for the ADMP621 MEMS microphone

Frequency Response

The frequency response of the ADMP621 MEMS microphone shown in Figure 3 below is not that of a Class I instrumentation grade microphone, but is quite adequate for the spatial correlation requirements of the wavenumber analysis array.

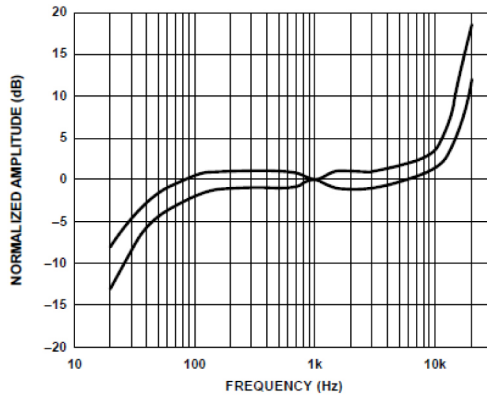


Figure 3. Frequency response tolerance mask for the ADMP621 MEMS microphone (from [12])

Dynamic Range

The full-scale digital output (0 dBFS) of the ADMP621 is mapped to an acoustic input of 140 dB SPL. The microphone clips (THD = 10%) at 133 dB SPL (see Figure 4); however, it continues to output an increasingly distorted signal above that point. The peak output level, which is controlled by the modulator, limits at about -3 dBFS.

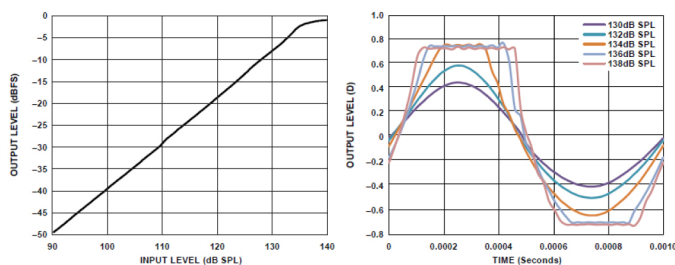


Figure 4. Linearity (left) and Clipping Characteristics (right) for the ADMP621 MEMS microphone (from [12])

To fully use the 111 dB digital dynamic range of the output data of the ADMP621 in a design, the digital signal processor (DSP), analog-to-digital converter (ADC), or codec circuit following it must be chosen carefully. The decimation filter that inputs the PDM signal from the ADMP621 must have a dynamic range sufficiently better than the dynamic range of the microphone so that the overall noise performance of the system is not degraded. If the decimation filter has a dynamic range of 10 dB better than the microphone (121 dB), the overall system noise only degrades by 0.4 dB.

Direct-Data-to-Memory Configuration

The MEMS microphone array design meets the low profile requirement vi., the conformable surface requirement vii., and the “stick-on / peel-off” requirement viii. with a direct-data-to-memory (DDTM) configuration which stores the PDM digital output from each microphone directly to digital random access memory (RAM)

chips, on a flexible printed circuit board (PCB). Locating the RAM chips immediately adjacent to the MEMS microphones means all array wiring is reduced to traces on the multi-layer PCB and a single USB connection to facilitate data download after each test.

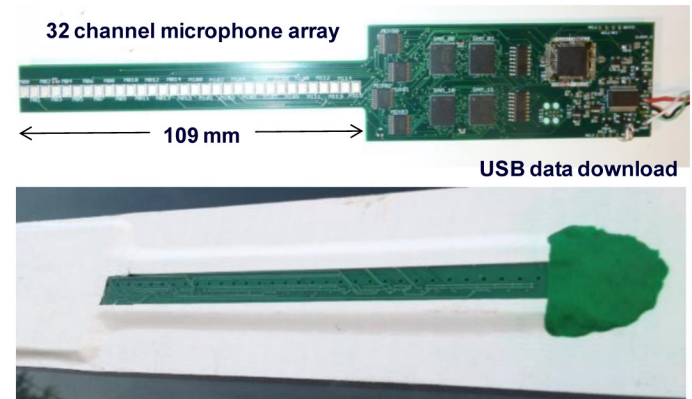


Figure 5. 32 channel MEMS array, direct-wired to digital memory on a flexible PCB (top), showing microphone ports exposed on measurement surface (bottom)

A prototype array has been designed, built and is currently being tested against these requirements. The prototype array uses thirty-two MEMS digital microphones shown in Figure 5 (top). The MEMS sensors are mounted on a flexible PCB substrate at uniform 3.5mm centers to form a simple line array.

The holes in the other side of the PCB (Figure 5, bottom) are the pressure measurement ports. The flexible PCB design tolerates bending of the array when it is taped to the doubly-curved glass surface, thus satisfying the conformal array requirement iv. above.

Appendix A of this paper summarizes the acoustic test procedures used to calibrate the wavenumber analysis function of the array.

ROAD TEST OF ARRAY

Fluctuating surface pressure data was acquired on the road at 80 mph with the array taped to the passenger side glass of a test automobile, as shown in Figure 6 (left). Measurements were taken at four different array locations, as shown in Figure 6 (right).



Figure 6. Stick-on/peel-off array applied to an automobile side glass (left) at four measurement locations (right)

The 32 digital outputs were recorded directly in RAM for an eight second sample period and subsequently downloaded to a host PC using the USB port. The MEMS PDM digital outputs were then converted to digital pressure time histories using a 24 KHz FIR filter.

Data Linearity Check

Fluctuating pressure histograms were generated for each of the 32 MEMS microphone signals to check linearity. With very few exceptions, the microphones stayed within their linear range at all four side glass measurement locations, with normal distributions of random pressure, as shown in Figure 7 (left). When the array was located directly behind the mirror (position not shown in Figure 6) the first ten MEMS microphones did experience some overloading, as indicated by the skewed histogram in Figure 7 (right). Array measurements directly behind the mirror have therefore been excluded from results presented in this paper.

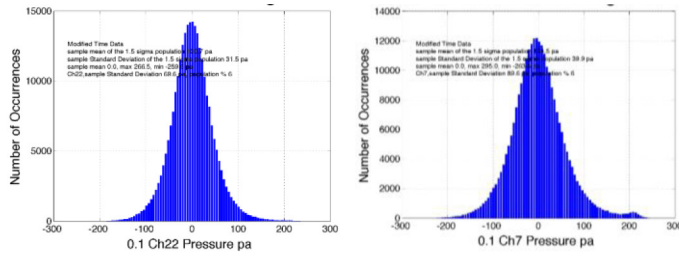


Figure 7. Fluctuating pressure histograms for typical MEMS microphones measured at 90 mph (left) and histogram for over-loaded microphone under highest intensity mirror wake pressure (right).

Microphone Self Noise

Frequency analysis of initial measurements contained unexpected high frequency components which scaled in amplitude with a high exponent of air speed. The source was deduced to be self noise due to flow interaction with the small microphone ports in the printed circuit board. The self noise was most pronounced at center glass locations - close to the re-attachment line of the A-pillar vortex - where some of the flow may impinge normal to the array surface.

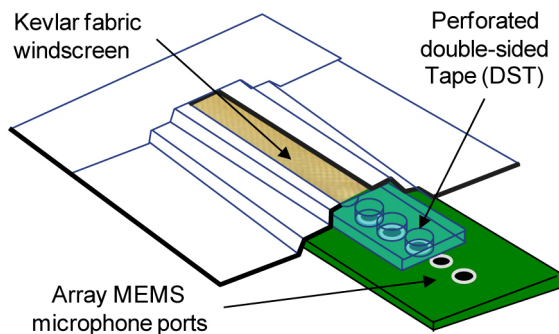


Figure 8. Application of kevlar fabric windscreen to the MEMS array, using perforated double-sided tape.

Following the experiments of Fleury et al [14] a Kevlar fabric windscreen - applied as shown in Figure 8 - was found to be effective at minimizing self noise, without significantly impacting microphone sensitivity. The reduction in self noise measured in center glass position 1 at 80 mph, is shown in Figure 9, below.

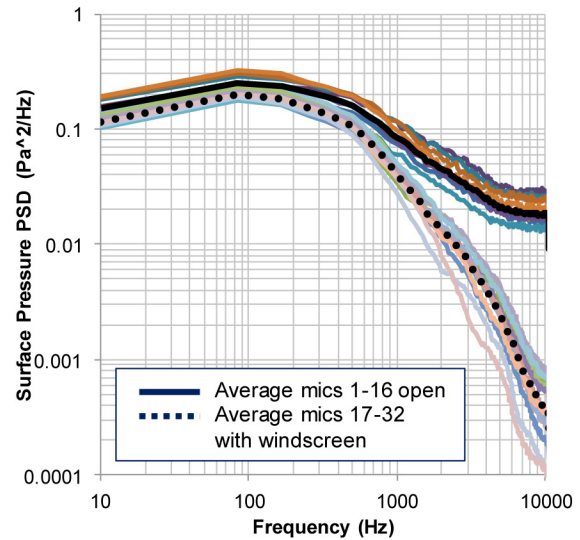


Figure 9. Surface pressure auto spectrum at center glass, showing reduction of self noise with application of Kevlar fabric windscreen.

Surface Pressure Autospectra

The resulting digital pressure time histories were Fourier transformed in time to provide the surface pressure auto power spectral density (PSD) spectrum for each microphone position x in the array $G_{pp}(x, \omega)$. The auto spectra in Figure 10 exhibit differences corresponding to the expected changes in flow over the side glass.

The highest levels are measured in the wake of the mirror (position 7) which exhibits some locally strong, periodic turbulence in the frequency range 150-250 Hz. At position 3, the mirror wake has dissipated and the auto spectrum transitions to an expected form [15],[16] for homogenous turbulent boundary layer (TBL) flow.

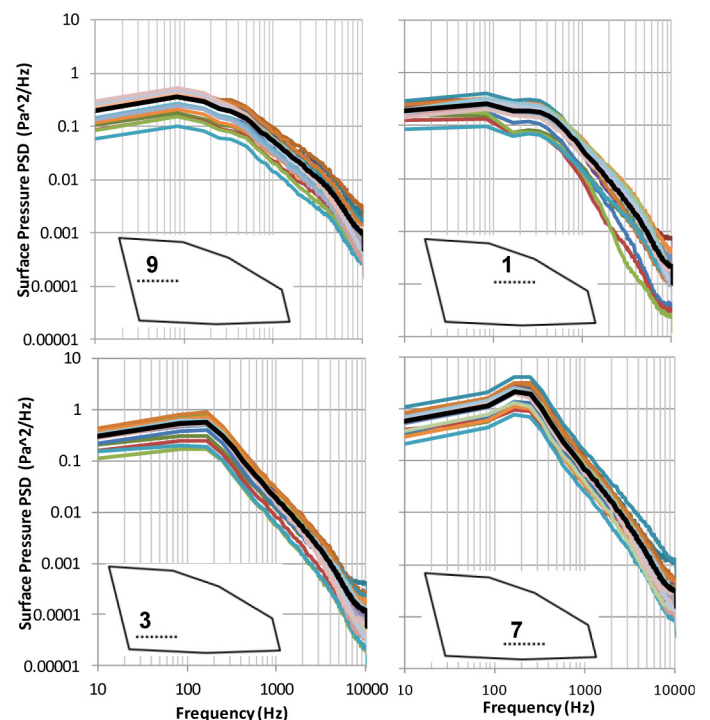


Figure 10. Array surface pressure PSD measured at four positions on side glass at 80mph, with mirror deployed.