Army Research Laboratory

Assessment of Operational Progress of NASA Langley Developed Windshield and Microphone for Infrasound

by W.C. Kirkpatrick Alberts, II, Stephen M. Tenney, and John M. Noble

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14. ABSTRACT

A recent National Aeronautics and Space Administration (NASA) effort to create a compact alternative to porous hose windscreens for infrasound applications resulted in the creation of spherical, closed-cell polyurethane foam windshields. Some researchers suggest that closed-cell foam windshields, at infrasound frequencies, sound should pass through the material of the foam to reach the enclosed microphone. This report details an U.S. Army Research Laboratory attempt to independently observe the experimental results reported in the literature and to evaluate compact, non-porous, spherical windshields for use in Department of Defense infrasound applications. Transfer functions between an instrument grade microphone and an infrasound microphone covered by eight different densities and thicknesses of spherical closed-cell foam windshields demonstrate at least a 30 dB decrease in sound level at the interior microphone across all of the frequencies studied regardless of foam density or thickness.

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Infrasound, windscreen, close-cell foam

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1. Introduction

Traditional windscreen technology for acoustic signals (above 20 Hz) has been based on a spherically-shaped, open-cell foam cover that is placed over the microphone. The intention is to cause the wind convection to lose speed in the foam, allowing the acoustic waveform to continue on to the microphone. For long wavelength infrasound signals, the open-cell foam windscreens would need to be very large, so the two most popular approaches are radial lengths of porous soaker hose dispersed on the ground or large grids of pipe arrays covering an equally large area. Both the porous hose and pipe array approaches cause the microphone to become an area sensor that spatially averages out the affect of the wind generated turbulence that causes acoustic noise that interferes with microphone performance (*1*). The closed-cell foam approach reported experimentally in Shams et al. (*2*) and theoretically in Zuckerwar (*3*) is unique in that it is a windshield that prevents wind turbulence from reaching the microphone.

The closed-cell polyurethane foam used in Shams et al. (*2*) had a density of 128.1 kg/m^3, which is commercially available as 8-lb/ft^3 foam. Polyurethane foams can be machined and cast. Table 1 shows various material properties of 8- and 18-lb/ft^3 (128.1- and 288.3-kg/m^3, respectively) foams for comparison (*4*).

Table 1. Closed-cell foam characteristics (*4*).

Foam Characteristics	"8 lb"	"18 lb"
Density (kg/m^3)	128.1	288.3
Parallel Compressive Strength[a] (MPa)	1.72	6.97
Parallel Tensile Strength (MPa)	1.73	5.50
Shear Strength[b] (MPa)	1.23	4.58
Flexural Strength[b] (MPa)	2.30	7.82

[a]Strength specified at 75 °F.
[b]Shear and flexural strengths measured with rise parallel to width and span, respectively.

From table 1, it is clear that these foams become quite strong at higher densities. Using material that have the strength of wood and that can be machined into microphone enclosures makes the closed-cell foam windshield approach to wind noise reduction more protective of deployed microphones than currently employed infrasound windscreen technologies. Further, closed-cell foam windshields allow infrasound sensors to behave as point sensors.

These windshields place a closed wall between the microphone and the sound source. In so doing, the windshields attenuate the sound reaching the microphone to a significant extent; although, recent literature suggests little attenuation for cylindrical nonporous windshields (*2*).

Based on the increased rigidity of the 288.3-kg/m^3 foam shown in table 1, it should produce greater acoustic attenuation than the 128.1-kg/m^3 foam. Also, the 288.3-kg/m^3 foam would provide more structural strength and would not require the same thickness for sufficient rigidity. These assertions imply that there is a tradeoff in thickness, strength, and acoustic attenuation.

A number of windshields in various densities from 128.1 to 480.6 kg/m^3 have been discussed, but no direct comparison of the effectiveness of these materials showing acoustic attenuation, wind noise reduction effectiveness, and structural strength has been offered. U.S. Army Research Laboratory (ARL) personnel witnessed comparative testing of spherical windshields fabricated from this material but did not see any quantitative review of performance. Given the performance from a typical 128.1-kg/m^3 foam windshield in a given wall thickness, the comparison of other densities of foam should be conducted across a variety of thicknesses. The question to be answered is: given the attenuation of a thickness of closed-cell foam, does the signal-to-noise ratio improve and how does the windshield reduce the measured wind noise? In order to fully analyze the performance of wind mitigation technology, a microphone with windshield should be collocated with a wind anemometer so that the wind speed and gusts can be correlated with noise on the microphone. This sort of analysis of wind noise reduction for windshield configuration was not apparently available from the National Aeronautics and Space Administration (NASA). This requires anechoic chamber testing of the microphone windshield assemblies in various thicknesses to establish attenuation values, before extended testing is done outdoors in a variety of wind environments and known signals to compare wind noise reduction versus available signal-to-noise.

NASA has developed an electret-based microphone that is presented as superior to the widely used microphone for infrasound from Chaparral Physics. Prototypes of this microphone have been fabricated for NASA by PCB Piezotronics, Inc. (PCB), and the microphone has a PCB part number (377M06) (*5*). Specifications presented relative to the Chaparral Physics (Chaparral) Model 25 suggest that the NASA microphone performs well. The sensitivity is about the same as the Chaparral, while the noise floor seems to be better and the power consumption is much lower. Current reports show that the power required for the NASA microphone is 90 mW, while the Chaparral requires 480 mW. During our visit it was apparent that NASA was still conducting development of the power conditioner/supply for the microphone attempting to reduce power even further. The goal is to reach about 50 mW through the use of a more efficient Direct Current-to-Direct Current (DC-to-DC) converter. There was discussion about a variety of engineering tasks being conducted relative to improvements or additions to the microphone. Of course, the quality of the power provided to the sensor will establish the noise floor of the output signal. Noise generated by a DC-to-DC converter can directly impact sensor performance. A publication from 2008 suggests that this microphone was in existence at that time (*6*). It appears that engineering changes are still being made to the existing microphone configuration. No actual price figures for the microphone have been made available nor has availability been predicted.

The next section describes the experimental configuration used to compare the windshields under laboratory conditions in an anechoic chamber. Section 3 presents results of the study and offers an analysis. The final section presents conclusions reached during the research.

2. Experimental Configuration

For the tests reported in this technical report, eight different windshields were compared, see table 2. In the eight windshields, there were four different densities: 12, 18, 20, and 30 lbs/ft^3 (these densities are the industry designation; their SI [International System of Units] equivalents are given in table 2). In table 2, each of the windshields has been labeled with a letter for brevity during the discussion of the experimental configuration and the results.

Table 2. Densities and thicknesses of foam windshields used during the experiments.

Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Density (kg/m^3)	192.2	288.3	288.3	320.4	320.4	320.4	480.6	480.6
Thickness (cm)	1.27	0.9525	1.27	0.635	0.9525	1.27	0.635	0.9525

Figures 1a through 1c show drawings of the experimental configuration used to investigate the effects of the various windshields. Figure 1a shows the relative position of the reference microphone, a Brüel and Kjær (B&K) 4193 with low-frequency adapter UC0211, and the PCB microphone, model 377M19, when investigating the response of the PCB relative to the B&K. Figure 1b depicts the position of the B&K relative to the PCB in preparation for installing the windshields and figure 1c shows a windshield installed over the PCB microphone. Figure 1d is a photograph of an uncovered PCB microphone in the housing to which the windscreens were attached. Shown in figure 1e is one of the windscreens, H, used in the experiments as it was mounted to the microphone housing in figure 1d. A 0.46-m loudspeaker was positioned in the corner of the anechoic chamber at a distance of approximately 2.7 m from the microphones, which were resting on the floor of the chamber. The speaker was broadcasting broadband pink noise generated by an ACO Pacific, Inc. model 3024 signal generator. Both microphone signals were recorded by a 24-bit National Instruments PCI-4472 data acquisition card at a sample rate of 1 kHz. The only filtering applied to the microphone signals was the internal anti-aliasing filters in the National Instruments board.

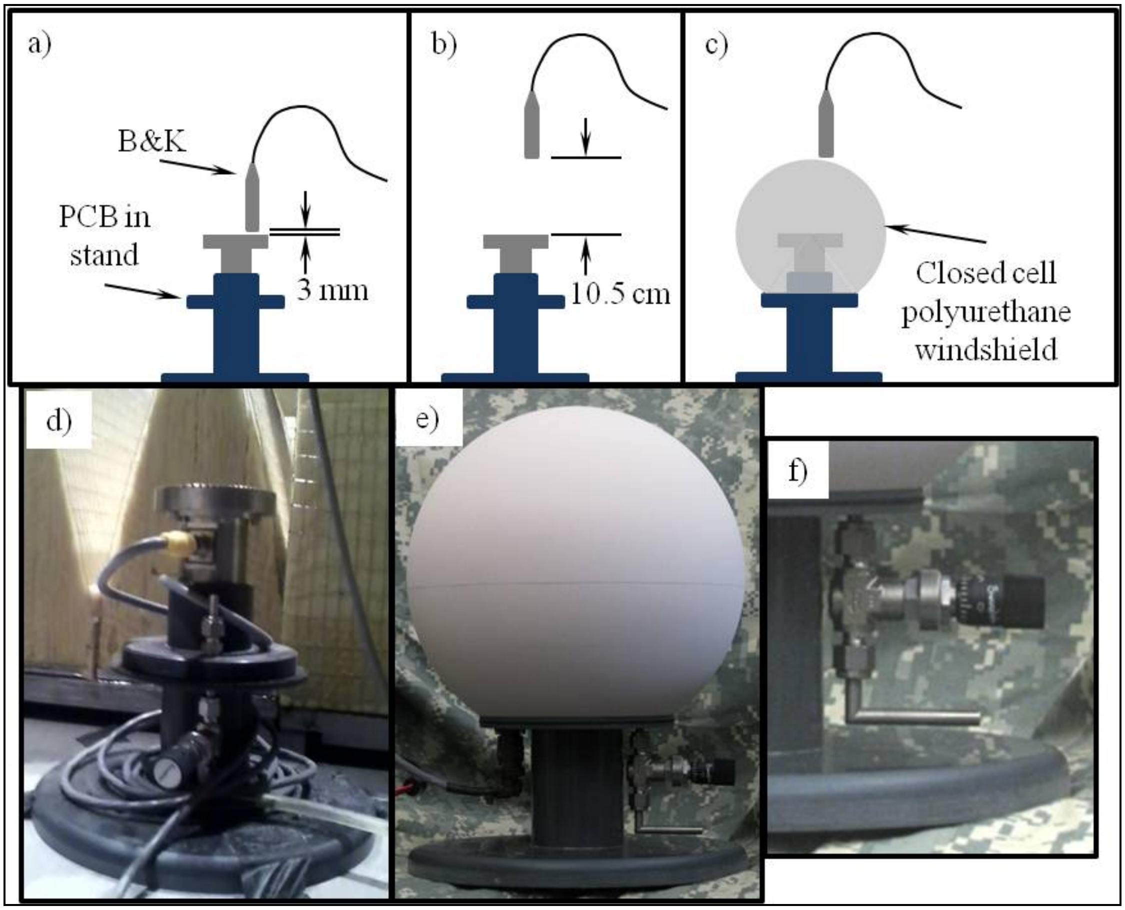

Figure 1. Relative positions of B&K and PCB microphones during experiments: B&K 3 mm from PCB (a), B&K 10.5 cm from PCB (b), and windshield installed between microphones (c). The windshield in the drawing is translucent to show the approximate position of the diaphragm inside the windshield. Parts d and e show photographs of the PCB housing without and with, respectively, a windshield installed. Part f is a zoomed image of the pressure equalization valve.

Throughout the experiments, the B&K microphone was used as the reference. Figures 2a and 2b show the magnitude and phase, respectively, of the frequency response of the PCB as compared to the B&K. The magnitude and phase shown in figures 2a and 2b were recorded with the face of the B&K microphone positioned 3 mm (blue) and 10.5 cm (green) above the face of the PCB with no windscreen present. Figure 2c depicts the coherence between the PCB and B&K microphones for each of the scenarios in figures 2a and 2b. Throughout most of the 0- to 250-Hz frequency range, the microphones are coherent with minor decreases in coherence at roughly 10, 155, and 240 Hz. Below approximately 1 Hz, the coherence between the two sensors decreases significantly so the minimum valid frequency of this study will be limited to 1 Hz. Small spectral deviations of the PCB from the B&K may be due to slightly decreased coherence, which may be an artifact of the chamber not being anechoic below 150 Hz. The plots in figure 2 demonstrate that the PCB and B&K microphones return nearly identical spectra until a frequency of approximately 100 Hz. The best agreement between the microphones occurs below 50 Hz.

Thus, subsequent discussions of the PCB and B&K transfer functions with windshields present will be restricted to a maximum frequency of 50 Hz. The transfer functions in figure 2 were created using a frequency resolution of 0.5 Hz with a 50% overlap which resulted in 19 averages per transfer function. The transfer functions were calculated by dividing the cross power spectral density of the two microphones by the power spectral density of the B&K. The cross-power spectral density is defined as

$$P_{xy}(\omega) = \sum_{m=-\infty}^{\infty} R_{xy}(m) e^{-i\omega m} \tag{1}$$

where $R_{xy}(m)$, the cross correlation, is the expected value of the signal x_{n+m} and the complex conjugate of the signal y_n for $-\infty<n<\infty$. The calculation of the transfer functions was done using the MATLAB,* Signal Processing Toolbox function "tfestimate" (*7*). This function returns a complex transfer function, from which the magnitude and phase are then calculated. This method was used for all transfer functions shown in this report.

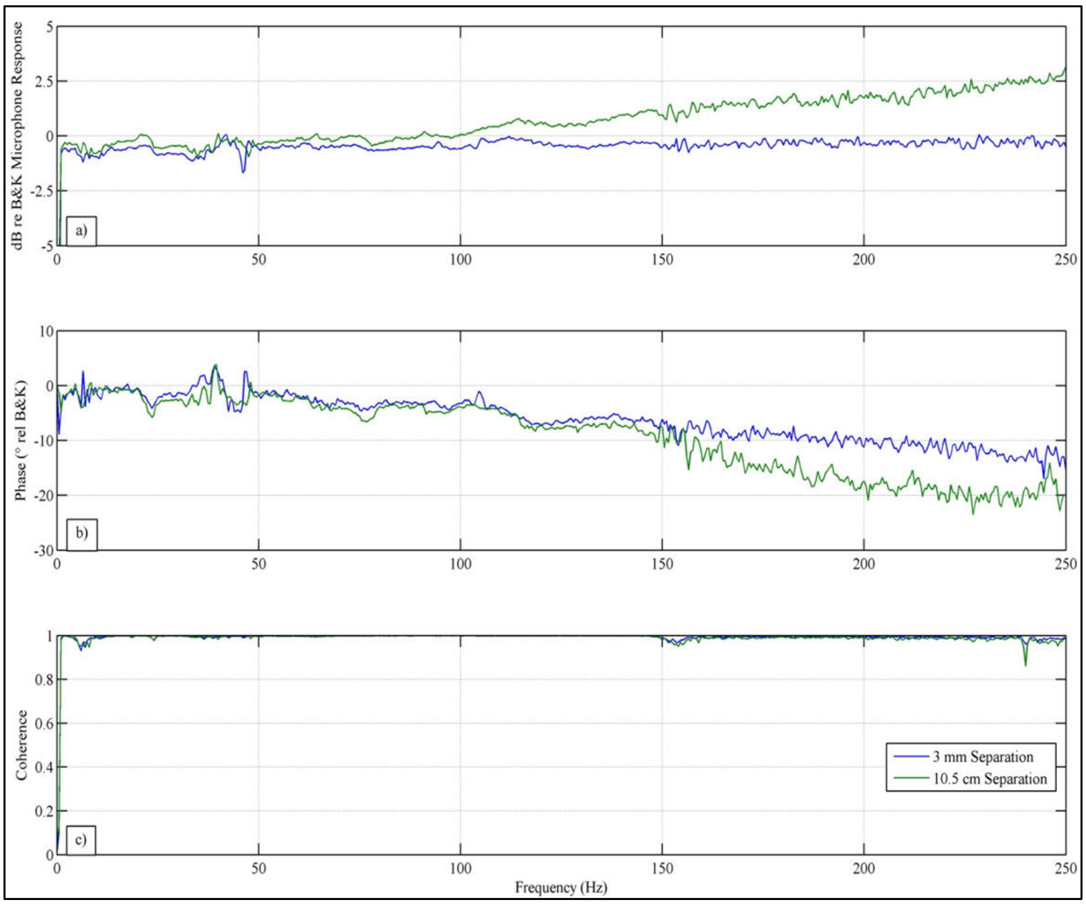

Figure 2. Magnitude (a) and phase (b) of the transfer function of the PCB relative to the B&K at 3-mm separation (blue) and at 10.5-cm separation (green). Also shown is the coherence (c) between the two microphones at the same separations.

* MATLAB is a registered trademark of The MathWorks, Inc.

Figure 1f is a close-up of a pressure relief valve attached to the chassis that supports the microphone and windshield. This relief valve consists of a short length of approximately 5-mm inner-diameter steel tube connected to a micrometer adjustable flow metering valve (Swagelok model SS-4L-MH), which is connected to the microphone housing by another short length of tubing. The purpose of this port is to equalize the internal pressure inside the windscreen with ambient atmospheric pressure. Equalizing the pressure eliminates adverse effects on the sensitivity of the microphone due to increased or decreased static pressures, relative to ambient, from diurnal heating/cooling of the windshield. Because the open pressure equalization port might act as the dominant acoustic path at low frequencies, each of the windshields was characterized with the port both open and closed. For windshield A, the valve was opened in steps of two full rotations of the valve knob to show the change in the transfer function between the PCB and the B&K due to the reduced resistance of acoustic propagation through the tube, see figure 4 and accompanying discussion. The valve was fully open after 12 full turns.

3. Results and Analysis

The magnitudes (a) and phases (b) of the transfer functions shown in figure 3 were taken with each of the windshields in table 2 installed on the PCB microphone housing. Above 20 Hz, the magnitudes of the transfer functions consistently show a decrease in interior sound level, relative to the B&K, from 30 to 60 dB across the frequency range shown regardless of windshield density or thickness. Below 20 Hz, however, the transfer functions shift up or down (this is most noticeable at frequencies below 5 Hz) depending on windshield density and thickness with the overall trend being shifts toward greater attenuation as the density and thickness increase. Above 5 Hz, all of the windshields show a greater than 20-dB attenuation of the sound level relative to the exterior of the windshield. Below 5 Hz, all of the transfer functions show an increase in the interior sound level. However, contrary to Shams et al. (*2*) and Zuckerwar (*3*), all but windshield G still show some attenuation. In all of the windshields, the passage of sound through the foam creates a significant change in phase relative to the B&K for all frequencies in the figure.

Figure 4 shows the magnitude of the transfer function (PCB spectrum divided by B&K spectrum) and the phase difference between the PCB and B&K microphones with windshield A installed. Also shown in figure 4 is the effect of incrementally opening the pressure relief valve, see figure 1e. As the valve is opened in steps of two turns, the magnitude of the transfer function, figure 4a, increases from less than 20 dB down relative to the B&K, at frequencies below 5 Hz that is equivalent to the no windshield case (solid blue line). Above 5 Hz, the magnitude of the fully open case decreases until it overlaps the magnitude of all of the other cases at roughly 40 Hz. As the valve is opened, the phase shown in figure 4b changes from an erratic, noisy behavior with the valve closed to a smooth curve transitioning from nearly in-phase with the B&K to roughly 150° lagging the B&K with the valve fully open (12 turns). The curves in figure 4 imply that as the valve is opened, it becomes the primary acoustic path at frequencies below 40 Hz.

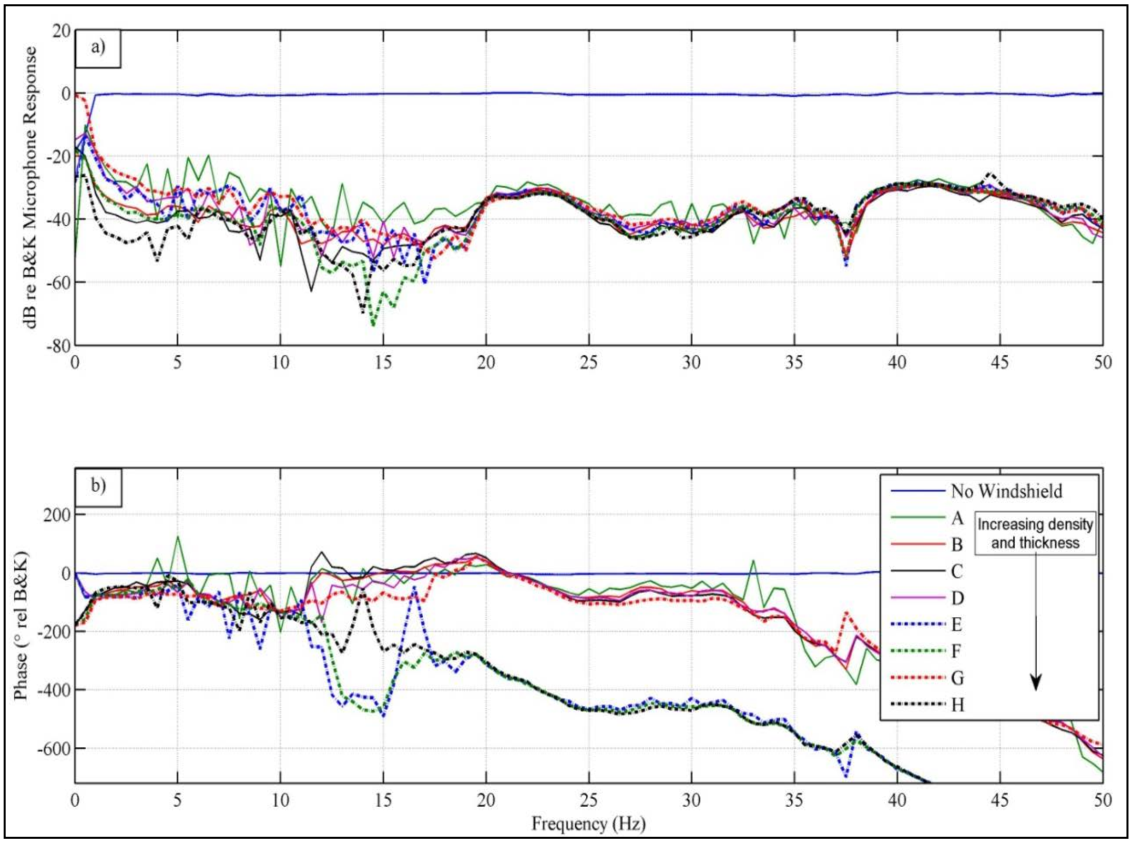

Figure 3. Magnitudes (a) and phases (b) of transfer functions between the PCB and B&K microphones with various windshields installed and pressure relief valve closed: no windshield (solid blue), A (solid green), B (solid red), C (solid black), D (solid magenta), E (broken blue), F (broken green), G (broken red), and H (broken black).

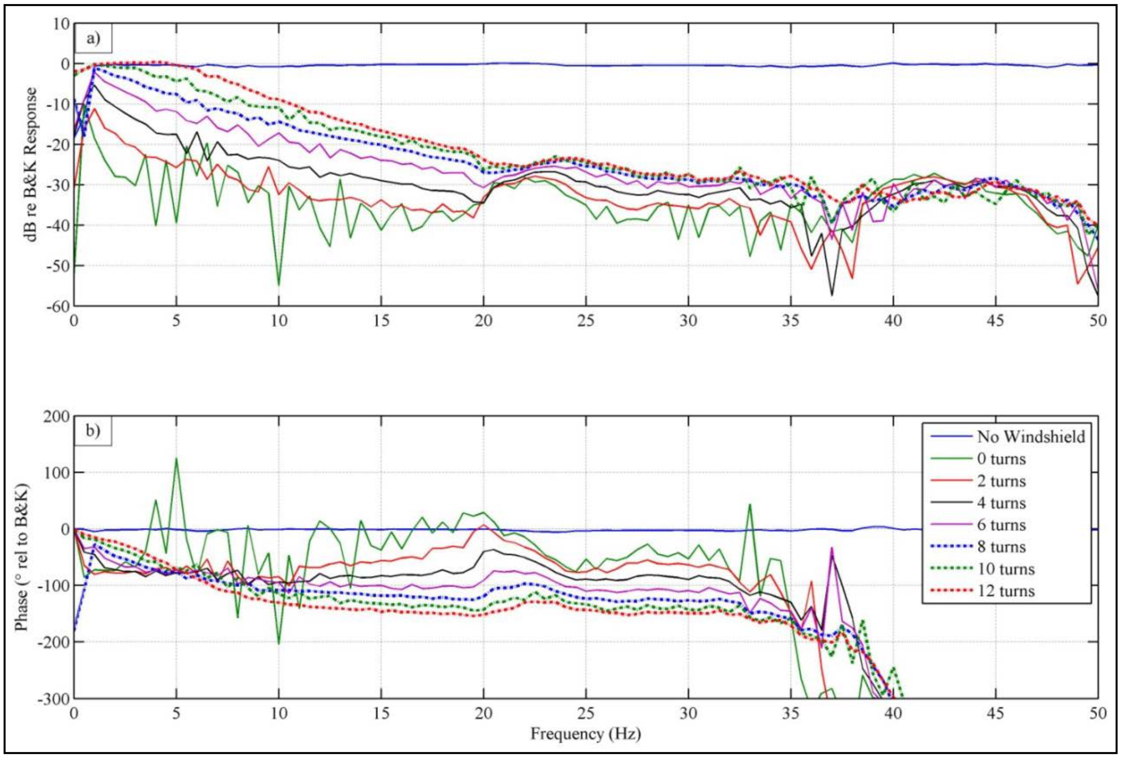

Figure 4. Magnitude (a) and phase (b) of the transfer function between the PCB microphone without (solid blue) and with windshield A for various turns of the relief valve: 0 (solid green), 2 (solid red), 4 (solid black), 6 (solid magenta), 8 (broken blue), 10 (broken green), and 12 turns (broken red).

Figure 5 shows magnitudes (a) and phases (b) of the transfer functions between the PCB and B&K with each of the remaining windshields installed. In figure 5, the valve was opened completely for each measurement. All of the curves, with windshield installed, in figures 5a and 5b, are nearly identical. Further, observation of the "12 turns" curves (broken red) in figures 4a and 4b with windshield A installed shows that they are similar to the magnitude and phase curves in figure 5. Since the magnitude and phase of the transfer functions between the PCB and the B&K are nearly the same for all densities and thickness of windshields, it can be concluded that the system consisting of the volume inside the windshield, the tube, and the open valve dominates the response of the PCB microphone when enclosed in a windshield with the pressure relief valve open.

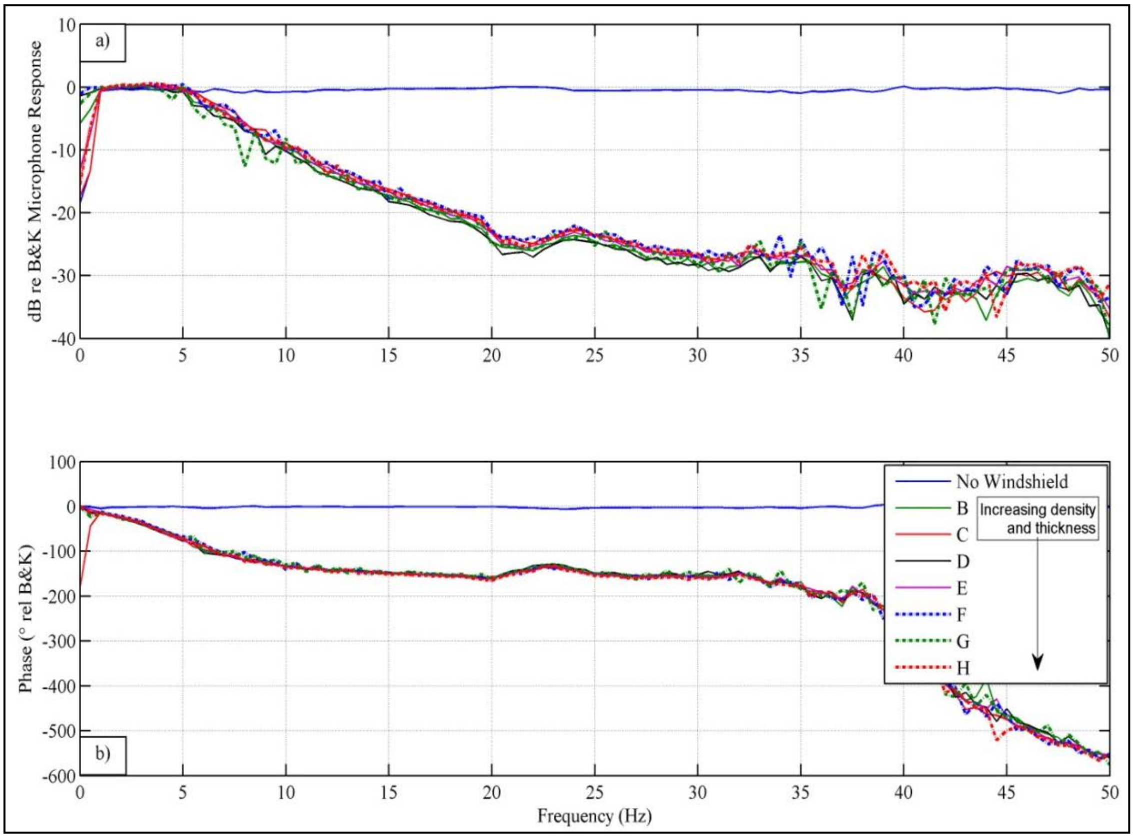

Figure 5. Magnitude (a) and phase (b) of the transfer functions between the PCB and B&K with various windshields installed: no windshield (solid blue), B (solid green), C (solid red), D (solid black), E (solid magenta), F (broken blue), G (broken green), and H (broken red), relief valve opened.

Because it is clear that some sort of pressure relief is necessary, an attempt was made to isolate the mouth of the pressure relief pipe by placing an approximately 9 m length of Tygon* tubing on the end of the pipe. This was done and a transfer function was taken with the tubing coiled next to the PCB housing inside the anechoic chamber. The transfer function was then repeated with the mouth of the tubing in the antechamber of the anechoic chamber and again with the mouth of the tubing in the hall. The results of these tests are shown in figure 6. In the magnitudes of the transfer functions shown in figure 6a, the addition of the tubing to the opened pressure relief system has the effect of reducing the influence of the valve and tube in all cases. With the tubing coiled inside the anechoic chamber, the transfer function consistently matches the closed-valve case after roughly 35 Hz. With the mouth of the tubing either outside the room or in the hall, the transfer functions become consistent with the closed-valve case after approximately 20 Hz. The phases of the transfer functions with the tubing installed are erratic but tend to reproduce the slope of the closed-valve case over most of the frequency range. The installation of the tubing appears to have removed some of the influence of the pressure relief

* Tygon is a registered trademark of Saint-Gobain Performance Plastics Corp.

system, but it has likely added a secondary complication in that sound appears to be entering through the wall of the tubing during both cases where the mouth of the tubing was external to the anechoic chamber.

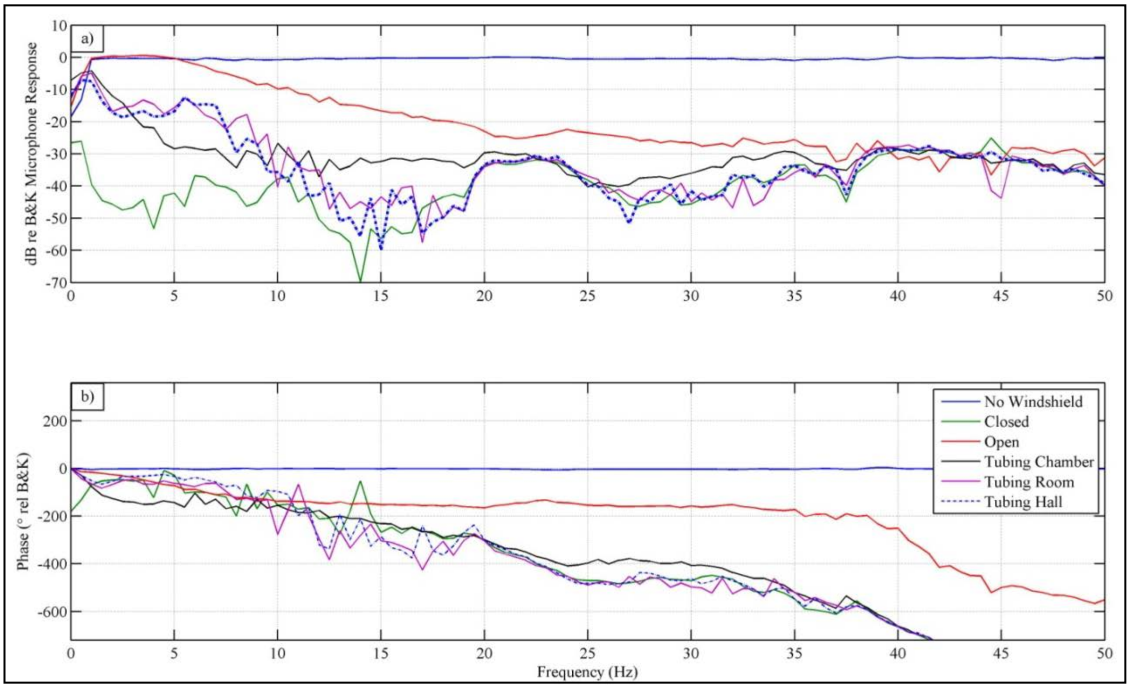

Figure 6. Magnitudes (a) and phases (b) of the transfer functions between the PCB and B&K with windshield H installed and Tygon tubing attached to pressure relief valve: no windshield (solid blue), valve closed with no tubing (solid green), valve open with no tubing (solid red), tubing coiled in chamber (solid black), tubing mouth in antechamber (solid magenta), tubing mouth in hall (broken blue).

Long-term tests of the stability of the microphone-windshield system under thermal variability and the effect of wind on the open pressure relief valve could not be studied for this report. In addition, variability in the magnitudes and phases of the transfer functions across windshields of the same density and thickness could not be investigated, the results of which would illuminate the potential degradation in array performance due to large windshield-induced phase differences across the elements in an array. Research regarding thermal stability and wind effects on the pressure relief valve will be conducted. Further research will also involve a study of the change in signal-to-noise ratio with and without the windshield under realistic conditions.

4. Conclusions

PCB and B&K microphone measurements of pink noise in an anechoic chamber have demonstrated that the PCB and B&K microphones are within 1 dB of each other at frequencies up to 250 Hz when the diaphragms are within 3 mm of one another and that the microphones are within 1 dB of each other up to 50 Hz when separated by 10.5 cm. Pink noise measurements with various spherical, closed-cell polyurethane windshields installed between the PCB and B&K microphones demonstrated attenuation of the acoustic signals reaching the enclosed PCB of greater than 20 dB. In addition, significant phase shifts from the external microphone have been shown for all of the windshields tested here. Opening of the pressure relief valve has shown that, as it is opened, the valve becomes the dominant acoustic path below 35 Hz with an accompanying large phase shift of the sound reaching the PCB. Efforts to restore the windshield as the dominant acoustic path to the PCB while retaining the pressure relieving capabilities of the valve were unsuccessful.

The overall conclusion is that the NASA-developed PCB microphone is a low-power, instrument-grade, microphone that appears to be equivalent in performance to conventional infrasound microphones, based on the limited testing performed for this report. The NASA developed windshield concept is a unique approach to reduce the sensor footprint that might offer the potential to place an infrasonic microphone on an aerostat at altitude to get it above low level winds and ground impedance, which would be a new capability. However, the extremely large reduction in signal levels reaching the enclosed microphone would significantly reduce the detection range of infrasonic sources. Based on this information, the closed-cell foam windshield technology, subsequent to the results reported in this report, does not perform well enough to be a replacement for currently utilized porous hose windscreens given the operational requirements of deployed infrasound listening arrays.

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