Development of a weatherproof windscreen for a microphone array

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This paper presents the development of a windscreen used on an array of five microphones located around a 0.1143-meter (4.5-inch) cylinder. The design criteria consisted of having a wind noise attenuation of at least 8 dB at 20.9 km/h (13 mph), an insertion loss of less than 1 dB from 50 to 1000 Hz, a phase shift error between each microphone of less than 3% over the same frequency range, and the ability to protect the array from natural elements such as sand and other debris. Computer simulations and experimental testing were employed to select two basic designs. The first design consists of two foam-filled concentric cones set around the microphone array. The second design consists of tubes that project outward from each microphone and then curve downwards. Both final windscreen designs meet the desired requirements. They both reduce wind noise by approximately 9 dB in a 20.9 km/h (13 mph) wind and over 16 dB in a 32.2 km/h (20 mph) wind. They also have negligible insertion loss, have a phase shift error of less than 3%, and are very efficient at blocking particles from entering the windscreen. **© *Institute of Noise Control Engineering***

Primary subject classification 31, Secondary subject classification 34

1 INTRODUCTION

Microphones are used to measure the acoustic pressure field in many different applications and settings. When a microphone is placed in an environment where wind is present, the ability of the microphone to measure the acoustic pressure field can be significantly degraded. Wind typically induces noise in the microphone measurement by a combination of three processes. First, because wind is not a steady state condition, the fluctuations in the wind velocity cause low-frequency pressure fluctuations at the microphone diaphragm (turbulence in the free stream). Second, as the wind blows over the diaphragm and microphone casing, it creates a more turbulent flow, which also induces pressure fluctuations at the diaphragm. Third, as the wind passes around other objects, pressure waves can be created, (flow separation), which are then picked up by the microphone as sound.[1,2]

Although there are many different types of windscreens, they can typically be grouped as either basket or foam types. Historically, the first type of windscreen to be used was the basket windscreen.[1] It is made by completely enclosing a microphone with an acoustically transparent material, such as silk or fine-mesh cotton, which presents a large resistance to the wind. Because the basket is larger than the microphone, it creates greater turbulence in the air than an unshielded microphone, but the turbulence is located farther away from the diaphragm, thus lowering the wind noise.[3] A common type of basket windscreen is made by surrounding the microphone with a wire mesh. These wire mesh windscreens are not as effective as other basket windscreens at reducing wind noise because they are smaller and they do not add as great a resistance to the wind velocity. As a result, foam is normally added inside the wire mesh for greater wind noise attenuation. This type of windscreen inherently induces an area averaging effect as well. Larger basket windscreens made from silk or other light materials are better at attenuating wind, but because of their fragility, size, and cost, they are only used when wind attenuation is paramount and cost is not an issue. One such application is outdoor film production.

Today, the most widely used windscreen is made by surrounding a microphone with a streamlined porous solid made of reticulated open cell polyurethane foam. This is because of the foam's relative acoustic transparency and ability to impede the air flow. Foam can either be placed directly around a microphone diaphragm or placed so there is an air gap between the foam and the diaphragm. An air gap will increase the attenuation of the windscreen, but also requires a larger overall windscreen volume. Advantages of using a foam windscreen are that the wake caused by the windscreen is reduced,[4] the foam does not need any external support, and the windscreen is very resilient. One disadvantage associated with foam windscreens is that they tend to attenuate higher frequency signals, e.g., those approaching 20 kHz or higher.[5] Other disadvantages are that the foam breaks down under ultraviolet (UV) light (a lifetime of less than one year under ordinary weather conditions is standard),[6] water can clog the pores, and small particles (dirt or sand) can become trapped and drastically increase the insertion loss of the windscreen.

Other materials have been used to make windscreens, including fur and synthetic fibers. Fur creates very little noise as air passes through it and reduces wind noise very effectively. However, fur is much more expensive than foam. Additionally, work has been done on protecting microphones from rain by covering them with a rubber[7] or a spandex[8] membrane. Unfortunately, this work has had only limited success because

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the membrane degrades the frequency response of the microphone/windscreen combination.

Multi-stage windscreens are another type of windscreen used when wind noise must be reduced drastically. These combine multiple layers of windscreens in order to increase wind attenuation. For example, a multi-stage windscreen might consist of an inner core of foam, followed by an air gap, then another layer of foam or wire mesh. While multi-layer windscreens do reduce the wind-induced noise, they are usually more expensive, can be more fragile, and may have a higher insertion loss than single-stage windscreens.

The objective of most windscreens is to reduce the mean flow velocity and turbulence at the microphone diaphragm.[8] As the mean flow velocity and turbulence are lowered, so is the wind noise picked up by the microphone. Typically, a windscreen should have a small or negligible insertion loss while attenuating as much of the wind velocity noise as possible. Currently, commercial foam windscreens have insertion loss values of 0.1 to 0.6 dB and provide between 15 to 25 dB of wind noise attenuation for winds of up to 48.3 km/h (30 mph).[9]

Current windscreen designs have focused almost exclusively on reducing wind noise and minimizing insertion loss. Under short term or indoor operating conditions, these are the only two significant criteria. However, under other conditions, additional criteria may become important. For example, microphones used permanently in outdoor settings must be protected not only from the wind, but also from other natural elements, such as moisture, sand, and other small particles so that the microphone is not damaged and the acoustical properties are maintained. Maintaining the proper magnitude and phase between each microphone is another design constraint when dealing with windscreens used for microphone arrays. In this work, it was desired to maintain an insertion loss of less than 1 dB and a phase shift error of less than 3% over the range of 50 to 1,000 Hz.

The objective of this research was to design a windscreen that meets the design constraints summarized in Table 1. There are no fixed size constraints on the design except that the windscreen must fit over the 0.1143-meter (4.5-inch) microphone array. In order to achieve these design criteria, a number of design steps were followed. First, computer simulations, explained in section 2.1, were developed in the computational fluid dynamics (CFD) software package, FLUENT.[10] Using these simulations, a velocity field was created to simulate wind around the windscreen and particles were added to the simulation to act as dirt or sand particles. The windscreen was placed in these simulations to understand how it would perform given a variety of wind speeds and particle sizes. Using this computer model, a general geometry of the windscreen was determined.

Table 1- Windscreen design constraints

1. Have a wind noise attenuation of at least 8 dB in a 20.9 km/h (13 mph) horizontal wind
2. Protect an array of five microphones from sand and dirt particles
3. Have an insertion loss of no more than 1 dB from 50 to 1000 Hz
4. Maintain the phase shift between each microphone within 3% from 50 to 1000 Hz
5. No real size constraints except to fit over the 0.1143-meter (4.5-inch microphone array and be practical)

After two basic windscreen designs were chosen, they were optimized using factorial experiments as explained in Sec. 2.2. The results of these tests are given in Secs. 3.1 and 3.2, along with the optimal windscreen geometry. Section 4 gives a comparison between each windscreen and a commercial foam windscreen. In this paper, only a horizontal wind direction perpendicular to the axis of the microphone array was considered.

2 COMPUTATIONAL AND EXPERIMENTAL METHODS

2.1 Computer Simulation

In order to evaluate multiple windscreen designs quickly, a CFD package was used. FLUENT was chosen as the CFD package because of its ability to model velocity fields, pressure fields, and free particles. Using a CAD package, different windscreen designs were modeled and imported into FLUENT. Wind was simulated by forming a velocity flow around the windscreen. While the CFD models were not used to predict the actual wind noise attenuation of a given windscreen, they were used to give an indication of how well a particular design reduced the mean flow velocity at the microphone diaphragms. In this same velocity field, particles were inserted to see how well the windscreen would protect the microphones from flowing particles. For each of these tests, the particles were modeled with a density of 1500 kg/m^3 and a diameter ranging from 0.02 to 2 mm. FLUENT uses a lumped-element model to simulate airflow, and therefore does not exactly model intrinsic turbulence in the air. As a result, FLUENT shows that a particle either always or never enters the windscreen. Consequently, FLUENT cannot be used to predict the number of particles that will enter the windscreen, but can be used to determine the effectiveness of a specific geometric configuration. For this reason, any time a particle enters the windscreen in these simulations, it is considered unacceptable.

Using this approach, two different windscreen designs for the microphone array were chosen, and were optimized through experimental testing. The first design, hereafter called the cone windscreen, is composed of two concentric aluminum cones surrounding an array of five microphones, as shown in Fig. 1. The five microphones face outward on the outside surface of a cylinder. The two cones then slide over the cylinder and are vertically offset in order to create an air passage for sound waves to reach the microphones. The slant of the cones force impinging particles approaching from the horizontal direction downward, away from the foam and microphones. In Fig. 1, h is defined as the overlap, w is the gap, and θ is the cone angle. A 3-D view of the windscreen is illustrated in Fig. 2. Dividers were added between microphones to decrease the phase shift error between microphones. Because the foam is enclosed

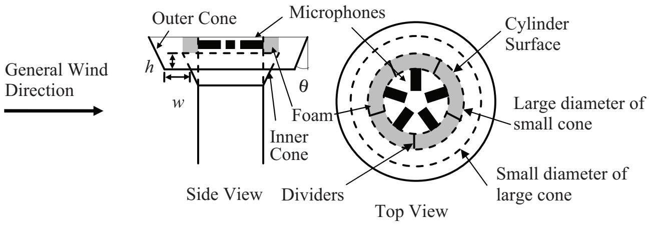

Fig. 1. 2-D side and top view of conical windscreen

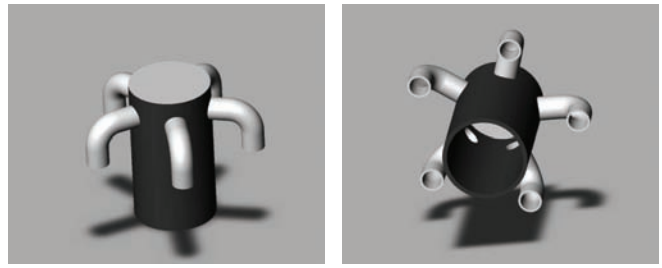

Fig. 3. 3-D images of the spider windscreen design

by the cones and is not subject to direct UV light, it should have a much longer lifetime than a regular foam windscreen. The lower cone was left empty for the results presented in this paper. This allows any particles or moisture to exit the bottom of the windscreen if they do enter.

The second windscreen design, hereafter called the spider windscreen, consists of tubes rigidly attached to the cylinder directly around each microphone. The tubes project outward from each microphone and curve downward, as shown in Fig. 3. Each tube is then filled with open-cell foam to increase the wind noise attenuation. In addition, the end of each tube is covered with Gor-Tex® to increase wind noise attenuation and lower the amount of sand particles that enter the windscreen. This design effectively creates individual, tubular windscreens for each microphone. The four variables of interest are *g*, the tube gap at the entrance of the tube, *L*, the vertical length of the tubes, *D*, the tube diameter, and *w*, the distance the tube protrudes from the cylinder. These four variables are shown in Fig. 4.

Computer simulation can be used to model the insertion loss and phase shift of the microphone windscreen, but it is very computationally intensive. For this reason, computer simulations were not employed for such tests; experimental testing was performed instead.

2.2 Experimental Setup

Two different sets of experimental tests were carried out on each of the two configurations. First, using a 2^4 factorial experiment, the significant variables were found. A factorial experiment is able to predict optimal values for each variable in a system, while reducing the number of tests that must be performed.[11] Three values of each variable are used: a high, a low, and a center value. Each variable is tested at a high and low value which produces 2^k runs (k = number of variables). Experiments at the center point of each variable are performed to find any curvature in the model. Therefore, this requires $(2^k + 1)$ runs Using statistical relationships, each variable is rated for its effect on the overall system. Some variables are statistically insignificant and can be ignored, while others have a greater impact on the final results. (For additional discussion on statistical testing, see Ref. 11.) Using the results from the factorial tests, a final windscreen prototype for each design was built which met all the design criteria. These final prototypes were then tested to ensure compliance with the stated design criteria.

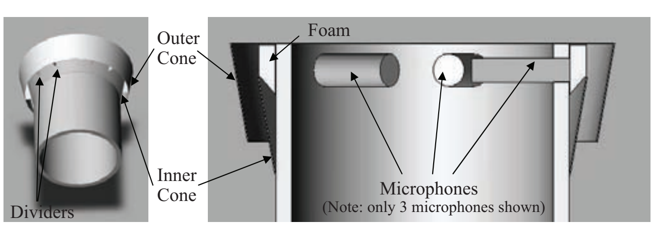

Fig. 2. 3-D CAD drawings of cone windscreen design

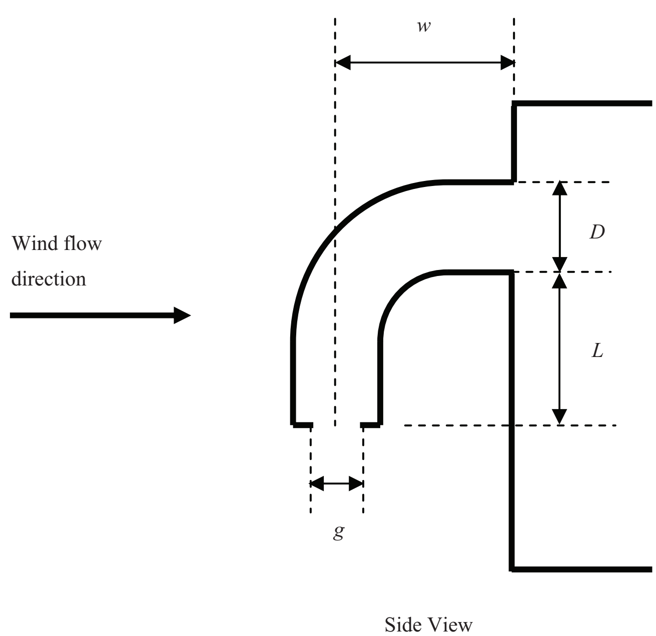

Fig. 4. 2-D view of a portion of the spider windscreen showing the definitions of the design variables

For factorial testing, Larson Davis[12] microphones comprised of half-inch diameter prepolarized free-field transduction elements (Model 2551) and PRM426 ICP® preamplifiers were used. To test the final prototype windscreens, new one-inch diameter microphones (Model 377M03) were made available by PCB Piezotronics.[13] These microphones were designed specifically for this application and their assembly with the preamplifier resulted in a 2.54 cm (D) x 2.54 cm (L) form factor. This allows all five microphones to be set in a compact cylinder at 72° increments, as shown in Fig. 5.

To measure wind noise attenuation, wind was created at two speeds using two different fans. The array was placed in the velocity flow to measure the wind noise. The wind noise attenuation was computed as the average difference between the signals measured with and without the windscreen over a given frequency range. In this research, for the wind noise attenuation measurements, the average sound pressure level (in dB) was measured over a frequency range of 0 to 100 Hz. This range of frequencies was chosen because it has been shown elsewhere that on average, 95% of the energy of wind-induced noise is located below 30 Hz.[14] Therefore, 0 to 100 Hz will capture most, if not all of the wind-induced energy. Testing was performed in an anechoic chamber to minimize the ambient noise of the measurement and to minimize the adverse effects of reflected sound waves. The chamber is anechoic for frequencies above approximately 70 Hz.

One of the primary purposes of this research was to design a windscreen that would protect an array of microphones from sand and dirt particles in the air. In order to test the effectiveness of the windscreen, an experimental apparatus was built that allowed for the insertion of sand into a horizontal stream of high-velocity air, as shown in Fig. 6. After a predetermined time, the amount of sand that entered the windscreen was measured, and compared to the amount of sand that entered a foam windscreen in the same amount of time. A 0.61 m x 0.61 m x 0.91 m (2 ft x 2 ft x 3 ft) box was constructed from wood, with an open top. During testing, the top was covered by foam to minimize the amount of sand that escaped from the box. The sand was poured into a funnel through a control valve which allowed the particles to enter the air stream. During the 4-minute test, 0.9 kg of sand was poured into the high velocity air stream of approximately 80 km/h. The amount of sand that entered the windscreen was measured by weighing the windscreen on a scale with a precision of 0.1 grams before and after sand was blown. The difference between the two measurements was the amount of sand that entered and remained in the windscreen. Optimally, there would not be any sand present in the windscreen after the test.

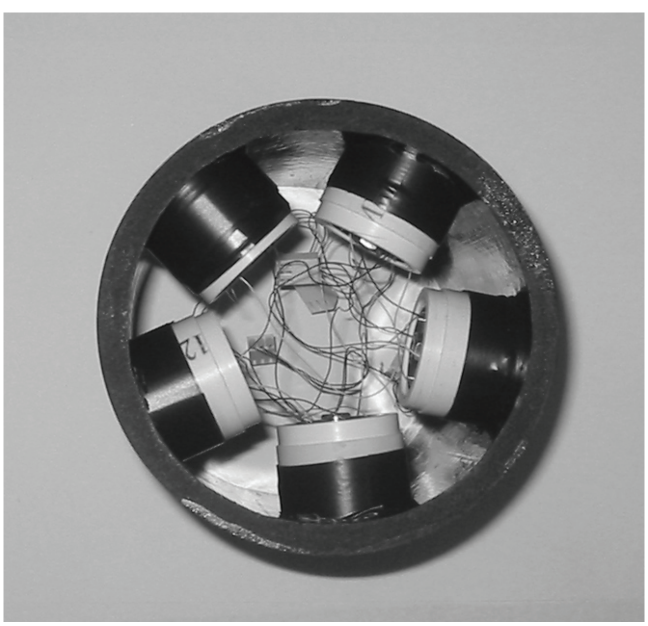

Fig. 5. Placement for five PCB 1 inch diameter microphones

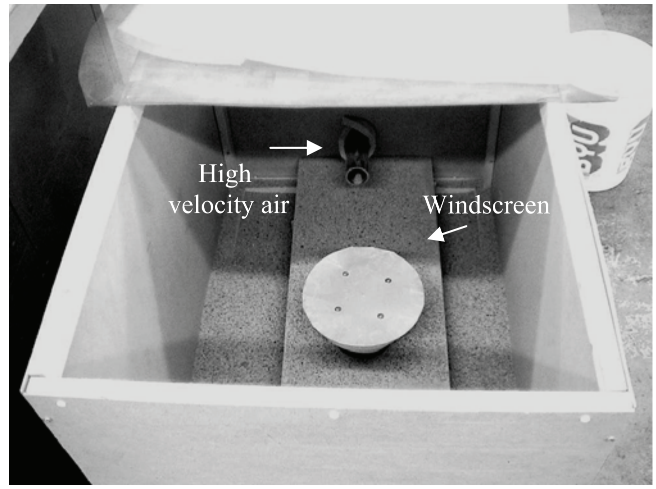

Fig. 6. Sand blaster for testing windscreens in a particle flow

The insertion loss was tested by placing the microphone arrangement in the far field of a loudspeaker in an anechoic chamber. The loudspeaker was located in the same horizontal plane as the microphone array. The amplitude of the output signal with the given input was measured at the microphone with the windscreen and was compared to the amplitude measured at the microphone without a windscreen. A function generator was used to produce the noise, sending a 2 volt peak-to-peak sine wave to the speaker. This was done for frequencies ranging from 0 to 10,000 Hz in increments of 50 Hz. The insertion loss testing was performed over a much larger frequency range than the wind noise attenuation testing to see the effect at higher frequencies. The microphone cylinder was rotated in the horizontal plane and the insertion loss was measured for each rotational position. This ensured that the location of the microphone on the cylinder did not change the insertion loss.

The same apparatus used for the insertion loss testing was also utilized to determine the phase response of the microphones in situ. Two different experiments were performed to determine the phase response. First, for the windscreens used for factorial testing, two microphones were located inside the cylinder, and the outputs of both were recorded simultaneously as a known sine input was played over the source speaker. The phase difference between each microphone and a given input was calculated with a windscreen, and compared to the same measurement without a windscreen. The percent difference between the two was recorded. For the final testing, all five microphones were used. The entire 5-microphone array was rotated and the phase difference measurements were taken in increments of 10°. Eight measurement positions were made for a total rotation of 70°. Using the 70° rotations for the 5-microphone array a 360° plot was generated with the phase difference from each of the microphones for the entire windscreen. This testing was performed at 10 frequencies from 0 to 100 Hz.

Each of these four tests was performed at least 4 times for each windscreen configuration. Statistical analysis was performed to determine which factors were significant and to ensure that the recorded values were consistent.

2.3 Data Acquisition

The data acquisition system used for the wind noise attenuation, insertion loss, and phase measurements consisted of a Data Physics DP620 dynamic signal analyzer. A Hanning window was used and exponential averaging, with 10 repetitions. Wind speeds were measured by placing a Kestrel 1000 wind meter in front of the windscreen at the position of the microphone.

3 RESULTS

3.1 Cone Windscreen Results

For the cone windscreens, the 17 factorial tests (2^4 plus 1 center value) resulted in wind noise attenuation values between -3 dB and 9 dB, particle entrapment between 0.5 and 52.3 grams of sand, insertion loss of less than 1 dB for all windscreens, and phase shift error between 0 and 120%. As can be seen from these results, some windscreen configurations performed very well, while others were much worse than expected. Through this factorial testing, the final cone windscreen geometry was found, as indicated by the parameters in Table 2. A prototype was built using these values, and each test was performed again to ensure that all design criteria were satisfied.

Table 2 - Optimal conical configuration values

	Optimal
Angle θ	10°
Overlap h	3.81 cm
Gap w	0.79 cm
Foam Thickness	1.27 cm

Figure 7 shows the wind noise attenuation of the final cone windscreen, compared to the microphone array without a windscreen at 20.9 km/h (13 mph). As shown, although there are some dominant frequency peaks caused by the fan, there is still an obvious wind noise attenuation of about 9.1 dB, which is higher than the required design value. At 32.2 km/h (20 mph), the wind noise attenuation was 16.7 dB, as shown in Fig. 8. Similar to commercial windscreens, the trend of higher attenuation vs. higher wind speed is expected to continue for even higher speeds.[9] Two different fans were used to produce the two wind speeds in Figs. 7 and 8. That is why tonals due to the blade pass frequency appear in Fig. 7 and not in Fig. 8.

Sand particle entrapment was measured for the cone windscreen and also for a foam windscreen custom made in the lab having a thickness of 3.81 cm (1.5 in). The cone windscreen entrapped 0.1 grams of sand over a 4-minute period, while the foam windscreen entrapped 38.5 grams. This indicates a reduction of over 99% of sand entrapment in the cone windscreen for this test setup.

Insertion loss testing was done at frequencies ranging from 0 to 10,000 Hz in increments of 50 Hz. The data show that there is negligible insertion loss for the cone windscreen up to 2,000 Hz. The cone windscreen is nearly identical to the foam windscreen previously detailed until 1000 Hz, at which point it rolls off faster than does the foam windscreen. The average difference between 3.81 cm (1.5 in) of foam and the cone windscreen from 0 to 1,000 Hz is 0.15 dB, and is statistically insignificant. The average insertion loss under 1,000 Hz is less than 0.4 dB, which satisfies the insertion loss design constraint. Also, because this technology will only be applied at frequencies less than 1,000 Hz, the high-frequency

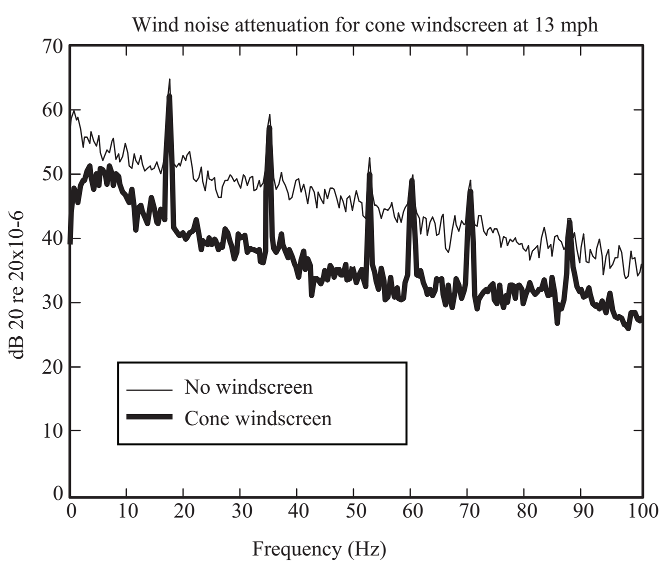

Fig. 7. Wind noise attenuation for the final conical windscreen at 20.9 km/h (13 mph)

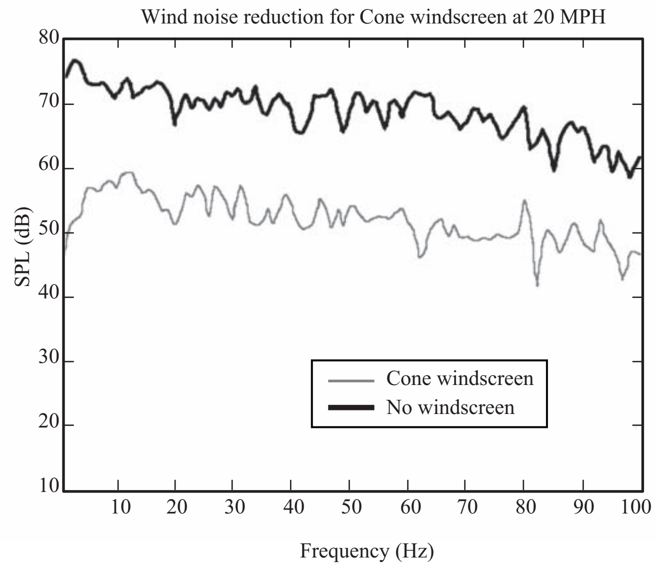

Fig. 8. Wind noise attenuation for the final conical windscreen at 32.2 km/h (20 mph)

roll-off is not considered an issue for concern. A plot of the insertion loss on a scale from 100 Hz to 10,000 Hz for various windscreens is shown in Fig. 9.

Using the five microphones, 360° phase error plots were constructed. In Fig. 10, an example of a typical phase plot illustrating the phase shift error between the microphone array with and without the cone windscreen at 50 Hz is shown. For all frequencies tested, the sound source was located at 0°, and as illustrated, all errors were less than 3%. Table 3 shows the results from these four tests compared to the results found for a 3.81 cm (1.5 in) foam windscreen.

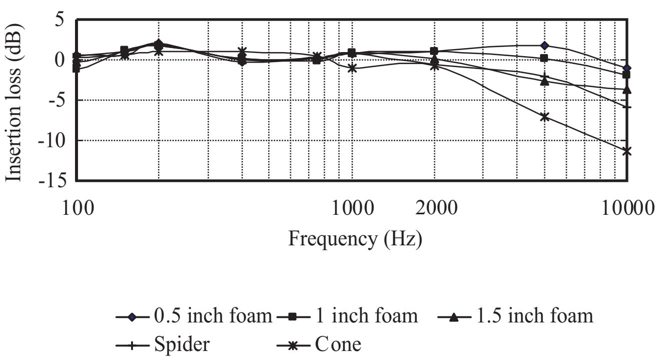

Fig. 9. Insertion loss plot for various windscreen designs

Table 3 - Optimal cone windscreen final results

	Cone	3.81 cm foam
Wind noise attenuation 20.9 km/h (13 mph)	9.1 dB	8.1 dB
Wind noise attenuation 32.2 km/h (20 mph)	16.7 dB	15.0 dB
Insertion Loss	< 0.4 dB	< 0.4 dB
Sand	0.1 g	38.5 g
Phase	< 3% error	≈ 0% error

3.2 Spider Windscreen Results

The spider windscreen with parameter values shown in Table 4 produced results very similar to the cone windscreen. It should be noted in Table 4 that *D* and *g* are the same value

Table 4 - Optimal spider configuration values

	Geometry (cm)
Leg Length *w*	3.81
Inside Tube Dia. *D*	2.54
Tube Drop *L*	3.81
Tube Opening *g*	2.54

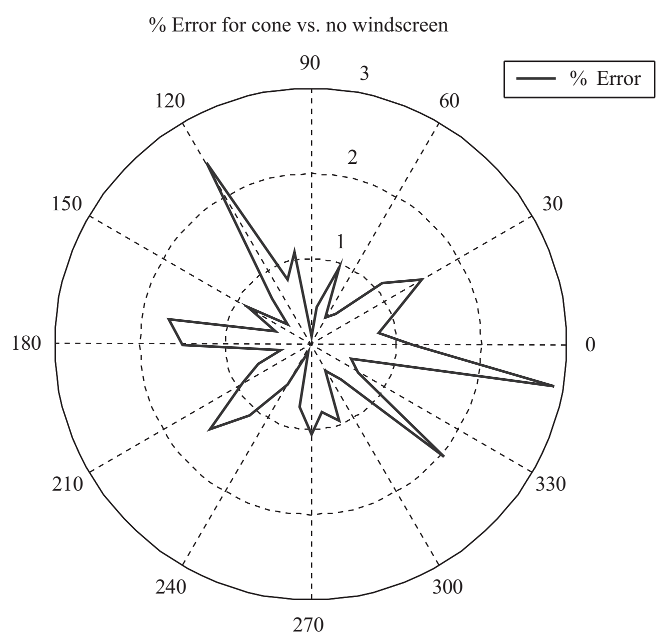

Fig. 10. 360° phase error plot for cone windscreen

but if a tapered pipe were used these values would be different. Fig. 11 shows the wind noise attenuation at 20.9 km/h (13 mph), which over the same frequency range as the cone, 0 to 100 Hz, is on average, 8.9 dB. At 32.2 km/h (20 mph), the wind noise attenuation was 22.2 dB, as shown in Fig. 12.

Regardless of the geometry of the tubular windscreen, the particle entrapment testing was the same. There was never a measurable amount of sand in the windscreen, even when the time was lengthened from 4 to 10 minutes.

Insertion loss testing was performed in the same manner as the cone windscreen design, and the results were very similar. Again, the average insertion loss of the windscreen was less than 0.4 dB, satisfying the insertion loss criteria.

Using the five microphones, 360° phase error plots were again constructed. In Fig. 13, the error between the microphone array with and without the spider windscreen is shown for the 50 Hz case. In all phase tests, the sound source was located at 0°. In all tests the errors were less than 2%. Table 5 shows the results from these four tests compared to the results found for a 3.81 cm (1.5 in) foam windscreen. Table 6 shows the design constraints for the windscreen and the results for both the cone and spider windscreen.

Table 5 - Optimal spider final values

	Spider	3.81 cm foam
Wind noise attenuation 20.9 km/h (13 mph)	8.9 dB	8.1 dB
Wind noise attenuation 32.2 km/h (20 mph)	22.2 dB	15.0 dB
Insertion Loss	< 0.4 dB	< 0.4 dB
Sand	< 0.1 g	38.5 g
Phase	< 2% error	≈ 0% error

Table 6 - Final results for cone and spider windscreen

	Requirement	Cone	Spider
Wind noise attenuation 20.9 km/h (13 mph)	> 8 dB	9.1 dB	8.9 dB
Sand reduction	> 90%	> 99%	> 99.8%
Insertion loss	< 1 dB	< 0.4 dB	< 0.4 dB
Phase shift	< 3%	< 3%	< 2%

4 CONCLUSION

The goal of this research was to design a windscreen that 1) has a wind noise attenuation of at least 8 dB, 2) protects an array of five microphones from sand and dirt particles, 3) has an insertion loss of no more than 1 dB from 0-1,000 Hz, and 4) does not alter the phase difference between each microphone by more than 3% over the same range. Two windscreen designs were developed that meet these requirements. Additionally, both windscreens are comparable to commercial foam windscreens in wind noise attenuation and insertion loss, while reducing the amount of particles trapped by the windscreen.

Through this research, methods for designing microphone windscreens were explored. Both computer modeling and experimental testing were used. A windscreen can be modeled in a CAD package, imported into a CFD package, and have the

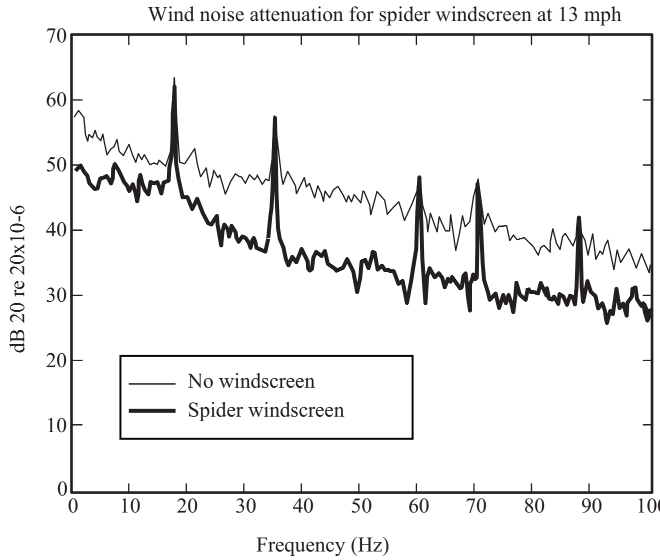

Fig. 11. Wind noise attenuation for the final spider windscreen at 20.9 km/h (13 mph)

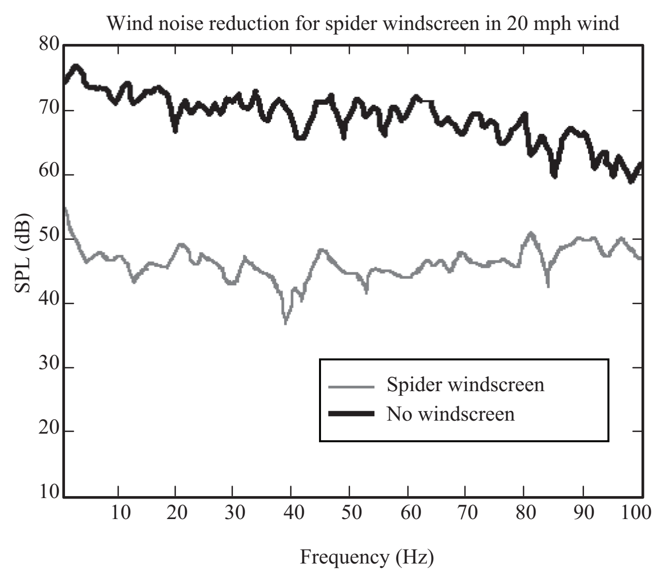

Fig. 12. Wind noise attenuation for the final spider windscreen at 32.2 km/h (20 mph)

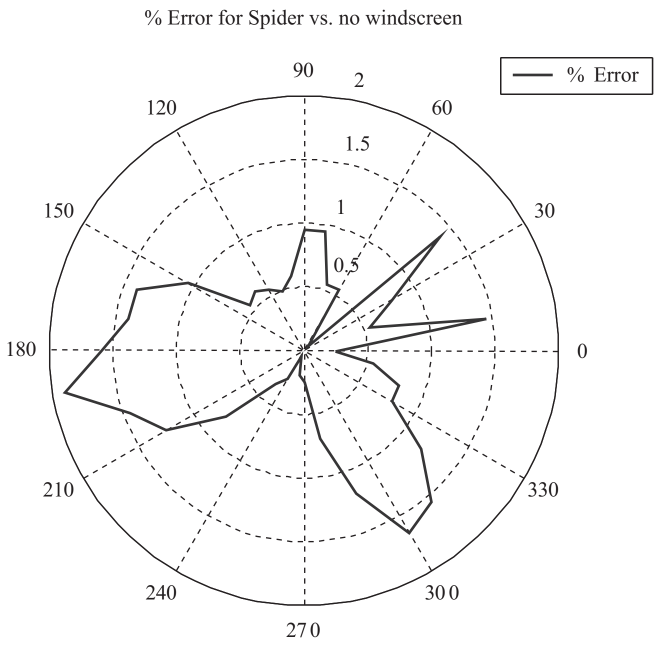

Fig. 13. 360° phase error plot for a spider windscreen

wind speed reduction computed. Small particles can also be modeled quickly. When experimental prototyping is feasible, it is recommended that it be used to fine-tune the geometry, after using a CFD package to design a basic geometry for the windscreen.

This research shows that windscreens can be designed for specific applications, such as harsh weather conditions and prolonged outdoor use. Following the design methodology of this research, unique windscreens for many different applications can be designed and built.

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