COMPARATIVE EVALUATION OF SELECTED INFRASOUND NOISE REDUCTION METHODS

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ABSTRACT

The objective of this project is to identify and characterize potential low-cost alternatives to the conventional pipe array wind-noise-reduction method. Initial efforts have focused upon the use of a porous medium as a wind noise filter. A simple theoretical model of wind-generated noise in a rigid, porous medium has been developed. This model predicts that the attenuation, A_w , of the noise in this type of medium is related to the observation depth, *d,* by an equation of the form;

$$A_w = \exp(-\alpha_w d) \qquad 1$$

where

$$\alpha_w = \mathrm{Re}\left(\frac{\omega^2}{c^2} + i\frac{\sigma\omega}{P_0}\right)^{\frac{1}{2}} \qquad 2$$

and, c, is the convection velocity of the wind-generated pressure field, σ, is the effective flow resistance of the medium, and P_0 is the static atmospheric pressure at the elevation of the observation point. The results of a small-scale field trial are described in the main body of this report. They validate the predicted exponential attenuation of the wind noise. They also indicated that a finite, porous body would act as a half-space for wavelengths that are less than 3-4 times its horizontal dimensions.

The theoretical model of Attenborough et al (1986) has been adopted to predict the attenuation of airborne sound in a porous medium. This model predicts that the attenuation, A_i , of the infrasound signal in this type of medium is related to the observation depth, *d,* by an equation of the form;

$$A_i = \exp(-\alpha_i d) \qquad 3$$

Sabatier et al (1993) have shown that in the bandwidth of interest to the infrasound community

$$\alpha_i \approx \mathrm{Re}\left(i\frac{\sigma\omega}{P_0}\right) \qquad 4$$

The combined wind noise and infrasound signal models therefore predict that infrasound signal-to-noise ratios will exponentially increase as a function of the observation depth in a frequency range defined by the constraint that;

$$f > \frac{\sigma c^2}{4\pi P_0} \qquad 5$$

where f is the frequency.

The preliminary results of a field experiment to test this constraint and a discussion of its practical implications are summarized in the main body of this report.

KEY WORDS: infrasound, wind noise, attenuation

OBJECTIVE

Atmospheric pressure changes generated by the local surface are the primary factor limiting the infrasonic detection threshold in the 0.02-to 5.0-Hz bandwidth. Two-dimensional spatial filters are used to combat this problem. In the currently favored approach, the filters consist of acoustically coupled, hollow, rigid tubes that contain or permit access to a distribution of small inlet ports. These filters are commonly referred to as "pipe" arrays. The maximum linear dimensions of a "pipe" array are chosen to yield a flat response to infrasonic signals below some selected cut-off frequency; whereas its spatial configuration is chosen to provide an azimuthal response to infrasound signals that is approximately isotropic. Finally, the inlet port distribution is chosen to promote the cancellation of those components of the local atmospheric pressure field that are characterized by relatively short correlation lengths. The "pipe" arrays recommended by the Provisional Technical Secretariat (PTS) for use at stations in the International Monitoring System (IMS) infrasound monitoring network are the most recent examples of this particular type of spatial filter.

While the 'pipe" array approach has been used with success in the past to enhance infrasound signal-to-noise ratios (SNR) in the bandwidth of interest, it is expensive to implement. For example, it is conservatively estimated that the fabrication and deployment costs for the installation of one of the PTS-recommended "pipe" arrays at each of the elements of an IMS infrasound array will account for as much as 25-35 % of the total expenses incurred for sensor element deployment. The objective of this project, therefore, is to identify and evaluate alternative approaches to infrasonic spatial filtering that have the potential to yield SNR improvements equivalent to or better than the "pipe" array approach, but at a substantially lower implementation cost.

RESEARCH ACCOMPLISHED

Prior research has identified two low-cost alternatives to the "pipe" array approach for infrasonic spatial filtering. These are:
- The use of a porous medium as a spatial filter; and
- The use of compliant tubing for the configuration of infrasonic spatial filters.

Project research to date has focused exclusively on the evaluation of the porous medium alternative. The essential results of this research are summarized in the following paragraphs.

Theory

It is a common observation to note that airborne sound is attenuated by its passage through a porous medium. Sabatier et al (1986) have shown that in a semi-infinite poroelastic solid such as porous ground, this phenomenon is both frequency and wavelength dependent. Attenborough et al (1986) have also demonstrated that in the audible frequency range, the attenuation of airborne sound in a porous medium is dominated by the wavelength dependent term. However, arguments offered by Sabatier et al (1993) imply that in the infrasonic frequency range of interest to the nuclear explosion monitoring community, the attenuation of airborne sound is dominated by the frequency dependent term. In particular, the results of the research cited above imply that if the inlet port to a microphone or microbarograph is placed at a depth, d, beneath the surface of a semi-infinite porous solid, then the attenuation operator, A_I, is of the form;

$$A_i(d) = \exp(-\alpha_i d) \tag{1}$$

where α_i is referred to as the infrasound dissipation function and in the infrasound bandwidth of interest;

$$\alpha_i \approx \mathrm{Re}\left(\sqrt{i\frac{\gamma\sigma\omega}{\rho_o c_o^2}}\right) \tag{2}$$

The variables and parameters appearing on the RHS of equation 2 are defined as follows:

γ = specific heat ratio for air
σ = effective flow resistance of the porous solid
ω = angular frequency **3**
ρ_0 = density of air at the observation point
c_o = sound speed in air at the observation point

Sorrells (2001) has shown that a similar operator describes the attenuation of wind-generated atmospheric pressure changes in a semi-infinite porous medium. Specifically he has shown that if A_w is this operator, then;

$$A_w(d) = \exp(-\alpha_w d) \tag{4}$$

where α_w is the wind noise dissipation function and is given by

$$\alpha_w = \mathrm{Re}\left(\sqrt{k_w^2 + i\frac{\sigma\omega}{P_o}}\right) \tag{5}$$

The variable, k_w , that appears on the RHS of equation 5 represents the horizontal wavenumber characterizing the wind generated pressure field and may be treated as a complex number to account for its correlation scale. The parameter, P_o , is defined to be the standard atmospheric pressure at the elevation of the observation point. It therefore follows that if $\Delta\, SNR(d)$.is the change in the infrasonic SNR at depth, d**,** relative to observations made at the surface, then

$$\Delta SNR(d) = \exp[d(\alpha_w - \alpha_i)] \tag{6}$$

It is seen from equation 6 that the SNR increases exponentially as a function of increasing depth provided that $\alpha_w > \alpha_I$. Now, for the purposes of illustration, it will be assumed that k_w is real. Therefore,

$$k_w = \frac{\omega}{c_w} \tag{7}$$

where c_w is the horizontal advection speed of the wind generated pressure field. Furthermore, it may be reasonably assumed that the ideal gas law describes the equation of state for air. Therefor

$$\frac{\rho_o c_o^2}{\gamma} = P_o \tag{8}$$

Then using these definitions and expressing the change in SNR in dB relative to the surface it follows that

$$\Delta SNR_{dB}(d,\omega) = 20Log(e)\left[d\left(\mathrm{Re}\left(\sqrt{\frac{\omega^2}{c_w^2} + i\frac{\sigma\omega}{P_o}}\right) - \mathrm{Re}\left(\sqrt{i\frac{\sigma\omega}{P_o}}\right)\right)\right] \tag{9}$$

By inspection of equation 9 it is seen that if f is the frequency in hertz then for

$$f << \frac{\sigma c_w^2}{2\pi P_o} \tag{10}$$

$$\Delta SNR_{dB}(d,\omega) \approx 0 \tag{11}$$

and for

$$f >> \frac{\sigma c_w^2}{2\pi P_o} \tag{12}$$

$$\Delta SNR_{dB}(d,\omega) \approx 20Log(e)\frac{\omega d}{c_w} \tag{13}$$

Clearly then, given the assumption of a real advective wavenumber, and assuming that the advective speed does not increase as a function of increasing frequency, there is always some "cross-over" frequency that satisfies the constraint implied by equation 12. It then follows that above this critical frequency, the use of a porous medium spatial filter will always increase the infrasound SNR. Whether or not this frequency can be placed near the lower end of the bandwidth of interest, through the choice of the material properties for the porous medium, is an issue of considerable practical significance.

An experimental project has been undertaken to address this issue as well as to validate the theoretical arguments presented above and to test the qualifying assumptions. In addition, a literature search is underway to identify low-cost materials with relatively low flow resistances that can be used as an effective infrasonic spatial filter. The results of these studies to date are briefly summarized in the following paragraphs

Experimental results

Equations 12 and 13 predict that any meaningful improvements in the infrasound SNR resulting from porous medium spatial filtering, are dependent only on the ratio of the installation depth to the advective wavelengths characterizing the wind generated components of the atmospheric pressure field. An important practical implication of this prediction is that the lateral dimensions of a porous medium spatial filter need only be large enough to accommodate the 'semi-infinite" assumption inherent to the theoretical model. Prior experience acquired during studies of wind generated seismic noise suggested that as a "rule of thumb", the "semi-infinite" assumption will be valid for all wavelengths that are less than 2-4 times the maximum horizontal dimensions of the porous medium spatial filter. A small-scale field experiment was planned to test this assumption. It was implemented in the fall of 2000 at the TXAR seismic array to take advantage of existing data acquisition and transmission assets. The configuration of the data acquisition elements used for the initial experiments is illustrated in Figure 1.

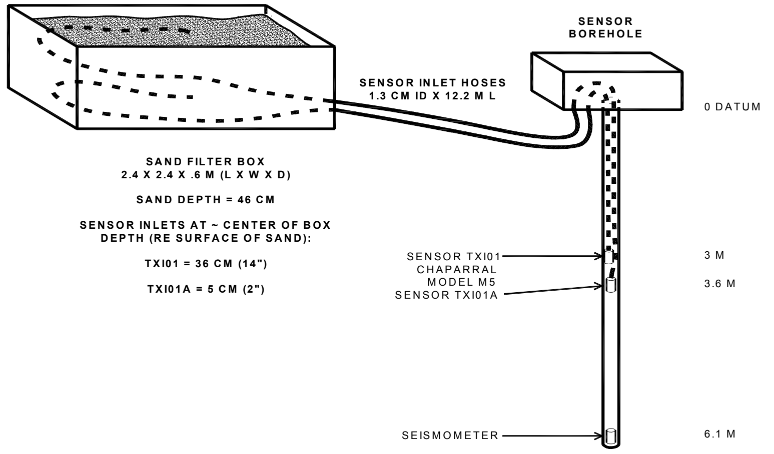

Figure 1. Configuration of the infrasound data acquisition system for the initial porous medium spatial filter field test.

The experimental porous medium spatial filter is simply a rectangular box filled with sand dredged from a nearby dry creek bed. The horizontal and vertical dimensions of the box are 2.4 and 0.6 meters, respectively. The thickness of the sand fill is approximately 0.5 meters. The inlet port of a flexible hose is placed at a depth of approximately 0.3 meter beneath the sand surface to couple the porous medium spatial filter to a Chapparal model MS microphone installed in a nearby bore-hole. This system is designated as TXI01. An identical system configuration is used to provide data referenced to the surface of the sand fill. This system is designated as TXI01A . The flexible hose inlet port for this system is placed at a depth of about 0.05 meters to avoid "whistling" noise during windy periods. It is also placed directly above the lower hose inlet port. Given this configuration, it is readily seen that the modulus of the transfer function relating observations acquired by TXI01 to those acquired by TXI01A yields the attenuation operators for this particular realization of a porous medium spatial filter. The data from the two systems are sampled continuously at the rate of 40 SPS and transmitted in real time to the Southern Methodist University (SMU) Geophysics Laboratory for permanent storage and analysis.

Prior to the porous medium spatial filter trials, the two flexible hoses were placed side by side to test for differences in the response characteristics of the two systems. The data for these tests were acquired during selected windy periods. Sample records, 15 minutes in duration, were simultaneously extracted from the windy period data and processed to yield power spectral density estimates and the transfer function characterizing the data recorded by the two systems. An example of the results obtained during these tests is shown in Figure 2. These results indicate that apart from a slight difference in gains, the response of the two systems is essentially identical. The gain correction factor derived from these tests is about 2 dB and has been incorporated into the data processing codes used for the porous medium spatial filter trials.

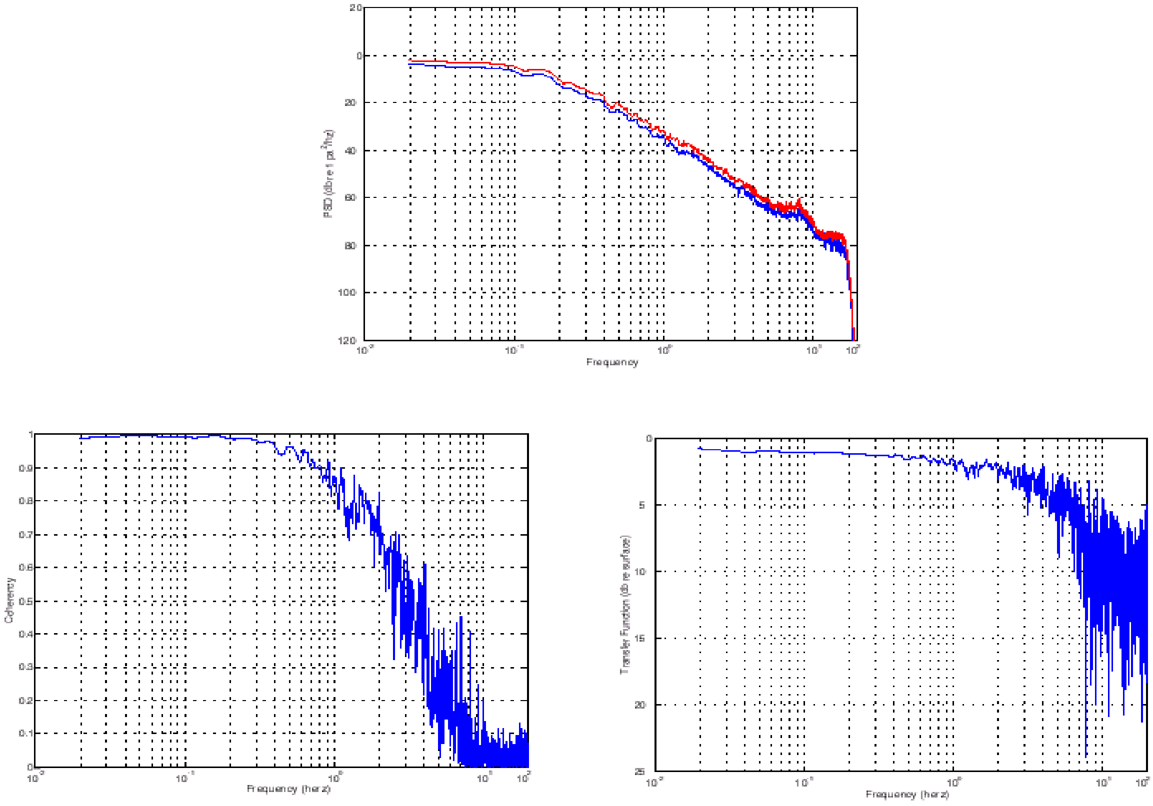

Figure 2. An example of one of the trials of the side-by-side system response tests. The upper panels compare the spectral estimates of noise recorded by the two systems during a fifteen-minute windy period. The lower left panel shows the coherence between the outputs of the two systems. The lower right panel shows the modulus of the transfer function relating the two outputs.

The data sampling and processing procedures used for the initial porous medium spatial filter trial were identical to those described above with the exception that sample data records were acquired during both low and moderate surface wind conditions and separated into two different files. The basis for this segregation is the reasonable expectation that the advective speeds characterizing the wind generated pressure field under low and moderately windy conditions will differ by a factor of 2 or more. Therefore, significant differences between the experimental attenuation operators characterizing the two different data sets are to be expected provided that:

- Equation 4 above adequately describes the attenuation of wind generated pressure changes in a porous medium;
- The wavelength dependent term appearing on the RHS of equation 5 above dominates the frequency dependent term, at least during low wind conditions;
- The horizontal dimensions of the experimental porous medium spatial filter described above satisfy the qualitative "semi-infinite" assumption identified above over some observable frequency range.

The experimentally determined attenuation operators showed considerable sample-to-sample variation in both data sets. The logarithms of these operators were averaged to reduce this variation. The resultant average attenuation operators characterizing low and moderately windy conditions are shown as irregular solid lines in Figure 3. The smoothly varying solid lines seen in this figure are the "best fit" predicted attenuation operators. Equation 4 was used for their calculation, given the assumption of a real advective wavenumber. The corresponding "best fit" average advective speeds were found to be 6 meters/sec for the low wind data set and 12 meters/sec for the moderate wind data set. The clear separation between the two experimentally determined operators at frequencies above 1 Hz is interpreted to mean that the experimental porous medium spatial filter approximates a semi-infinite porous solid for advective wavelengths shorter than about 6-12 meters.

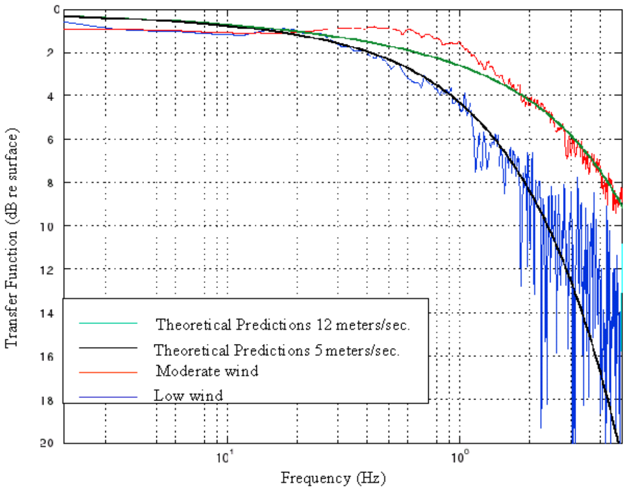

Figure 3. A comparison of the experimentally determined attenuation operators for time periods characterized by low and moderately high surface wind speeds. The irregular curves identify the experimentally determined operators. The solid lines identify the "best fit" predicted attenuation operators for both cases.

The success of the initial experiment encouraged the decision to expand the field test to evaluate the theoretical predictions and qualifying assumptions listed above. Accordingly, the vertical dimensions of the experimental porous medium spatial filter were doubled to 1.2 meters, and the thickness of its sand fill was increased to approximately 0.9 meters in early April 2001. The inlet port for the flexible hose component of the TXI01 system was placed at a depth of 0.84 meters relative to the surface of the sand fill. The inlet port for the flexible hose component of the TXI01A system was placed at a depth of 0.1 meters relative to the surface of the sand fill and directly above the TXI01 inlet port. In addition, a Texas Electronics Instrumentation Package, containing a Model TD-104D Wind Direction Sensor and Model TV-114 Wind Speed Sensor, was coupled to a REFTEK Model 72A-08 data acquisition system and deployed near the experimental porous medium spatial filter to provide the off-line capability to record wind data during this field trial. Since the completion of the augmentation of the experimental porous medium spatial filter, 67 sample data records have been acquired, using procedures identical to those outlined above. However, at the time for submission of this report, the processing and analysis of the wind data for the corresponding time periods was not complete. Therefor, no attempt has been made to segregate the sample records into wind related categories. The logarithmic mean of the existing sample population of experimental attenuation operators is shown as the solid line in figure 4. The curves formed by discrete stars (*) seen in this figure define the standard deviation bracket of the sample population. It is clear from these results that the current configuration of the experimental porous medium spatial filter effectively attenuates wind noise. Before it intersects the system noise threshold near one hertz, The mean attenuation is about 40 dB. The increase in the mean attenuation operator above two hertz is attributed to the to the finite box dimensions. While this appears to be a significant feature of the experimentally derived transfer functions, actual contributions to the attenuated wind noise spectrum are negligible. The substantial expansion of the width of the standard deviation brackets that is seen to occur at frequencies greater than about 0.25 hertz should also be noted. We believe this phenomenon reflects;

- The location of the so-called "cross-over" frequency, where according to equations 5 and 12 the wavelength dependent term exceeds the frequency dependent term in the wind dissipation function characterizing the porous medium spatial filter.
- An increasing contribution of wind generated pressures changes to the background noise at frequencies greater than 0.25 hertz, and;
- The variability of the advective speeds and correlation states of the wind generated pressure field sampled by our data acquisition procedures.

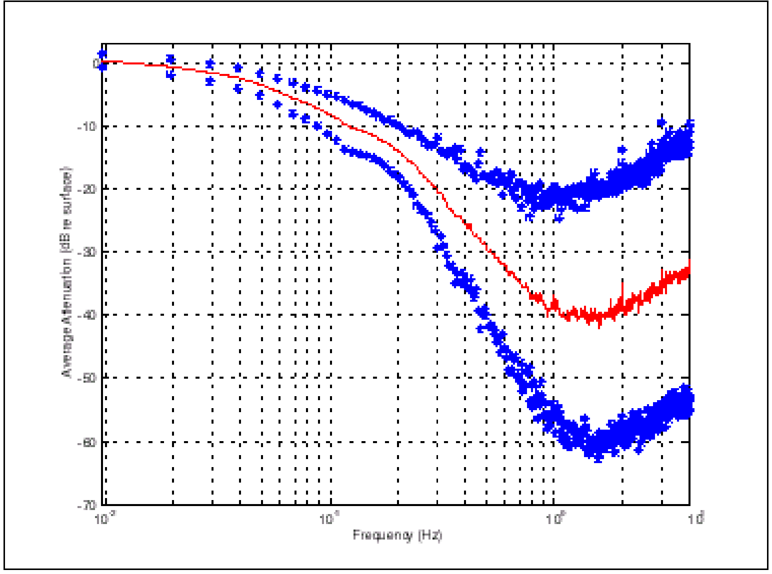

Figure 4. Wind noise attenuation data. The mean wind noise attenuation operator characterizing the augmented experimental porous medium spatial filter for a sample population containing 67 fifteen-minute records is shown as the solid line. The curves identified by stars(*) are the mean values + and - the standard deviation of the sample population.

The corresponding infrasound attenuation operator for this particular realization of a porous medium spatial filter has yet to be defined experimentally. Despite a careful visual search of the TXAR infrasound and seismic records since the beginning of the second field trial in April 2001, we have been unable to confirm the detection of any infrasound signals. However, assuming the validity of equations 2 and 8, and given a reliable measurement of the effective flow resistance of the sand fill, a theoretical infrasound attenuation operator can be derived with the aid of equation 1. The ubiquitous occurrence of microbaroms in the 0.15- to 0.3-Hz bandwidth provides the experimental basis for the measurement of the effective flow resistance of the sand fill, since they are, insofar as we are concerned, a narrowband infrasonic signal. Observations made during calm periods indicate that the microbaroms are attenuated by about 8-10 dB by the current configuration of the porous medium spatial filter. Assuming a mid-point frequency of 0.2 hertz for the microbarom band it may be found from the use of equations 2 and 8 that this value implies an effective flow resistance of ~200,000 n-sec/m^4. The predicted infrasound attenuation operator for a porous medium with a flow resistance of this magnitude and an observation depth of 0.8 meters is compared to the mean wind attenuation operator for the experimental porous medium spatial filter in figure 5. It is seen from this comparison that the predicted average SNR enhancement provided by this particular configuration of a porous medium spatial filter reaches a maximum of ~20 dB at 1 hertz. It should be pointed out, however, that this maximum is achievable only if the surface amplitudes of the infrasound signals are at least 18-20 dB above the system noise level at frequencies less than 1.0 hertz.

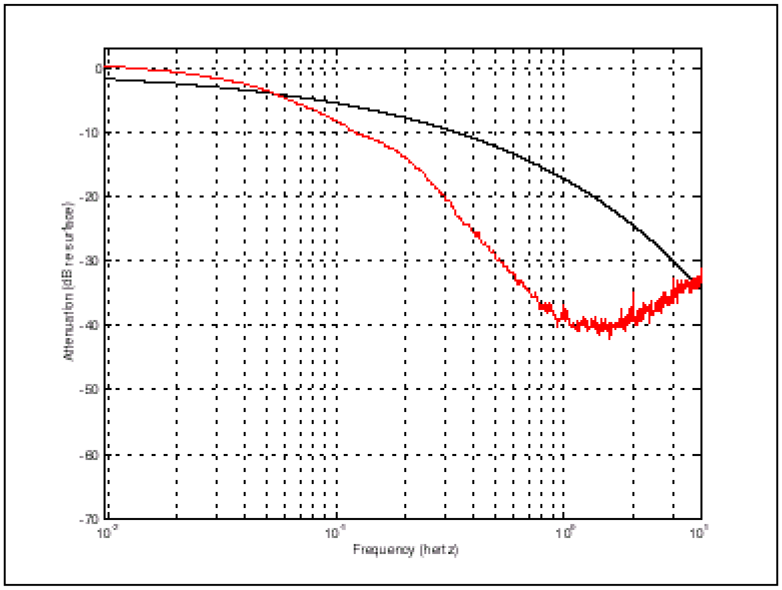

Figure 5. A comparison of the mean wind noise attenuation operator with the predicted infrasonic signal attenuation operator for the experimental porous medium spatial filter.

CONCLUSIONS AND RECOMMENDATIONS

The results of this project to date demonstrate that a relatively simple, low-cost configuration of a porous medium spatial filter effectively reduces wind noise in the infrasound bandwidth of interest. Moreover, if the existing theory correctly predicts the attenuation operator for the experimental spatial filter, then average gains of about 20 dB at frequencies near 1 Hz are possible. Therefore, the experimental confirmation of the predicted infrasound attenuation operator assumes a high priority for future studies.

It is also important to recognize that since a porous medium spatial filter attenuates both signals and wind noise, the relative magnitude of the system noise can impose an important constraint upon the realizable SNR gain. It appears that this problem can be partially resolved by choosing fill materials with much lower effective flow resistances than the dredged creek sand used in this experiment. Examples of granular materials with effective flow resistances of the order of 10^4 n-sec/m^4 or less may be found in Sabatier et al (1993) and Attenborough (1983). The use of a fill material with an effective flow resistance of this order of magnitude is expected to reduce the predicted attenuation of infrasonic signals for a given observation depth, as well as reduce the "cross-over" frequency for the wind dissipation function. Consequently, any future studies in this area should be designed to assess the value of using low effective flow resistance materials in porous medium spatial filters.

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