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# Infrasound Sensor and Porous-Hose Filter Evaluation Results

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## ABSTRACT

The Ground-Based Nuclear Explosion Monitoring Research and Development (GNEM R&D) program at Sandia National Laboratories (SNL) is regarded as the primary center for unbiased expertise in testing and evaluation of geophysical sensors and instrumentation for nuclear explosion monitoring. Over the past three years Sandia has evaluated over 60 Chaparral Physics 2.5 low-gain infrasound sensors. Parts of the delivered product to the customer are the sensitivity and an estimated pole-zero instrument response for the individual sensors. Once these sensors are installed in the field, the sensors inlets are typically attached to a wind-noise reduction system (e.g. porous-hose array). The addition of the wind-reduction system to the calibrated sensor brings into question the reported results, until the new system (sensor + wind-reduction technique) is evaluated for its response, both amplitude and phase, to both coherent and incoherent signals. One area of focus has been to understand the effects of porous-hose filters used at some monitoring sites for reducing acoustic background signals. A set of experiments were designed to estimate the relative gain of the porous-hose filter system in various configurations: Fiskers and Garden Rite brands at lengths of 25, 50, and 75 feet; a group of 10 “aged” Fiskers hoses; a set of three “new” Garden Rite hoses; a comparison between the field performance of a single coiled hose and one stretched out in a straight line; and a controlled indoor experiment with coherent signals. The basic plan is to first characterize three Chaparral Physics 2.5 low gain infrasound sensors at a single frequency and verify their instrument responses versus a reference Microbarometer 2000. The initial test configuration was to place and coil the hoses within an acoustic isolation chamber. Acoustic “white noise” is fed into the chamber and data is collected for a half-hour. The relative gain of the porous-hose filters are estimated by computing the ratio of the power spectra. With the chamber experiment complete a single 50’ porous-hose was fielded in both a coiled and straight configuration and acoustic background was used to show the hose response to a random acoustic source. The final experiment was setup to determine the response of the porous-hose to coherent acoustic signal generated within a controlled indoor environment. Results show differences in the high-frequency filtering amplitude response between the different porous-hose configurations and the acoustic input signals.

## OBJECTIVES

Over the past year the Component Evaluation project of the Ground-Based Nuclear Explosion Monitoring Research and Engineering program at Sandia has taken the initial steps in better understanding the complexities of the porous-hose wind-filter reduction systems used at some infrasound stations. The complexities arise when only the sensors are evaluated for their instrument response (both amplitude and phase) to dynamic input signals and the porous-hoses portion of the field system is left uncharacterized, or ignored. Here we show results of the variability in filtering characteristics observed between different brands of porous-hose, lengths' of hose, and within a single brand to a random "white" acoustic signal. We then move into the field with a set of experiments to show the differences between the coiled-hose chamber experiment and a typical deployment of the porous-hose. The acoustic input was limited to using acoustic background signals for analysis. The final experiment was to deploy a single 50' porous-hose in a controlled indoor environment to observe the response of the porous-hose to coherent acoustic signals. Through these experiments we show the variability of the porous-hose wind reduction system to a variety of acoustic sources.

### Introduction

Air Force Technical Applications Center (AFTAC) is tasked with monitoring compliance of existing and future nuclear test treaties. To perform this mission, AFTAC uses several different monitoring techniques to sense and monitor nuclear explosions, each designed to monitor a specific domain (e.g. space, atmosphere, underground, oceans, etc.). Together these monitoring systems, equipment, and methods form the United States Atomic Energy Detection System (USAEDS). Some USAEDS seismic stations may be included in the International Monitoring System (IMS). Each agency involved in the monitoring community has requirements which the system and components (sensors and data loggers) must for pass before deployment and later certification. Historically, Sandia National Laboratories has been involved in the testing of seismic systems to monitor for compliance with terms of nuclear weapon test ban treaties. With the recent addition of infrasound and seismo-acoustic stations, Sandia has worked to develop the capability and procedures to perform the characterization of infrasound sensors, infrasound systems and seismo-acoustic systems.

Over the past two years Sandia has evaluated over 60 Chaparral Physics model 2.5 low-gain infrasound sensors. Once the sensors are evaluated they are returned to the customer for deployment. The sensors are evaluated for sensitivity, noise, dynamic range and instrument response. When the sensors are deployed in the field they are typically attached to a wind-noise reduction system (WNRS). These WNRS can take several forms, e.g. rosette pipe, or porous-hose array. In this paper we will take a look into the filter characteristics of the porous-hose WNRS and its effect on both incoherent and coherent signals. Our goal is to better understand the implications of not correcting infrasound time series data for the amplitude and phase response of the WNRS.

The research for this paper was separated into four main areas:

1. Characterize Digitizers and Sensors to be used in Study
2. Laboratory Evaluation of porous-hoses
3. Field Exercise using Acoustic Background (single hose and random acoustic input)
4. Controlled Exercise (single hose and coherent acoustic input)

## RESEARCH ACCOMPLISHED

### Evaluation of Reference Sensors

For this experiment, three Chaparral Physics model 2.5 infrasound sensors were used. Their calibration was done using a technique referred to as "Comparison Calibration" (CompCal), which allowed us to transfer a calibration of a known reference sensor to the unknown sensors. The CompCal technique requires a reference sensor with well known characteristics (e.g. self-noise, amplitude and phase response). We used the Microbarometer 2000, SN1380 as our reference sensor. Figure 1 shows our infrasound test bed with isolation chamber, acoustic source and reference sensor. A Smart24 digitizer was used to record the output of the four sensors, as well as generate the calibration sinusoid used as input to the acoustic source. A 5 Vpeak-to-peak 1 Hz sine wave was generated and the output of the acoustic source was recorded by the four sensors. Table 1 shows the results of using a sine-fit algorithm to determine the characteristics of the recorded signals.

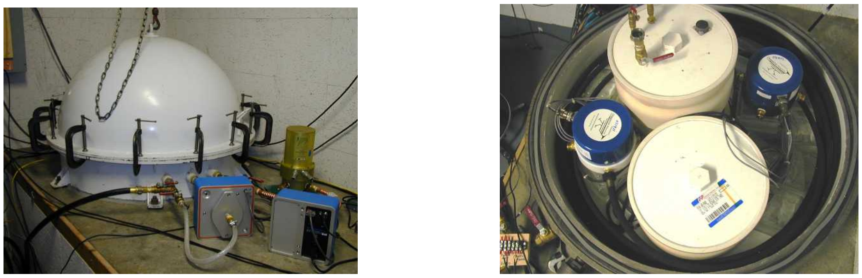

**Figure 1 Sandia's acoustic test chamber (white dome), acoustic source and MB2000 (Left) and inside acoustic test chamber. Showing two CP 2.5 sensors, porous-hose and volume reducing fixtures (Right).**

**Table 1 Compiled results from comparison calibration of the Chaparral 2.5 sensors relative to the MB2000.**

| Sensor | Output Voltage (V) | Sensitivity @ 1Hz (V/Pa) | Acoustic output (Pa) | DWR LSB (V/Count) | Calibration @ 1Hz (Pa/Count) |
|---|---|---|---|---|---|
| 1380(MB) | 0.576 | 0.1000 | 5.7638 | 3.27E-06 | 3.270E-05 |
| 071911 | 2.558 | 0.4439 | 5.7638 | 3.27E-06 | 7.367E-06 |
| 071912 | 2.334 | 0.4049 | 5.7638 | 3.27E-06 | 8.075E-06 |
| 071959 | 2.312 | 0.4012 | 5.7638 | 3.27E-06 | 8.151E-06 |

The next step is to perform the Response Verification test on the three CP 2.5 sensors. This test requires a "white" noise acoustic signal. A WaveTek model 132S signal generator was used to produce the input to our acoustic source (APS Dynamics Model 330 piston-phone). This produced a consistent signal that will be used in subsequent testing to characterize the filtering effects of the porous hoses. We observe the sensors to have a common response to the acoustic signal between 0.1 and 30 Hz. We applied the single frequency calibration (1Hz) calculated previously to the raw waveforms. Deviations in the power spectrum represent variations in the instrument responses not accounted for in our procedure. The final step is to ratio the spectra relative to the MB 2000 to give the "relative gain" between the two acoustic systems. In this case they are identical over the pass band and result in the expected unity gain.

**<u>Chamber Evaluation of Porous-Hose Filter</u>**

With the calibration factors calculated and sensors characterized we can focus on characterizing the filtering characteristics of the hoses attached to the sensors to reduce undesired signal content. In the past, the Fiskers® brand has been accepted as the preferred brand to use. Recently, the Fiskers® brand has become unavailable due to the manufacturer ending production. The Garden Rite® brand is being considered as a replacement. We are looking to determine if the two brands have a consistent response to our control acoustic signal. We also looked at the effect of the hose length at 25, 50 and 75 feet. These tests were performed with the hoses coiled within the acoustic test chamber.

**<u>Fiskers</u>**

Comparing the spectra of the three lengths of Fiskers hose relative to the open reference sensor, we obtain the gain response plot show in Figure 2.

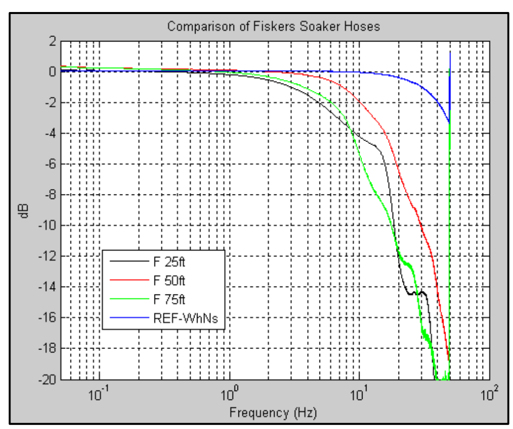


**Figure 2 Comparison of relative gain for Fiskers brand porous-hose filters to the control "white noise" spectrum.**

We observe different low-pass characteristics of the Fiskers brand. The -3dB corner varies from 16.4Hz for the 50ft length to 6.6Hz for the 25ft length. Unity gain is observed between 0.05 and 0.4 Hz. No clear change in response is observed with the change in hose length.

**<u>Garden Rite</u>**

Comparing the spectra of the three lengths of Garden Rite hose relative to the open reference sensor, we obtain the gain response plot show in Figure 3.

We observe unique filter characteristics of the Garden Rite brand. The -3dB corner is much higher at 40Hz, and varies little between the different lengths. Unity gain is observed between 0.05 and 2.0 Hz. Above 2 Hz, the gain increases above unity before continuing to roll off. The Garden Rite brand appears to be more consistent in response independent of hose length.

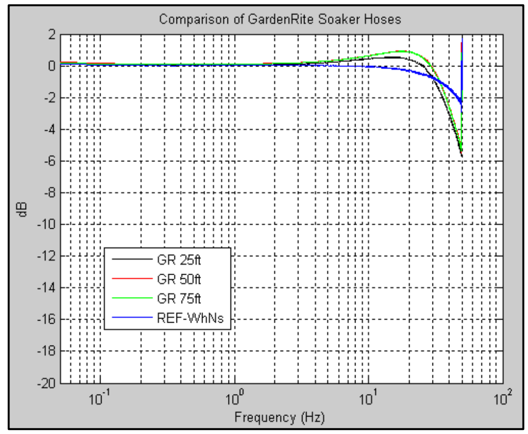


**Figure 3 Comparison of relative gain for Garden Rite brand porous-hose filters to the control "white noise" spectrum.**

**<u>Field Exercise with Incoherence Signals</u>**

Since July 2008 Sandia has had three element infrasound arrays operational with the intent of better understanding the wind-noise reduction of the porous-hose filter. Each site has two co-located chaparral physics 2.5 sensors. One test consisted of configuring the two sensors as follows: one sensor is exposed to open acoustic input, while the second is attached to a single straight 50 ft hose. A second test (during a different time period) had the hose in a coil of the same approximate dimensions as tests done in the acoustic chamber.

A three hour segment of acoustic background was analyzed. Power spectra and relative gain were computed. The power spectra for the open port (no wind reduction system attached to sensor) show strong harmonics at 16 and 32 Hz. But most importantly, the low frequencies 0.03 to 10 Hz are unaffected.

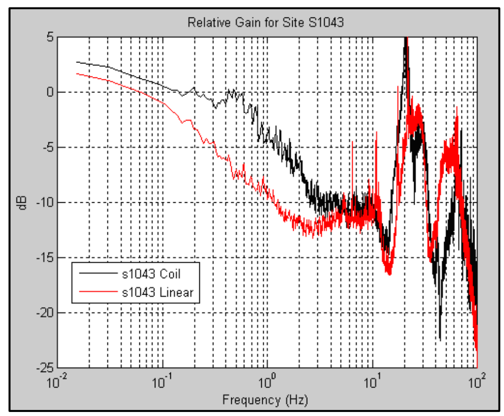


**Figure 4 Relative gain for site s1043 illustrating differences between the linear and coiled porous-hose configurations to background acoustic input.**

We observe a difference between the linear and coil porous-hose configurations, which may be due to the differing times of data acquisition between the two configurations. A slight gain reduction was observed (1.7 dB) at 0.1 Hz, with change in corner frequency; 0.2 Hz for the linear hose and 0.8 Hz for the coil. This field test should be repeated with the co-location of three sensors configured to record the same acoustic input with one sensor open to acoustic input, the second attached to the linear hose and the third in the coiled configuration.

**<u>Controlled Exercise with Coherent Signals</u>**

In June 2009 an experiment was setup to determine the filtering characteristics of a single 50' porous-hose to a coherent acoustic source. The experiment was conducted in a sealed building with a hallway long enough to deploy the 50' porous hose. The sensors and digitizer used in this stage were different than the ones used in previous experiments and therefore were first characterized for sensitivity at 1 Hz. The sensor and digitizer characterization results are given in Table 2 with the applied calibration factor for at 1 Hz.

**Table 2 Compiled results from comparison calibration of the Chaparral 2.5 sensors relative to the reference MB2000 serial number 1380 and DC-Accuracy test of digitizer for LSB determination.**

| Sensor | Sensitivity @ 1Hz (V/Pa) | DWR LSB (V/Count) | Calibration @ 1Hz (Pa/Count) |
|---|---|---|---|
| 071943 | 0.418 | 3.28122E-06 | 7.8479E-06 |
| 061809 | 0.381 | 3.27698E-06 | 8.6078E-06 |

Prior to attaching the porous hose to either sensor, two sets of data were collected to document the baseline differences between the sensors. The main differences between the sensors are their sensitivities 0.418 versus 0.381 V/Pa; which equates to approximately -0.8 dB for sensor 061809 to sensor 071943. The first data set was collected with both sensors co-located and all four inlets uncapped. The second data set was collected with both sensors co-located and three of the four inlets capped. The second data set was seen as a closer approximation to the final comparison where one sensor would have the hose attached to the fourth uncapped inlet. Figure 4 show the results of determining the relative gain between the two sensors. The gamma squared coherence was above 0.98 for the pass band of 0.01 to 10 Hz, allowing for broad band interpretation of the results. Results show the expected relative gain at 1 Hz is approximately -0.8 dB and the relative phase differences are low, less than +/- 4 degrees between 0.01 to 10 Hz.

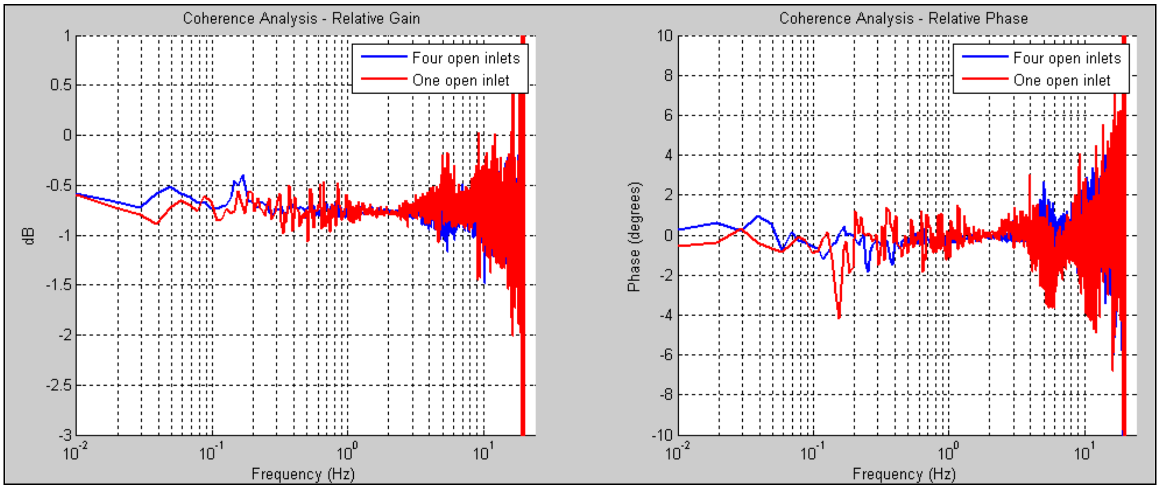


**Figure 4 Relative gain and phase for co-located sensors to determine the baseline characteristics of sensors prior to attaching porous hose for coherent acoustic signals.**

In the next two sets of data collected the porous hose was first connected to the open inlet on sensor 071943, while sensor 061809 was open to acoustic input. The second data set was then collected with the porous hose moved to sensor 061809 and sensor 071943 was open to acoustic input. This was done to verify that any changes from the baseline datasets could be traced to the sensor with the porous hose attached. Figure 5 show the results of determining the relative gain between the two sensors. The gamma squared coherence was above 0.95 for the pass band of 0.01 to 2 Hz, allowing for a slightly smaller amount of pass band for interpretation of the results. Results show the porous hose has a flat filter response from 0.01 to 0.1 Hz with no gain or attenuation. Above 0.1 Hz we see an unexpected amplification, gaining of the input signal as seen by the sensor with the hose attached relative to the open port sensor. The amplification peaks at 1 Hz, by almost 2.8 dB, and is characterized by a non-uniform gain relationship for the 0.1 to 2 Hz band. We also observed a considerable change in the phase relationship between the two sensors. Above 0.1 Hz the sensors varied by as much as 8 degrees near 1Hz.

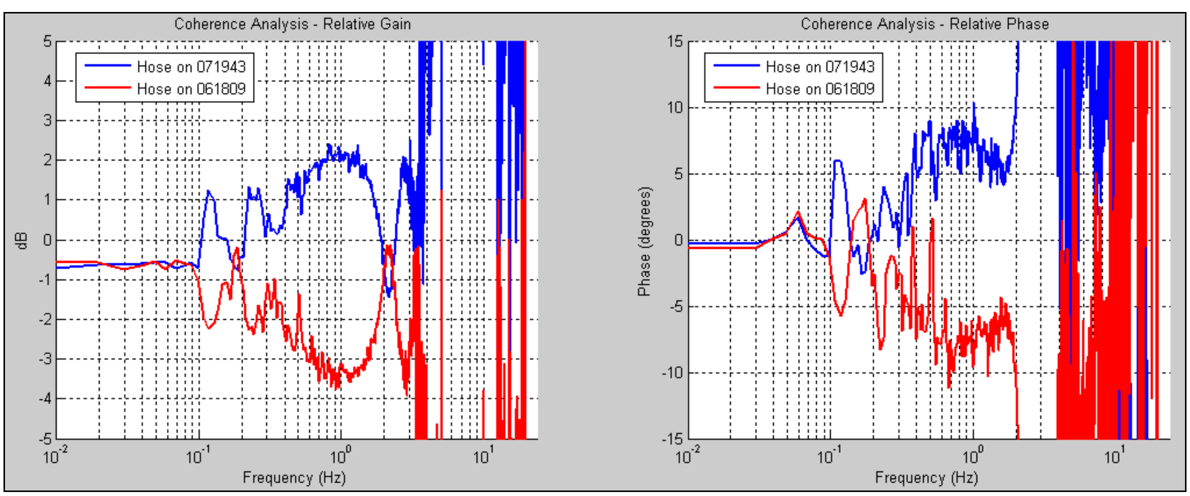


**Figure 5 Relative gain and phase for co-located sensors with attached porous hose for coherent acoustic signals.**

In the final data set the porous hose was switched to the sensor that was previously considered to be the open port sensor. In using the coherence analysis technique we consistently selected the same channel as the reference (channel 2 for sensor 071943) and channel three (for sensor 061809) as the one for comparison. This allowed for the same relative gain at low frequencies, as shown by the overlying relative gain plots for the 0.01 to 0.1 pass band for the two different configurations of the porous hose between the two sensors used in the experiment. We observed that by moving the porous hose to the sensor that previously was open, the relative gain is inverted compared to the previous configuration. This indicated that by moving the porous hose to the other sensor the same gain and phase effects follow the hose.

## CONCLUSIONS AND RECOMMENDATIONS

- There exists a large variation in the filter characteristics among different brands of porous-hose.
- Length appears to be a lower order of influence on the filter characteristics when coiled than manufacturing of the hoses.
- A large amount of corner frequency variation was observed within the Fiskers brand (5-18.6 Hz).
- The Garden Rite brand passed 2-4 dB more acoustic signal at 10Hz.
- These tests show the Garden Rite brand has insufficient filter characteristics for monitoring activities.
- Field testing the coil versus the linear hose configuration showed that coiling the hose increased the pass band corner frequency.
- We observe a high variability in the characteristics exhibited by the hose filters. Hoses are typically not part of the calibrated system response. This could result in a great deal of misunderstanding of the amplitude response.
- For coherent signals, as one might expect from an explosive source, we observed no gain or attenuation effects for the 0.01 to 0.1 Hz pass band.
- Above 0.1 Hz we observed an unexpected gain, amplification of the coherent signal, as picked by the sensors with the porous hose attached, by as much as 2.8 dB relative to the collocated open port sensors. Not only was the amplitude affected by the porous hose, we also observed that the relative phase increased and varied in a non-uniform manner (across frequency).

The experiments shown in this report were designed to address the undocumented filtering characteristics of the porous hose wind noise reduction system used at some nuclear monitoring stations. When considering the filtering effects to incoherent acoustic input, the porous hose performs as one would hope by reducing the amplitude of the random acoustic signals at primarily the higher frequencies. The Garden Rite brand appears to have a broader pass band (0.1 to 40 Hz) than the Fisker brand (0.1 to 10 Hz). More work should be done to determine if a larger sample set of Garden Rite hoses have the same filter response to incoherent acoustic input. By addressing the filtering characteristics of the Fiskers brand to coherent signals an unexpected results was observed. The acoustic signals observed by the sensor with the hose attached were of larger amplitude than that of the open port sensor. We are unsure of the mechanism than would cause such an amplification, but are working to explain this effect. As time permits Sandia will continue to conduct experiments to better understand the filtering effects in amplitude and phase that a wind-reducing filter has on both coherent and incoherent acoustic signals.


## ACKNOWLEDGEMENTS

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