

**THE DEVELOPMENT OF METHODOLOGIES FOR DETERMINING
NON-LINEAR EFFECTS IN INFRASOUND SENSORS**

Darren M. Hart, Harold V. Parks, and Randy K. Rembold

Sandia National Laboratories

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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 a primary center for unbiased expertise in testing and evaluation of geophysical sensors and instrumentation for nuclear explosion monitoring. Over the past year, four new infrasound sensor designs were evaluated for common performance characteristics, i.e., power consumption, response (amplitude and phase), noise, full-scale, and dynamic range. In the process of evaluating a fifth infrasound sensor, which is an update of an original design, SNL has observed a higher than expected variability in the sensor's analog output sensitivity as measured in units of volts per pascal. Variations in sensitivity by as much as 15% were observed within one hour. This is an issue because of the International Monitoring System infrasound sensor requirement for the uncertainty in the measurement to be less than 5%. An infrasound two-tone test and an extended duration single tone test demonstrated that this variability was due to large amplitude low-frequency weather signals affecting the response due to a non-linearity in the sensor.

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OBJECTIVES

Over the past three years several infrasound sensor designs have been evaluated for basic performance of sensitivity, linearity, response verification and self-noise. Of these the sensitivity, the conversion factor of the analog sensor's voltage output to measured geophysical unit (i.e., differential pressure for infrasound), should vary in a linear manner when compared to different external influences. Sandia identified one sensor that was observed to vary in its output sensitivity by as over 10% during one hour test. A typical expectation is the sensitivity of the sensors should vary less than 1% when tested against different external variables (e.g., temperature, humidity, barometric pressure, magnetic fields, etc.). Due to requirements to have known responses to within 5%, this sensor design should not be used at monitoring stations. Through two sequences of tests, an infrasound two-tone test and an extended duration single tone test, the initial observations of high variability in sensitivity were confirmed, and allowed us to speculate that the sensor design may have possible issues with non-linear components, out-of-band signal influencing in-band signals, or environmental sensitivities. The following sections describe our investigation into further understanding the observation made while evaluating this specific sensor design.

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

1. Summary of Results
2. Two-Tone Infrasound Test

RESEARCH ACCOMPLISHED

Summary of Results

We describe here our evaluation of a new infrasound sensor design (NSD). Initial tests of the sensors over various frequency and amplitude ranges produced inconsistent results. For example while running piston phone tests to try to measure variations in the sensitivity versus amplitude of a NSD sensor, the sensitivity was observed to vary by as much as 10% from run to run.

We believe that this variability in the NSD sensitivity is related to nonlinearity in the sensor response. Weather changes can easily cause pressure changes of tens of Pa over 10 minutes. The low frequency acoustic response of the NSD can be modeled by a single pole with a corner below 0.01 Hz. This allows the transducer to see pressure fluctuations of several Pa due to meteorological effects and any non-linearity in the transducer response will cause an apparent modulation of a high frequency signal riding on the low frequency background. Our tests were performed in a sealed chamber, but small leaks allow very low frequency signals to couple through efficiently.

To test this hypothesis, we performed a two-tone infrasound piston-phone test, where a 0.8 Pa 1 Hz tone was superimposed on a 9 Pa 0.02 Hz tone. The amplitude of the 1 Hz tone as measured by the NSD showed a 40% modulation in amplitude caused by the 0.02 Hz tone, while reference microphones (a Chaparral 25 and a MB2000) showed a much smaller modulation. We also ran a long duration sine test, where a single 1 Hz tone was applied for 7 hrs. The reference MB2000 sensor showed only a 0.25% variation in the 1 Hz tone amplitude over the duration of the test. The amplitude as measured by the NSD varied by 8%, and is clearly correlated with low frequency fluctuations in the piston-phone chamber pressure.

Two-Tone Infrasound Test

The two tone infrasound linearity test was parameterized to observe how a high amplitude (~9 Pa) low frequency (0.02 Hz) tonal signal can influence the secondary low amplitude (~0.8 Pa) and higher frequency (1.0 Hz) tonal signal. Under our initial assumption that the NSD is a linear system, then we should observe no change of the 1 Hz tone (in amplitude, frequency or phase distortion) on a time scale of the primary tone (i.e., 50 seconds).

Test Configuration

The signal source for this test is the low-frequency low-distortion oscillator (LFLDO) was input to the voice-coil driven piston of our piston phone chamber. The equipment was configured to output a two-tone signal. The first signal was set for 0.02 Hz and 1.3 Volts zero-to-peak sine. The second signal was set for 1.0 Hz and 0.3 volts zero-to-peak sine. A HP3458A multi-meter was used as a calibrated reference to record and verify the linearity of LFLDO two-tone signal. Figure 1 show results of performing sine fit on two cycles of 0.02 Hz tone LFLDO data.

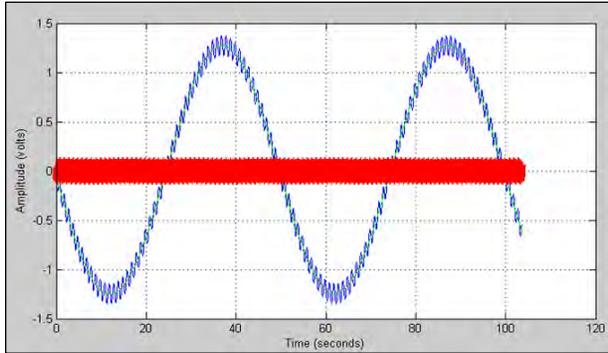


Figure 1. Results from sine fit algorithm for two cycles of 0.02 Hz tone data from the LFLDO during two-tone test. Blue line is output from LFLDO sensor, the green line is the best-fit 0.02 Hz sine model, and the red markers are the misfit between the raw data and the model fit which includes only the 0.02 Hz tone (leaving the unmodulated 1 Hz tone).

From Figure 2 we observe a well centered fit to the 50 second tone, with the misfit residuals on the order of the secondary 1 Hz tone. By bandpass filtering the data from 0.6 to 2 Hz we can also look at the sine fit characteristics of the 1 Hz tone. Figure 3 shows the results of performing the moving window sine fit analysis on two minutes of the LFLDO data set.

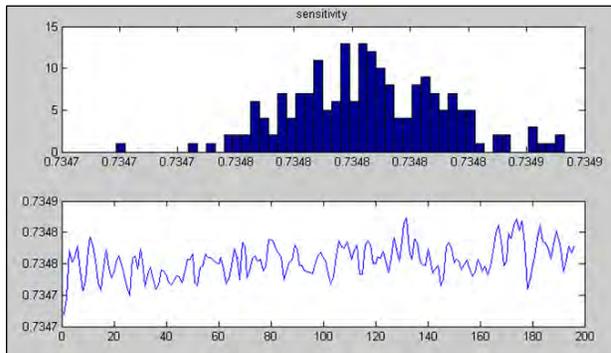


Figure 2 shows the 1 Hz secondary tone has no observable distortion related to the primary 0.02 Hz tone. The distribution has the expected Gaussian shape, with small standard deviation of 2.3×10^{-5} volts.

Figure 2. Results from moving window sine fit algorithm for two minutes of LFLDO data. Data were processed using two cycles of 1 Hz data and 50% window overlap (i.e., 1 cycle overlap). Upper plot is histogram of sine fit amplitudes for two minute window; lower plot is sine fit amplitude as function time along waveform.

Sensor Data

Several days of testing were spent addressing the two tone test set up and data processing for results interpretation. The following data set summarizes observations made during analysis of the complete set of tests.

Test data: 2/25/2010

The digitizer channel to sensor mapping for this test were:

Channel 1 C1P: MB2000 Absolute Pressure attached to chamber

Channel 1 C2P: GRAS 42 AE Microphone attached to chamber

Channel 3 C3P: No sensor

Channel 4 C4P: NSD - 051722 attached to chamber

Channel 5 C5P: Chaparral Physics model 25 082058 attached to chamber

Channel 6 C6P: MB2000 Filtered output attached to chamber

Figure 3 shows the raw data on channels C1P to C6P (waveform index 1-6) and the bandpass filtered, from 0.6 to 3 Hz, data for channels C3PBP to C6PBP (waveform index 7-10). The NSD, Chaparral 25 and MB2000 have been selected (as indicated by the red waveform color), a window 150 seconds (three sine cycles of 50 seconds period) has been set for processing. The GRAS 42AE microphone was not reported on, due to low SNR of the 0.02 Hz signal.

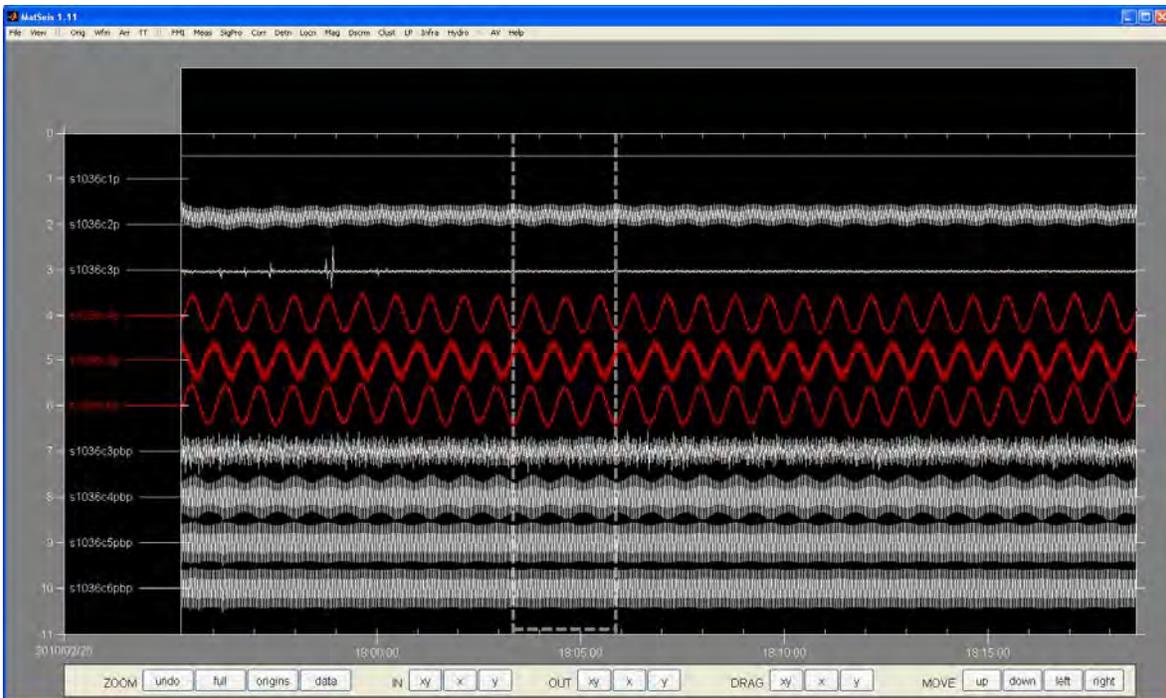


Figure 3. Screen shot of two tone linearity test data. Top six waveforms are raw data from two tone test in which the 0.02 Hz signal dominates. The lower four waveforms are the bandpass (0.6 to 2 Hz) filtered showing the 1 Hz secondary signal. The third trace from the bottom shows the 1 Hz signal from the NSD. The NSD displays a clear modulation in amplitude which is not present on the signals from the two reference sensors immediately below.

Figures 4a-c show the results of a sine fit to the 0.02 Hz signal for the NSD, the MB2000, and the Chaparral 25. The MB2000 and chaparral 25 shows slight drift over time, but no correlation to the primary tone of 0.02 Hz. Observed zero-to-peak pressure of the MB2000 was 7.7 Pa for the Primary 0.02 Hz tone. The NSD has a misfit residual with clear correlation to the primary frequency of 0.02 Hz, with a period of ~25 seconds; this is twice the primary period of 50 seconds, typically called the first harmonic. The SNR differences observed in the Figures 4a-c are due to the different response characteristics of the three sensors.

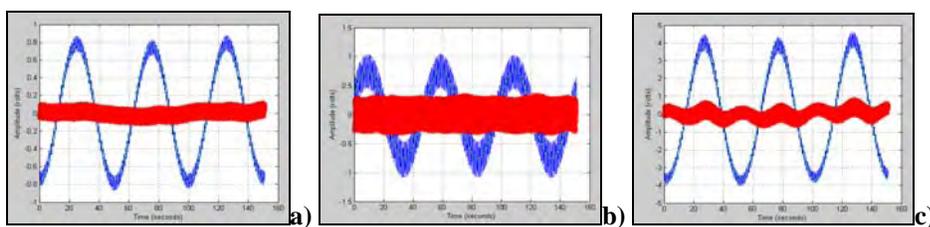


Figure 4a-c. a) MB2000 filtered output showing two-tone signal output in blue, best-fit sine in green, and the RMS residual in red. Misfit uncorrelated, by observation, to primary signal. b) Chaparral 25 output showing two-tone signal output in blue, best-fit sine in green, and the RMS residual in red. Misfit correlated to primary signals by first harmonic (observed as period of misfit). Note that the 1 Hz signal appears much larger relative to the 0.02 Hz signal than for the NSD or the MB2000. This is because the Chaparral 25 response has begins to roll off below 0.1 Hz. c) NSD output showing two-tone signal output in blue, best-fit sine in green, and the RMS residual in red. Misfit correlated to primary signals by first harmonic (observed as period of misfit).

When a narrow bandpass filter is applied to the raw data to remove the primary 0.02 Hz frequency, an interesting observation is made on the NSD and Chaparral 25 output for the 1 Hz tone. First, the NSD's 1 Hz signal has strong amplitude modulation, which can be measured by the modulation index (MI). The modulation index (MI) is calculated by taking one minus the ratio of the minimum (zero-to-peak) amplitude to the maximum (zero-to-peak)

amplitude obtained from a common analysis technique, e.g., our IEEE sine fit method. This was done for the four sensors: the MB2000, NSD and Chaparral 25, and the GRAS 42AE. The modulation indexes are given in Table 1.

Table 1. Modulation index of 1 Hz low amplitude secondary tone.

Sensor M	Minimum Amplitude (V)	Maximum Amplitude (V)	Modulation Index
MB2000	0.080	0.83	0.04
Chaparral 25	0.278	308	0.10
NSD	0.300	450	0.33
GRAS 42AE	0.043	0.45	0.04

From Table 1 the observations of amplitude modulation are quantified and we see relative differences between the sensors in this test. The MI values represent the amount the carrier amplitude varies by above and below its unmodulated level. The NSD and Chaparral 25 have the largest MI values at 33% and 10 % respectively; where both the MB2000 and GRAS both have relatively low MI values at 4%. The zero-to-peak pressure observed on the MB2000 for the 1Hz secondary tone was 0.8 Pa, approximately a factor of 10 less than the primary tone.

The results of this two-tone acoustic linearity test lead us to speculate on the possible reason for the observed MI observed on the NSD and Chaparral 25 sensors. If one starts under the assumption that the each sensor is a linear system, then one should be able to input a two-tone signal into a system and get same two-tone signal out of the system, with only relative amplitude changes based on sensor to sensor differences in output sensitivity. The simplest way to get amplitude modulated output of a two-tone signal is to introduce the first non-linear term in the Taylor series expansion of the model of the sensor. The quadratic term provides a modulation term (the product of two sinusoids of different frequencies) with the coefficient determining the relative strengths it plays in the sensors performance.

This sensor response can be approximates as:

$$V(t) = A * p(t) + B * p^2(t). \quad (1)$$

The V(t) represents the voltage output of the sensors over time, p(t) is the pressure input in the acoustic pass band of the sensor, A is the linear component of the sensors output, and B is the first order non-linear term.

For the two tone test, the input signal is:

$$P(t) = a_1 * \sin(\omega_1 t) + a_2 * \sin(\omega_2 t). \quad (2)$$

If this is inserted into the nonlinear sensor response equation for V(t), then the p²(t) term causes a modulation in the high frequency signal due to the low frequency signal.

Since all of the analysis has been done in the time domain, a longer duration two-tone test was run to look at the spectral content of the two-tone signals to make observations between the sensors. Two known effects of non-linear behavior are harmonic and intermodulation distortions. If harmonic or intermodulation distortions are observed in the spectral analysis, the non-linear explanation for the observations is further supported. Approximately an hour of data were collected. Individual sensor instrument responses were deconvolved from the time domain waveforms and power spectrum computed. The results are shown in Figure 5 for four sensors and the LF LDO. ****Note: The LFLDO does not have a transfer function to pressure, but is plotted along with the infrasound sensors.**** The Acoustic low noise model of Bowman (2004) was added for reference.

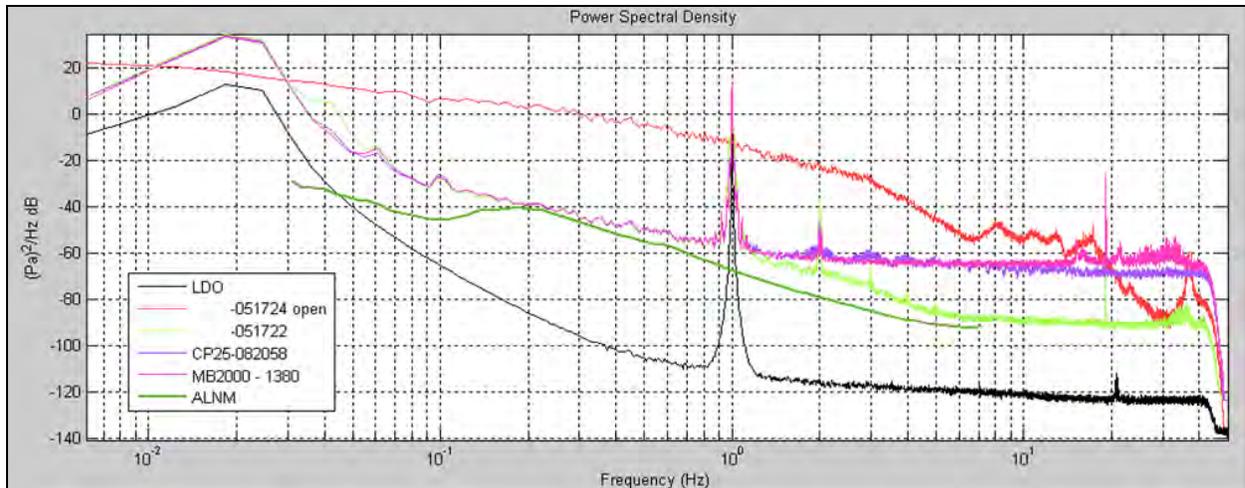


Figure 5. Spectral plot of an hour of two-tone data collected with three sensors attached to the test volume and one recording acoustic background. The red line is a NSD (051724) open to acoustic background, the black is the LFLDO output, the green line is the NSD (051722), the purple line is the chaparral 25 (082058), and the magenta is the MB2000.

From the broad observation the two tones are present in the spectral domain. If we zoom in to each of the tone, more information is obtained. Figure 6 shows the primary frequency of 0.02 Hz, we have less frequency resolution due frequency bin size. But over the broad sense, the spectral results match well except for the NSD. The NSD has extra energy (~10dB) in the area of the first harmonic (~25 seconds).

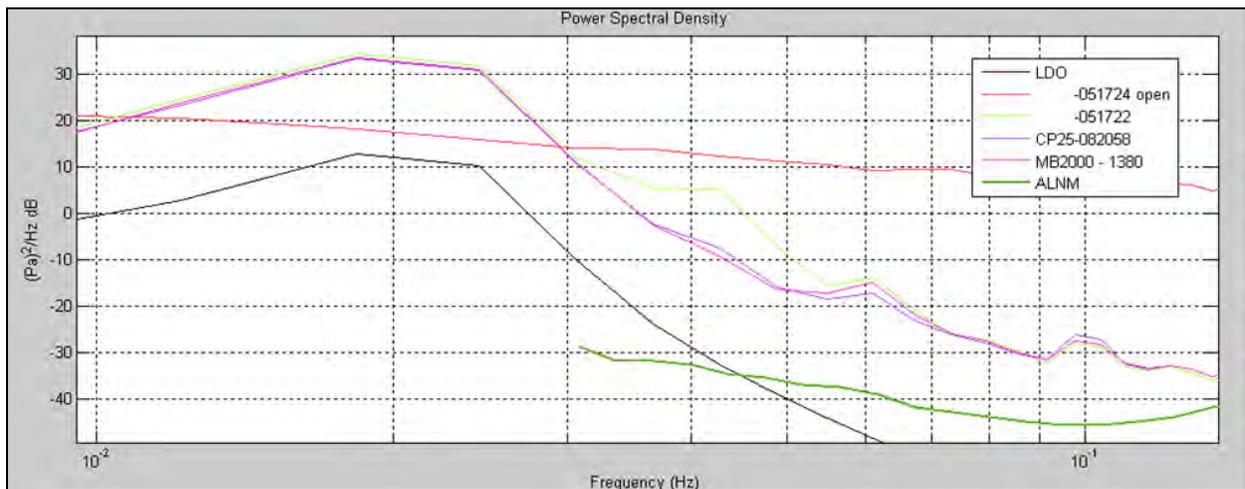


Figure 6. An enlarged view around the primary tone of 0.02 Hz from Figure 5; highlighting the spectral similarities and differences among the three sensor designs.

Figure 7 shows the secondary frequency of 1 Hz, now we have plenty of frequency resolution due frequency bin size. The spectral results match well at 1 Hz, but we observe several differences between the sensors spectral signatures. Each sensor has a second harmonic present, but the observed second harmonic is the largest on the NSD. The NSD also has a strong inter-modulation component, as observed by the spectral shoulders at 0.98 and 1.02 Hz on the green spectral line for the NSD attached to the test volume.

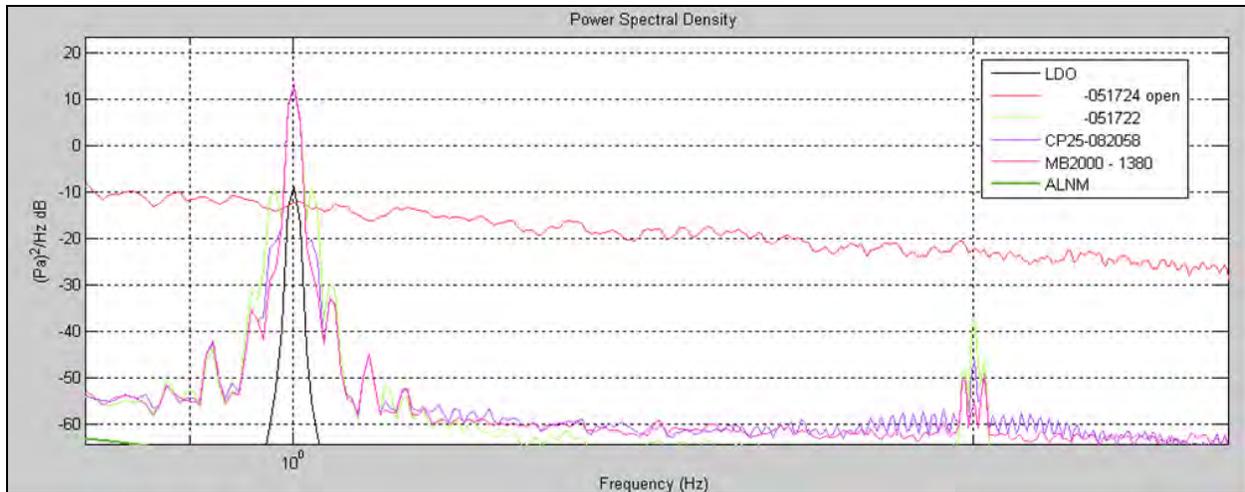


Figure 7. An enlarged view around the secondary tone of 1 Hz from Figure 5; highlighting the spectral similarities and differences among the three sensor designs.

Long Duration Sine Test

The long duration sine test was proposed to characterize the long term variability of the sine fit technique as the technique is applied to different sensors. Five sensors were configured to record the long duration acoustic sine signal. Figure 8 shows the 7 hours of data for this test.

The digitizer channel to sensor mapping for this test were:

- Channel 1 C1P: MB2000 Absolute Pressure attached to chamber
- Channel 1 C2P: GRAS 42 AE Microphone attached to chamber
- Channel 3 C3P: NSD 051724 open to acoustic input
- Channel 4 C4P: NSD 051722 attached to chamber
- Channel 5 C5P: Chaparral Physics model 25 082058 attached to chamber
- Channel 6 C6P: MB2000 Filtered output attached to chamber

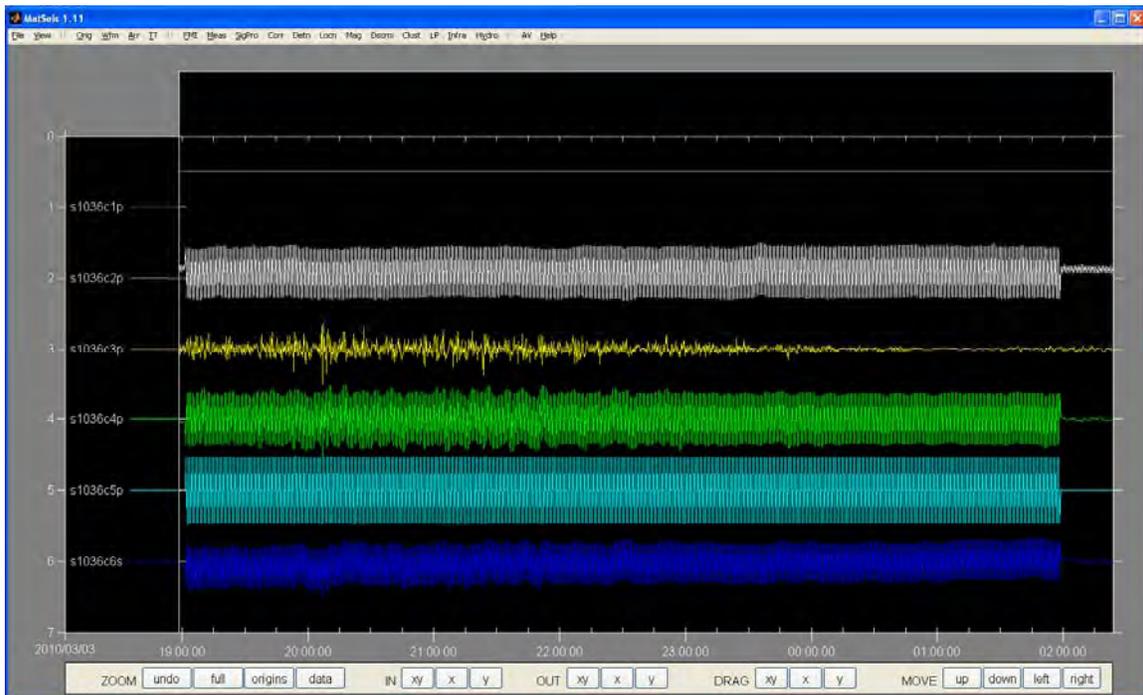


Figure 8. Illustration of the long duration sine test data.

From the raw data we can make a few observations:

1. The NSD open to acoustic background observed a significant change in background activity over the duration of the test. Strong background effects are observed from 2010/3/3 19:00 to 2010/3/4 00:00.
2. The NSD attached to the chamber observed the highest amount of variability of the sine tone over the duration of the test. Variations appear to correlate to observed background changes as seen on the NSD open to acoustic input.
3. The MB2000 filtered output was observed to have a moderate amount of variability of the sine tone over the duration of the test. Variations appear to correlate to observed background changes as seen on the NSD open to acoustic input.
4. The CP 25 attached to the chamber observed the least amount of variability of the sine tone over the duration of the test.

Processing: The data were processed using a standardized IEEE sine fit algorithm. First, a large window is defined which includes the full amount of tonal data to be processed. A smaller window of length defined by two sine cycles with 50% overlap is applied to each waveform and the sine fit parameters (i.e., amplitude, frequency, phase, RMS error, and SNR) are compiled for each realization. Amplitudes were normalized to the average observed amplitude and plots made for the MB2000 filtered output, NSD 051722. Figure 10a shows the results of applying a smoothing technique to remove the 1 Hz signal on the MB2000 filtered output signal. Figure 10b is absolute pressure within the test chamber as measured by the MB2000 absolute pressure output. Figures 10c and 11 shows the reported amplitude values obtained from the sine fit processing for the MB2000 filtered output and NSD 051722 over the seven hours of data.

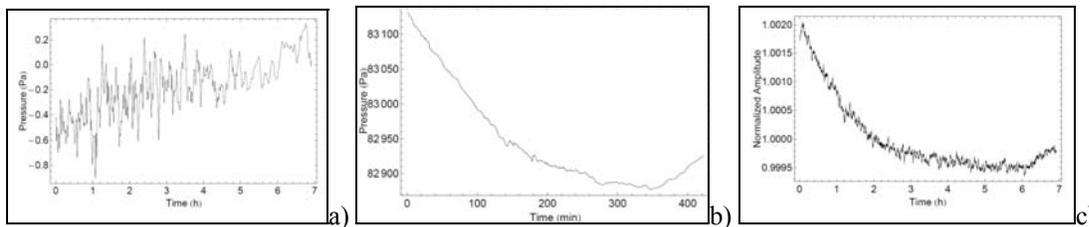


Figure 9a-c. a) MB2000 Filtered output with 1 Hz signal removed using smoothing filter. This is what the raw signal from the MB2000 would have looked like had the 1 Hz signal not been present. b) MB2000 observed absolute pressure within test chamber for long duration sine test. c) Normalized amplitudes obtained from sine fit algorithm for MB2000 filtered output for long duration sine test.

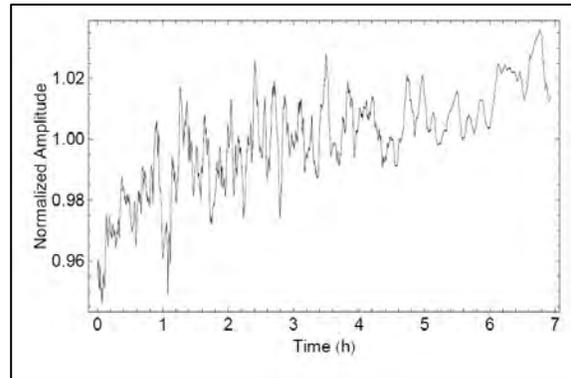
Noteworthy observations from Figure 9a:

1. Small pressure fluctuations (~ 1 Pa) were observed by sensors attached to chamber as documented by MB2000 filtered output with 1 Hz signal removed.
2. Background is coupling into chamber, via leak or transmission coefficient.

Noteworthy observations from Figures 9b and 9c:

1. Normalized amplitudes change by small amount over duration of test, on the order of 0.25%.
2. Strong correlation exists to the observed acoustic background coupled into the test chamber when compared to MB2000 absolute pressure output of Figure 9b. This is because the piston phone output is proportional to the ambient chamber pressure.

Figure 10. Normalized amplitudes obtained from sine fit algorithm for NSD - 051722 for long duration sine test. This signal looks very similar to Figure 10a, but it is from a different sensor processed in a different way. Figure 9a shows the background signal as seen by the MB2000 absent the 1 Hz signal. This plot shows the modulations in the 1 Hz signal that are present in the NSD output.



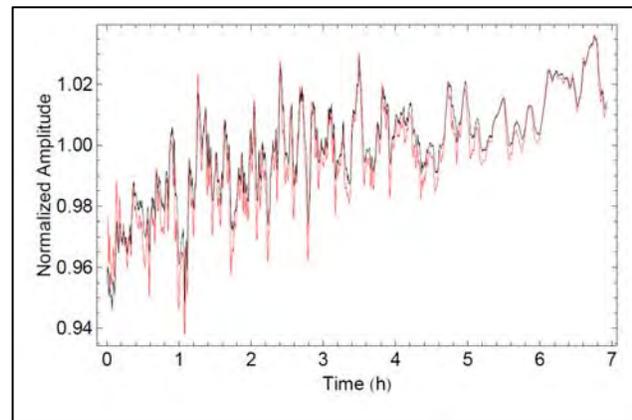
Noteworthy observations between Figures 9a and 10:

1. Normalized amplitudes change by significant amount over duration of test, on the order of 8%.
2. Strong correlation to coupled acoustic background observed on MB2000 filtered output shown in Figure 10a.

From the above results we observe the normalized sine fit amplitudes for the NSD and MB2000 filtered output are not correlated. Yet, the MB2000 filtered output background signal (once the 1 Hz signal is removed) and the NSD 1 Hz amplitude are strongly correlated.

For comparison, the MB2000 1 Hz signal removed filtered output (Figure 9a) data was biased and scaled (i.e., scaled by 8% and added 1) and plotted with the normalized output from the NSD 051722. Figure 11 shows this comparison with the NSD data in black and the MB2000 AP data in red.

Figure 11. Normalized amplitudes from sine fit algorithm for NSD - 051722 are shown in black. Background pressure fluctuations measured by the MB2000 are shown in red (the red trace was generated by taking the MB2000 filtered output and removing the 1 Hz signal). A very strong correlation between the NSD amplitude modulations and the background pressure fluctuations is observed.



The strong correlation between the background pressure fluctuations and the NSD is clear. This leads us to believe the NSD sensitivity is influenced by the pressure fluctuations, as observed from within the test chamber. As with the two tone test, the low frequency background causes a modulation in the apparent amplitude of the high frequency test signal as seen by the NSD. We note that we can filter the 1 Hz signal from the NSD output. Background fluctuations similar to those seen in Figure 10a are apparent but they do not exactly match the signals plotted in Figure 11. This is because the electronic filtering in the NSD distorts the low frequency signal that comes directly from the diaphragm. However the single electronic pole in the MB2000 low frequency response closely matches the single pole acoustic filter that is built into the NSD due to the leak between the fore and back volumes.

CONCLUSIONS AND RECOMMENDATIONS

To summarize, the two-tone test allows us to observe harmonic and inter-modulation distortion on varying levels for the sensors in this test. Both harmonic and inter-modulation distortions were observed and are known as measures of non-linearity. The long duration sine test allowed us to show the NSD design has a clear correlation between the background pressure fluctuations and the observed amplitude modulation. The results of this investigation have been forwarded to the manufacture and were immediately addressed. The primary non-linear component was identified and modifications were made to replace this component. Future work should focus on quantifying the non-linearity quantity of modulation index for different sensors designs using this newly developed two-tone infrasound linearity test.

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