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Viability of Acoustic Techniques for Density and Mass Flow in Enrichment Plants

Status Update Report

June 2016

P Ramuhalli
KM Denslow
MS Good
AM Jones
G Longoni
TL Moran
S Roy
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GA Warren

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Richland, Washington 99352

Summary

A key enabling capability for enrichment plant safeguards approaches being considered by the International Atomic Energy Agency (IAEA) is high-accuracy, non-invasive, unattended measurement of UF_6 gas density and mass flow rate. The Office of Defense Nuclear Nonproliferation is funding this project to evaluate the viability of acoustic techniques for measuring density and mass flow rate of UF_6 gas in scenarios typical of gaseous centrifuge enrichment plants, with the goal of achieving better than 1% measurements. This report is a review of the progress in the first five months of the project. Initial results are encouraging:

- Air is a suitable surrogate gas for UF_6 for the initial research effort
- Measurable acoustic energy transferred through the air from the transmitting to the receiving transducer for equivalent UF_6 pressures of 10 Torr.
- There is a monotonic relationship between air pressure and acoustic energy transferred through the air for equivalent UF_6 pressures down to10 Torr.
- The acoustic energy transferred through the air is observable above the acoustic energy transferred through the pipe wall.

While there is considerable research left to determine the viability of using acoustic techniques to noninvasively measure the gas flow for gaseous centrifuge enrichment plants, these initial results are very encouraging and warrant the continued research effort.

Acronyms and Abbreviations

GCEP	Gaseous Centrifuge Enrichment Plant
IAEA	International Atomic Energy Agency
kHz	kilo-Hertz
OD	outer diameter
OLEM	Online Enrichment Monitor
SNR	signal-to-noise ratio

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1.0 Introduction

The primary purpose of this research is to study the feasibility of acoustic signatures and sensors that could support the accurate, noninvasive and unattended measurement of UF_6 gas density and mass flow rate in scenarios representative of uranium enrichment plants under safeguards by the International Atomic Energy Agency (IAEA). The findings from the demonstration of a preliminary prototype design and first-generation analysis algorithms in this project will inform the safeguards community as to whether continued instrument and methods development are warranted.

1.1 Acoustic Measurements for Flow Rate and Density - Overview

Acoustic measurements provide a means for determining flow rate in a pipe using non-invasive ultrasonic transducers to propagate sound across the pipe. Sound is alternately transmitted in the direction of gas flow and against it to measure the time difference (Δt) between the two cases. The Δt value is then used with the cross-sectional pipe area and *a priori* sound velocity in the gas to calculate the average flow velocity through the pipe. A flow profile correction is performed to obtain the area averaged flow velocity, which is proportional to the volumetric flow rate. A conceptual illustration of this is provided in Figure 1. Gas density measurements, which use the same transducers, are estimated in one of two ways – either by measuring the attenuation of the acoustic energy as it propagates within the gas, or through a measurement of the acoustic impedance of the gas. For gas density measurements, in particular, the pressure may be used as a proxy for density, assuming that the ideal gas law holds. The combination of gas density and flow rate is used to obtain the mass flow rate of the gas.

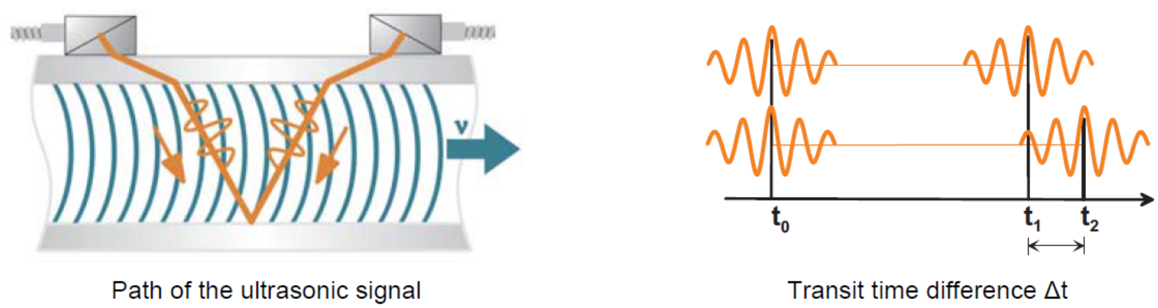

Figure 1: Illustrations of ultrasonic transducer configurations on and sound propagation through a pipe (left) and ultrasonic signals collected and analyzed for determining flow rate (right).

Acoustic flow meters have typically been applied to measuring flow rates in liquids (Lynnworth 1989), but they have recently gained popularity in the measurement of gases (Zarkova and Hohm 2002), though research in conditions representative of the safeguards scenario have been limited (Mohanty et al. 1975; Shakkottai et al. 1990). Much of the research on high-precision measurements in low-pressure gases requires contact between the acoustic probe and the gas; i.e., they are invasive measurements and not suited for this safeguards application (Hamot et al. 1989; Haran 1988; Mohanty et al. 1975). Several acoustic gas flow meters are available; however, these systems are limited in their applicability with respect to pressure and flow rates. For example, the General Electric CTF878 Flow meter is a commercial system for measuring gas flow, typically natural gas (GE 2009). The minimum operating pressure of that system is 1 atmosphere absolute (760 Torr), with an accuracy of better than 2% and repeatability better than 0.6%. Note that in higher-pressure applications (such as natural gas flow metering), ultrasonic flow meters achieve better than 1% accuracy with repeatability around 0.2%.

1.2 Acoustic Measurement Challenges in the GCEP Scenario

Noninvasive acoustic measurements offer a potential approach for independent measurement of pressure and mass flow rates in gaseous centrifuge enrichment plants (GCEPs) and can potentially support Online Enrichment Monitor (OLEM) measurements.

However, several factors challenge the ability to make reliable noninvasive acoustic measurements:

- Structural modes: Noninvasive acoustic measurements of gas-filled pipes requires acoustic energy transmission across the pipe wall-gas interface. The amount of energy transmitted is a function of the acoustic impedance mismatch across this interface, and for typical gases at atmospheric pressure, only a small fraction (about 1% or less) is transmitted. The rest of the energy is coupled into stress waves that propagate within the pipe structure, and interfere with the desired gas-coupled signal.
- Low pressures and variable temperatures: In the GCEP safeguards scenario, the gas in the unit header pipes is at very low and highly variable pressure/density. Gas pressures encountered (10–50 Torr) are more than two orders of magnitude lower than for the targeted application of commercial systems. While some of the measurement methods and sensor types utilized in commercial systems may be relevant to the GCEP application, novel approaches to extracting a weak gas signal from significant background terms are needed. Pressure wave (i.e., acoustic wave) propagation in gases at such low pressures is challenging and the resulting measurement is expected to have a low signal-to-noise ratio (SNR). In addition, the temperature in a typical GCEP plant varies over time (by about 20-30 degrees Celsius), and impacts the speed at which acoustic waves travel in the gas.
- The potential presence of wall deposits: Wall deposits of UF_6 are expected in GCEP header pipes. However, the exact thickness of deposits is often unknown and it is unclear at this stage whether such deposits will affect the ability to transfer energy across the pipe-gas interface.

Given these potential challenges to making noninvasive acoustic measurements in this application, a decision point was established within the project to determine if sufficient potential for reliable measurements exists. This report documents the findings of research to address the decision point.

2.0 Technical Approach for Acoustic Measurements

2.1 Key questions

For this project, several technical questions were formulated as a first step in addressing the general problem. These are:

1. Is there a signal at relevant pressures? – The question stems from the fact that at extremely low gas pressures (10–50 Torr), there may not be sufficient material medium (gas molecules) for the transmission of acoustic waves. Thus, it will be imperative to understand whether acoustic waves can travel across the pipe diameter at such low pressures, and also overcome acoustic impedance

mismatch at the pipe-gas interface to result in a signal of considerable strength that show sensitivity to the variations in pressure.

2. If so, can this signal be measured in the presence of noise? – The next challenge is to determine if the gas-coupled acoustic signal can be measured in the presence of noise. Noise will not only be due to the limitations of the hardware and instrumentation such as measurement drift, resolution error, and hysteresis, but will also be present in the form of background structural signal due to the propagation of stress waves along the pipe walls. It may turn out that the resulting noise may completely mask any contribution from the gas-coupled acoustic signal in the desired pressure range.
3. What is the optimum frequency, and what are other relevant measurement parameters for reliable measurements? – The next step would be to optimize the measurement parameters and sensing configuration in order to achieve a high signal to noise ratio (SNR) in the desired pressure range.
4. What are the uncertainties in the measured quantities? – Given that there a measurable signal of sufficient strength at the desired pressure range, the next challenge would be to quantify the uncertainties in measured quantities such as signal amplitude, time-of-flight, signal energy, and spectral information.
5. What are the uncertainties in the inferred quantities (i.e., pressure, density, and mass flow rate)? – This question deals with the ability to quantify the relationship between uncertainties in the observables and uncertainties in the inferred quantities related to the gas flow and gas density in the unit header pipe.
6. How can uncertainties be minimized? – The concluding step in this research would be to explore possible avenues to minimize the uncertainties in both the observables and the inferred quantities.

The decision point is primarily focused on the answers to the first two questions, as the availability of a measurable signal above the noise floor is critical to the project. This report focuses on answers to these first two questions and includes early research towards answering the remaining questions.

2.2 Limitations

The focus of the initial research is on measurements in a static setting, i.e., without gas flow. Furthermore, air is used as a surrogate for UF_6, which is discussed below.

2.3 Technical approach

The technical approach to answering these questions (and specifically the first two questions) revolves around three elements:

- Choice of an appropriate surrogate gas
- Acoustic measurements at pressure in the absence of structural noise
- Acoustic measurements at pressure in the presence of structural noise

In all cases, the measurements will need to be made using commercially available acoustic probes and instrumentation. The technical activities and capabilities developed for addressing each of these elements is described next.

2.3.1 Selection of Surrogate Gas

In general, the choice of a surrogate gas for UF_6 appropriate for acoustic measurements is a difficult proposition given the high molecular weight and density of the gas. However, for the purposes of acoustic measurements, the important quantities are acoustic impedance (which dictates the amount of energy transferred to the gas) and acoustic attenuation (which dictates the amount of energy available after the wave-gas interaction for measurement). The impedance is not a function of the frequency, but the attenuation is, and so the problem becomes one of jointly selecting frequency and the surrogate gas.

Based on calculations of acoustic impedance and attenuation, and using the values for attenuation in UF_6 documented in the literature ((Cravens et al. 1979; Bass and Rogers 1984; Bass et al. 1983), air was selected as the surrogate gas for initial measurements and assessment of the concept. The acoustic impedance of air (between about 30 Torr and 150 Torr) is a good match for that of UF_6 between 10 Torr and 50 Torr. However, the speed of sound in air is about 3.5 times faster than that in UF_6, and at the excitation frequencies examined in this project and the pressures noted above, the attenuation of air is roughly on the same order of magnitude of attenuation in UF_6. Note that air (due to the presence of O_2 and N_2 molecules) exhibits resonance behavior in its attenuation characteristics as a function of frequency. However, such behavior is at frequencies less than 50 kHz. Experimental data for UF_6 does not appear to show similar resonant behavior (Cravens et al. 1979).

ANSYS (a commercially available simulation software package for simulating acoustic wave and structure interaction) was used for simulating acoustic wave generation from acoustic transducers, interaction of the wave with the header pipe resulting in the generation of structural modes (structural signal), and the acoustic wave transmission and propagation in the gas (gas-coupled signal). The net received signal from an acoustic sensor due to the superposition of structural signal and gas-coupled signal on the opposite side of the pipe (Figure 2) was calculated from the simulations. Two sets of simulations were performed – one for air and the other with UF_6 – and the results analyzed to determine if air was an appropriate surrogate for UF_6.

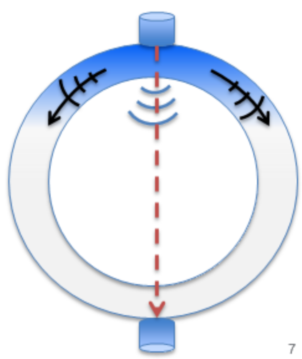

Figure 2. Cross-section of transmit and receive transducers arranged around the header pipe, with the structural and gas-coupled signals shown.

Figure 3 shows the results of this comparison between air (at 122 Torr) and UF_6 (at 40 Torr). These results show that the resulting signals are very similar, but the signals from UF_6 are delayed in time. This delay is expected due to the slow speed of sound in UF_6 when compared to air. *These, and similar results at other pressures, indicate that air, under appropriate pressure and frequency constraints, is a suitable surrogate for UF_6 for the purposes of acoustic measurements.*

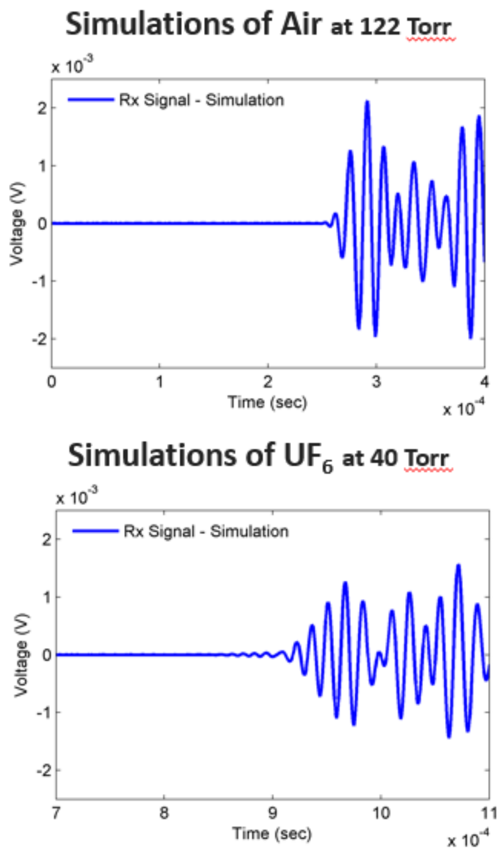

Figure 3. Simulated signals (using ANSYS) for air at 122 Torr (top) and UF_6 at 40 Torr (bottom).

2.3.2 Acoustic Measurements on Horizontally Split Pipes in Vacuum

Acoustic measurements in the absence of structural noise are easily accomplished using a pipe section split horizontally, thereby eliminating any direct structural connection between the transmit and receive sensors in Figure 2. However, maintaining this arrangement at low pressures requires a vacuum chamber (Figure 4). Transducers operating at multiple frequencies were adhesively bonded to the pipe, giving the ability to measure the gas-coupled signal at a number of frequencies.

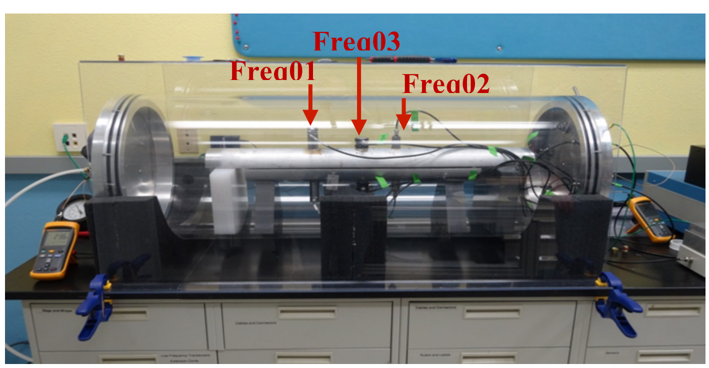

Figure 4.Vacuum chamber with horizontally split pipe. Transmit and receive transducers operating at different frequencies enable rapid measurements at a range of frequencies.

2.3.3 Acoustic Measurements with Structural Noise

Acoustic measurements in the presence of structural noise may be obtained through measurements on a sealed pipe, evacuated using a vacuum pump (Figure 5). Transducers applied on the external surface of this pipe will result in both structural and gas-coupled signals. While such measurements are relatively simple, previous measurements on similar setups has shown that the structural signal (noise) can be very high, resulting in an SNR less than 1. The SNR is improved through the use of appropriate damping mechanisms to absorb and dissipate structural signals.

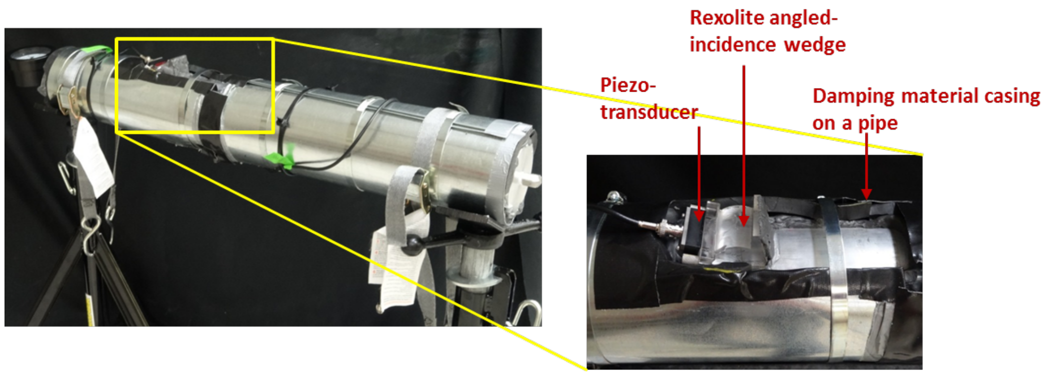

Figure 5. Sealed pipe, evacuated to pressures as low as 30 Torr. Transducers for acoustic measurements are bonded on either side of the pipe.

3.0 Results

The measurement systems described above were used to obtain a series of measurements to answer the various questions described earlier. A summary of the findings, organized in the same order as the list of questions in Section 2.1, is provided below.

3.1 Is there a signal?

There are two parts to this question. First, does a measurable acoustic gas-coupled signal exist? Second, does this signal show a measurable trend with pressure? Figure 6 shows an example of the measured signal, showing a strong gas-coupled signal at the expected time of arrival in air. The signals, measured at 150 Torr and 30 Torr, are shown in Figure 6 on the right. The data from this probe and similar results at other frequencies clearly show a measurable signal at the lowest pressure of interest.

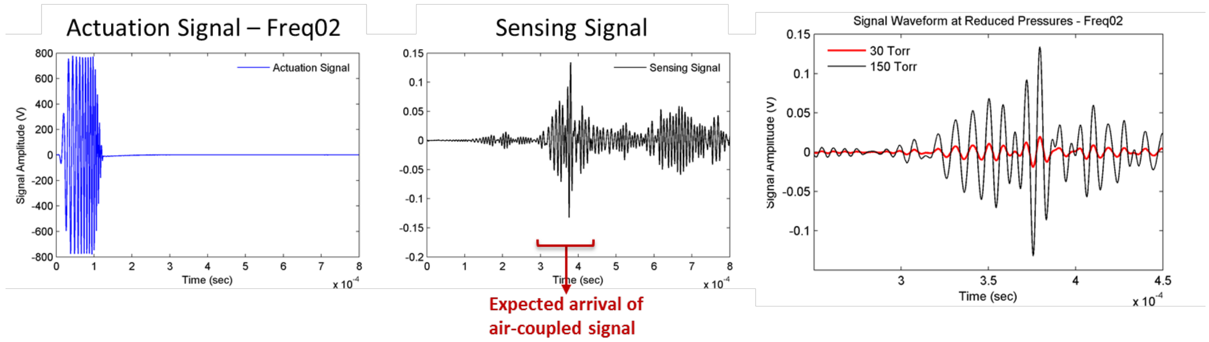

Figure 6. Measured signals in the absence of structural noise: applied excitation (left), measured response (middle), and gas-coupled signal at 150 Torr and 30 Torr.

Figure 7 shows the energy in the gas-coupled signal as a function of pressure at three different excitation frequencies. The data for the pressure range of interest (30 Torr – 150 Torr) is shown in expanded plots in the same figure. The data presented in this graphic shows 10 replicates (over a three-week period) and the 1-σ error bars computed from the replicates. As seen from the measurements, the data exhibit a measurable trend (with high repeatability) over the pressure range of interest. However, the trend at high frequencies (Freq03) and low pressures is not linear and the data exhibit signs of saturation. This is likely due to an increased attenuation at higher frequencies, an effect exacerbated by the increasing attenuation at lower pressures. However, in the absence of any structural noise, a measurable, repeatable signal that is correlated to the pressure (and therefore the density) is clearly present.

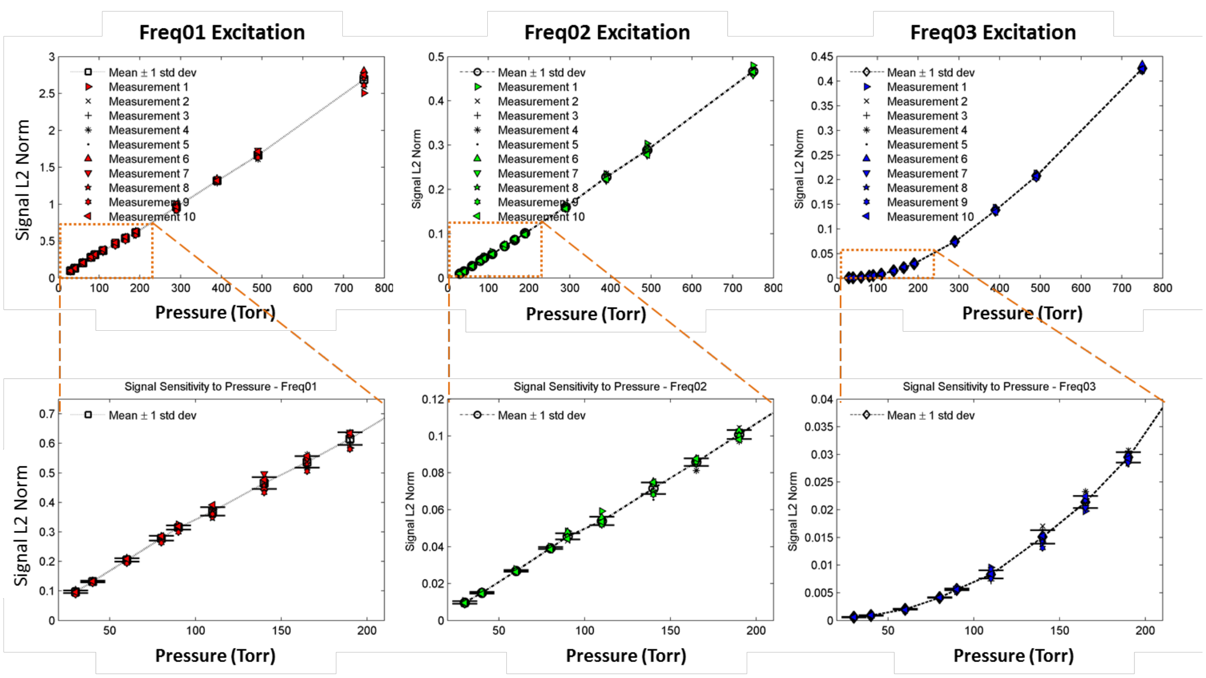

Figure 7. Acoustic gas-coupled signal energy as a function of pressure, at three different frequencies.

3.2 Can the signal be measured in the presence of noise?

Figure 8 shows an example of the measurements from the full pipe setup. Unlike the measurements on the split pipe in vacuum chamber, the acoustic probe setup was modified to resemble the probe setup needed for flow rate measurements. However, the measurements in Figure 8 are for a static arrangement (no flow).

This particular arrangement of probes results in the pipe section acting as a resonator, amplifying the gas-coupled signal by providing multiple opportunities for the structural signal to interact with the gas. The structural signal itself travels at a much higher speed than the gas-coupled signal and arrives at the receiving probe relatively early. As discussed earlier, appropriate damping mechanisms are used to reduce the structural signal. The result is a gas-coupled signal that is separated in time from any remaining structural signals. This gas-coupled signal is seen to change with pressure, indicating that the necessary signal may be measured in a repeatable manner in the presence of noise.

3.3 Optimal Frequency Selection

Figure 9 shows the signal-to-noise ratio for different frequencies as a function of pressure. The data in this plot includes both the split pipe measurements as well as the measurements from the full pipe. In an ideal scenario, the SNR would be constant as a function of pressure. This is generally the case, as seen from the lower frequency measurements in the split-pipe setup. The increased attenuation at lower pressures results in a slight drop in SNR. However, it is apparent from the high frequency (Freq04) measurements on the full pipe that the SNR is a continuously decreasing function of pressure. This is likely due to two factors – the increasing attenuation as pressure decreases, and the increased attenuation at higher frequencies. Further, the presence of a strong structural signal, which generally increases as the frequency decreases (Figure 10), results in a much higher noise floor.

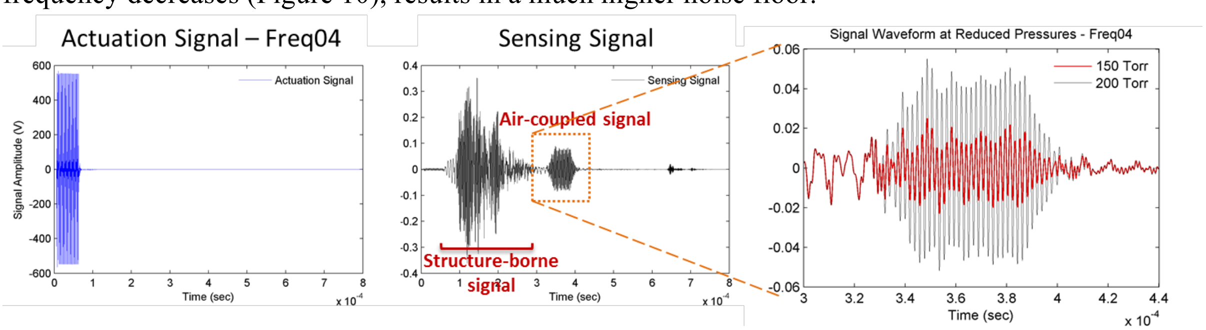

Figure 8. Measurements of gas-coupled signal in the presence of structural noise.

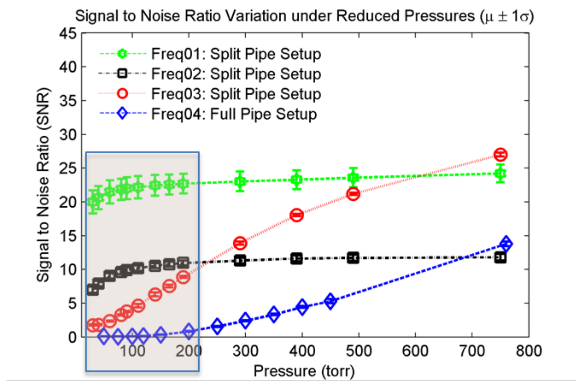

Figure 9. SNR as a function of pressure and frequency.

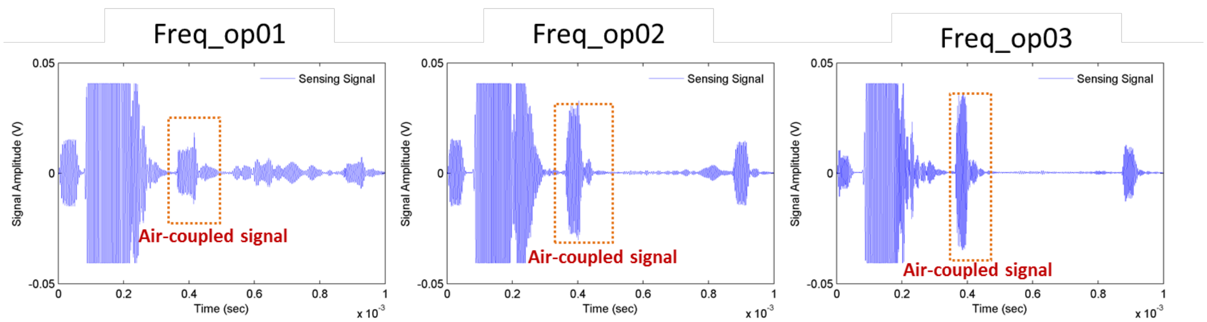

Figure 10. Measurements (at 760 Torr) as a function of increasing frequency from Freq_op01 to Freq_op03 showing increasing structural signal and reduced gas coupled signal (i.e., lower SNR) as frequency decreases.

3.4 Uncertainty in Observables

The data in Figures 7 and 9 summarize the variability in the gas coupled signal energy from 10 replicate measurements. The variability in the data comes from several sources, including environmental variations (in temperature and humidity), drift in instrumentation, and electronic noise. Limitations on accuracy of some of the instrumentation (used for measuring the environmental variables) also contribute to the overall measurement uncertainty. Based on the available data, the overall uncertainty in the measurements (observables – specifically the gas coupled signal energy) is approximately 5%. However, this uncertainty leads to uncertainty in the calculated quantity (pressure) and ultimately in the mass flow rate. This propagation of uncertainty has not yet been quantified, and is expected to be completed over the course of this project.

3.5 Uncertainty in Calculated Quantities

The goal of this project is to achieve 1% uncertainty on the mass flow. However, this goal is vaguely defined. After discussions with OLEM subject matter experts, it was decided that a better-defined goal is to measure 1% uncertainty of the mass flow during the reporting period of the OLEM, which is typically two hours. For the moment, the focus will be on precision, assuming that calibrations can resolve uncertainties related to accuracy. It is possible to take many acoustic measurements over the span of two hours. The natural question to pursue is what is the necessary precision required for each sample, as a function of sample rate, to achieve the 1% uncertainty? A simple Monte Carlo model was built to evaluate this question, with one of the results shown in Figure 11. This figure shows the sample rate required to achieve a desired level of uncertainty for a given sample precision. For instance, at 3% measurement precision, a 5 samples per hour or more is required to achieve a measurement uncertainty over the reporting time of 1% or less. *By aggregating the results from multiple samples, it is possible to significantly relax the required precision for any one sample measurement and achieve 1% uncertainty.*

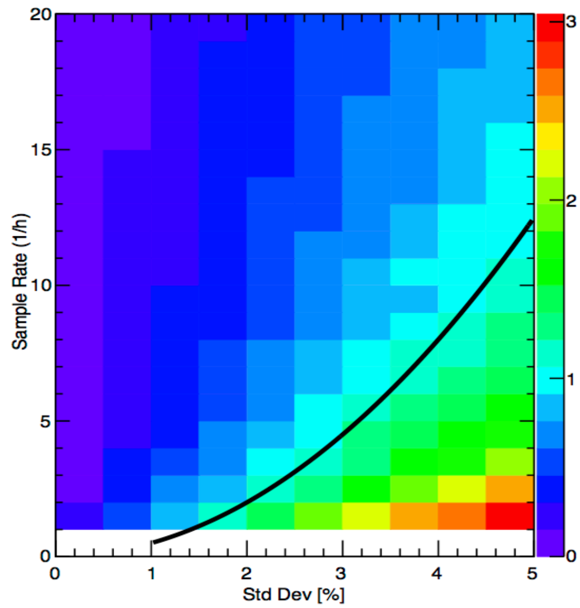

Figure 11. Results from Monte Carlo showing the uncertainty in the extraction of the mass as a function of the sample rate and the precision of the sample assuming an exponential dependence on the pressure. The color axis is in percent. The black line represents the ideal statistical case for 1% uncertainty.

3.6 Approaches to Reduction in Uncertainty

As discussed earlier, there are many sources of uncertainty in the observable that contribute to the uncertainty in the mass flow rate. The impact of these sources of uncertainty may be minimized using a combination of improved instrumentation and data processing. For instance, low noise instrumentation, along with filters (powerline filters and signal filters) have already contributed to reducing the measurement uncertainty in this project. Averaging of multiple measurements is being performed to minimize the impact of electronic noise. High precision instrumentation is being used to measure ambient conditions, and used in measurement compensation for variability in these quantities. As the project progresses, these techniques will continue to be used. In addition, improved analysis methods are expected to further reduce the impact of these sources of variability.

4.0 Summary

This document summarizes the results of research to date, to assess the feasibility of using acoustic measurements in low-pressure environments for measuring pressure, density and flow rate for calculating UF_6 mass flow rates in GCEP. Based on the results to date, the approach is seen to be promising with acoustic measurements shown to be possible at the desired pressures. However, additional research remains to be done to complete the viability assessment. The focus of ongoing research is on:

- Completing measurements to identify a narrow range of acoustic frequencies that provide the best tradeoff between measurement sensitivity and attenuation.
- Designing and fabricating a low pressure gas flow loop, and measuring gas flow rate using acoustic methods.
- Improved uncertainty quantification approaches for calculating the total uncertainty in the mass flow rate.
- Design and fabrication of a static cell for measurements with UF_6.
- Deploying and evaluating the measurement methodology on a UF_6 flow loop.

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