



Characterization of Quartzdyne Pressure Transducer Frequency Response

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ABSTRACT

In an effort to continuously improve product specifications, Quartzdyne has initiated an effort to understand the frequency response of its pressure transducer products. Mechanical and electrical systems, such as Quartzdyne transducers, generally have limited response times restricting higher frequency throughput. Both mechanical and electrical frequency response limitations of Quartzdyne transducers are studied in this report.

INTRODUCTION

Quartzdyne transducers operate using quartz thickness shear mode resonators with output frequencies proportional to pressure and temperature. A tradeoff between achievable frequency response and resolution occurs due to the nature of electrical circuits that count these frequencies. Circuit limitations are one factor to consider when sensing higher frequency pressure signals.

Quartzdyne transducer frequency responses are also limited mechanically. High frequency pressure signals compress and expand transducer components including the bellows, pressure fluid and pressure sensor. As frequencies increase, these components must deform faster reaching a limit where they simply cannot respond quickly enough. This limits the transducer's maximum detectable pressure frequency.

COUNTING CIRCUIT LIMITATIONS

In Quartzdyne transducers, achievable resolution and sampling frequency are directly proportional. The transducer crystal output oscillations are counted and compared with a known time base to determine frequencies. These frequencies are used as parameters in polynomial curve fit equations to determine pressure and temperature. This sensing method yields excellent accuracy and resolution, but also limits the transducer sampling frequency. In order to increase the sampling frequency of the transducer, one must choose to limit the achievable resolution by reducing the gate time as shown in the equation below. Given this limited resolution, high frequency signals must have sufficient amplitude to be distinguishable.

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$$R = \frac{F_p}{S} \left(1 - \frac{t_g}{t_g + \varepsilon + \frac{1}{F_R}} \right)$$

Where

F_p → Pressure frequency

S → Pressure sensitivity

t_g → Gate time

ε → Pressure frequency jitter

F_R → Reference frequency

Typically, Quartzdyne circuits have 100 ns of jitter, 7.2 MHz reference frequency, 2.5 Hz/psi sensitivity, and max pressure frequency of 100 kHz. Using these quantities along with a 1 second gate time, the achievable resolution is 0.01 psi. This is excellent resolution but note the gate time limits the sampling frequency to 1 Hz resulting very low achievable frequency response. Assume one wishes to sense pressure signal frequencies up to 500 Hz. The Nyquist criterion¹ dictates that the transducer must be sampling at twice the maximum frequency of interest or 1 kHz (1 millisecond gate time). Recalculating the achievable resolution with a 1 millisecond gate time gives 9.55 psi. Therefore, the high frequency portion of the pressure signal to be sensed must have tens of psi in amplitude. Clearly, the relationship between sampling frequency and achievable resolution is significant, and end users must carefully choose gate time to meet the requirements of a given application.

MECHANICAL LIMITATIONS

Pressure signals that are presented to the bellows of a transducer must then be transmitted through the bellows and fluid to the pressure sensor. During this transmission, the bellows and fluid generate miniscule amounts of heat that represent loss in the system. These losses increase with frequency limiting the maximum achievable frequency that can be distinguished by the sensor.

Quartzdyne engineers have tested the mechanical frequency response of transducers by deforming the bellows with known input frequencies and measuring the response using a spectrum analyzer. Note that these experiments were run without frequency counters eliminating the counter circuit limitations described above.

¹ http://en.wikipedia.org/wiki/Nyquist_frequency

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EXPERIMENT METHODOLOGY

The act of inducing a change in pressure into a transducer is performed on a daily basis during calibration and R&D tests. However, inducing pressure changes at high frequency posed a unique challenge. The solution comprised the coupling of an audio speaker to the pressure transducer bellows (Figure 1).

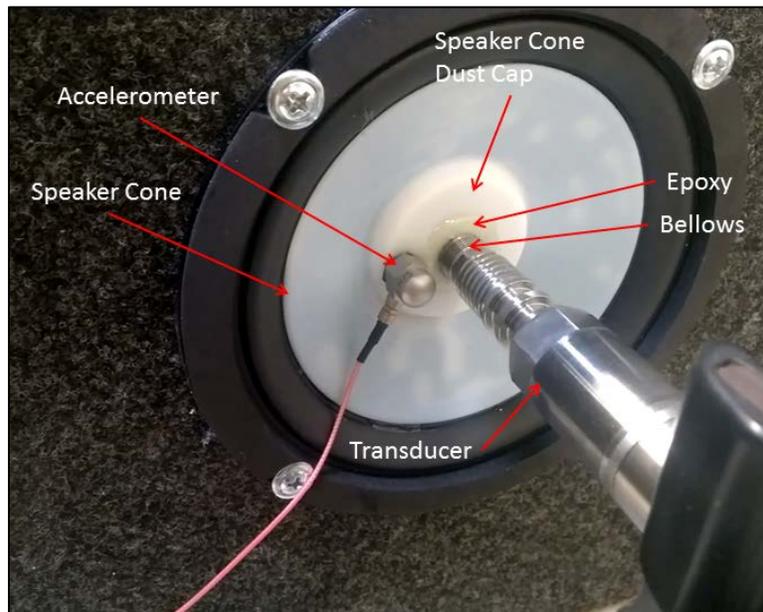


Figure 1. Transducer is attached to speaker to generate displacement and pressure. The accelerometer is present to control the experiment and create similar pressure changes at all tested frequencies.

A software sine generator was routed from a PC to a power amplifier. The amplifier in turn drove the speaker which then induced pressure changes into the sensor. A control accelerometer was placed in very close proximity to the transducer bellows interface to monitor the speaker response and normalize the displacement of the bellows at all frequencies. With the displacement at all frequencies held constant, it is presumed that the pressure increase within the transducer housing is also constant.

A 30K PSI 200C (P/N QMB015-30-200) was used for this testing. The results should be applicable across all frequency output product offerings.

In order to create constant displacement at all frequencies using an accelerometer, one must find a relationship between acceleration and displacement. Assume the displacement of the speaker/bellows interface is described as

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$$x(t) = \sin(\omega t)$$

Where

$\omega \rightarrow$ radian frequency (rad/s)

$t \rightarrow$ time (s)

Acceleration is found by applying the second derivative with respect to time

$$a(t) = \frac{d^2}{dt^2} x(t) = -\omega^2 \sin(\omega t)$$

This equation leads to the understanding that two signals will have similar displacements when their accelerations are related by the square of ratio between their frequencies. The table below demonstrates this relationship and describes the accelerations used for the following experiments.

Table 1. Accelerations chosen to ensure similar pressure changes at all frequencies.

Frequency (Hz)	Acceleration (g)
250	1
500	4
750	9
1000	16
1250	25
1500	36
1750	49

Using a speaker coupled to the bellows frequency modulates the pressure signal as shown below.

$$P(t) = \sin[2\pi F_{P0}t + x(t) * K * S]$$

Where

$F_{P0} \rightarrow$ Pressure frequency without pressure applied

$S \rightarrow$ Pressure crystal sensitivity

$t \rightarrow$ Time

$K \rightarrow$ Constant relating displacement and housing pressure

For small pressure (frequency) changes, the spectrum of $P(t)$ is simply a large peak at F_{P0} with a series of side lobes on either side separated by the modulation frequency, ω . These spectra were obtained using a spectrum analyzer while lobe frequencies and powers were recorded. The accelerometer output was observed and hand tuned to the values in Table 1 for each of the test frequencies.

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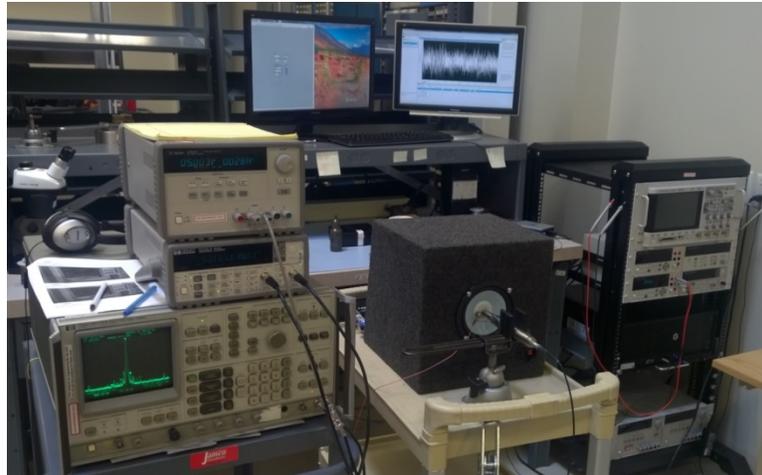


Figure 2. Experimental setup

Results

Figure 3 is a screen capture of the pressure crystal output at ambient conditions. The center frequency, F_{P0} , is 15,956 Hz and the peak power is 9.1 dBm. Note there are many other frequency components shown which are due to crosstalk and aliasing from the other oscillators in the circuit (temperature and reference).

Figure 4 is a screen capture of the pressure crystal, this time with a 250Hz input from the test equipment. The new frequency components (lobes) are denoted by red arrows at 15,704 Hz and 16,208 Hz ($\sim F_{P0} \pm 250$ Hz)

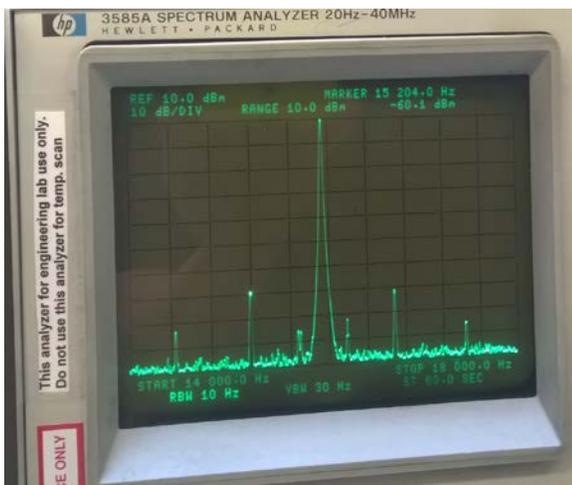


Figure 3. Transducer frequency spectrum without pressure frequency modulation.

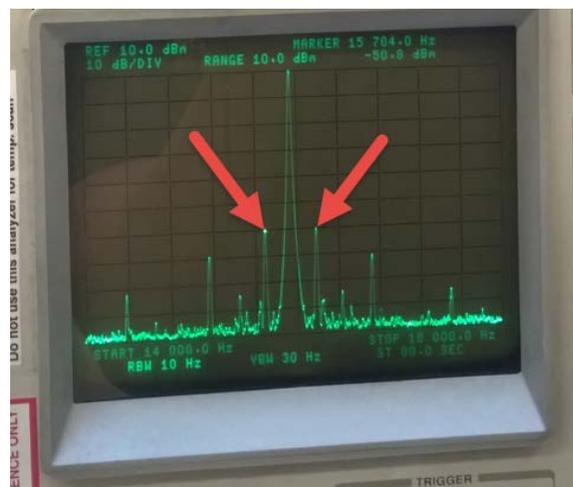


Figure 4. Transducer pressure frequency spectrum with 250 Hz frequency modulation. Note the two additional frequency components 250 Hz above and below the center frequency.

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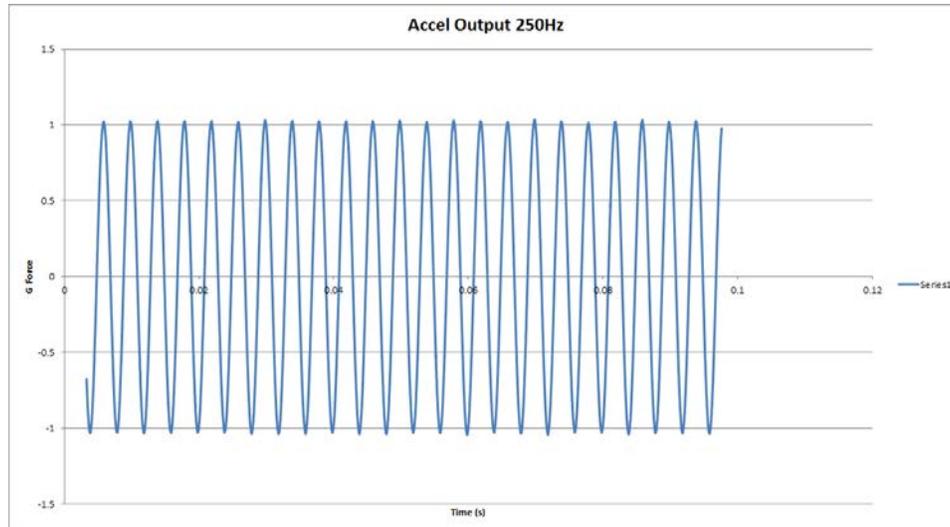


Figure 5. Accelerometer output during 250 Hz experiment. Note the amplitude is 1 g corresponding with Table 1.

The results from all experiments are summarized in Table 2 and the sidelobe power is plotted in Figure 6. As expected, the upper and lower sidelobes are shown and separated by the modulation frequency from the center frequency. Also note that the frequency response of the transducer is relatively flat all the way up to 1,750 Hz which was the highest frequency tested due to equipment limitations.

Table 2. Experimental Results

Frequency (Hz)	Acceleration (g)	Center Frequency, F_{P0} (Hz)	Center Frequency Power (dBm)	Lower Sidelobe Frequency (Hz)	Lower Sidelobe Power (dBm)	Upper Sidelobe Frequency (Hz)	Upper Sidelobe Power (dBm)
0	-	15,956	9.4	-	-	-	-
250	1	15,956	9.4	15,704	-50.8	16,208	-50.1
500	4	15,952	9.0	15,456	-54.0	16,456	-54.0
750	9	15,956	9.4	15,204	-45.6	16,708	-45.6
1,000	16	15,956	9.4	14,956	-41.2	16,956	-41.1
1,250	25	15,956	9.4	14,708	-40.8	17,204	-41.0
1,500	36	15,956	9.4	14,456	-45.4	17,460	-45.4
1,750	49	15,956	9.3	14,208	-53.0	17,712	-53.0

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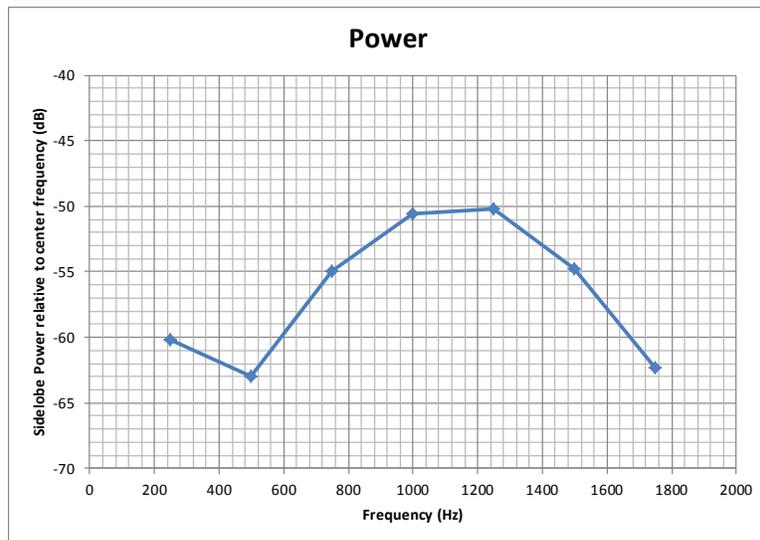


Figure 6. Side-lobe power relative to the center frequency power is relatively flat over the test frequency range. The transducer appears to transmit frequency information efficiently through the bellows and fluid at least up to 1,750 Hz.

PRESSURE MAGNITUDE

It is unknown at this time what the magnitude of the pressure changes were at the crystal during testing. Simulations were conducted to give an idea what they were. Using MathCAD, a simulated signal was generated using equivalent pressure, crystal sensitivity, etc. This worksheet is used to generate a signal that is frequency modulated like the transducer connected to a speaker. Then, an FFT is used to look at the signal spectrum. In the case of a strong pressure change (+/- 10 PSI), one can see that the carrier and modulated peaks become distorted as the signal changes rapidly. The responses each have two peaks. The separation between these peaks grows as amplitude (pressure) is increased (Figure 7).

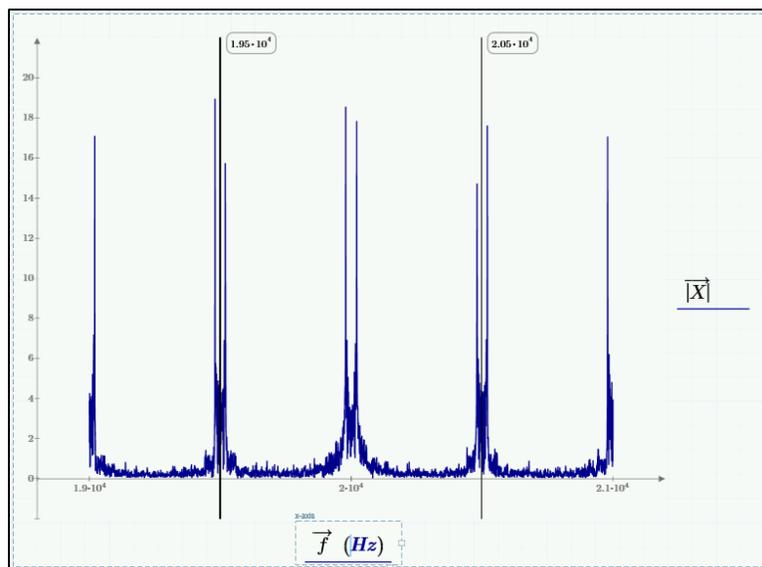


Figure 7. 10 psi input to the frequency modulation equation shows large distortions in the measure spectrum.

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However, very small pressure changes show the simple peaks that were observed on the spectrum analyzer during testing. Figure 8 shows the frequency response for a 20 kHz pressure signal modulated by a 500 Hz pressure change of 0.5 PSI. This is a good indication that the speaker above is creating very small changes in pressure, but the transducer is sensing without problems.

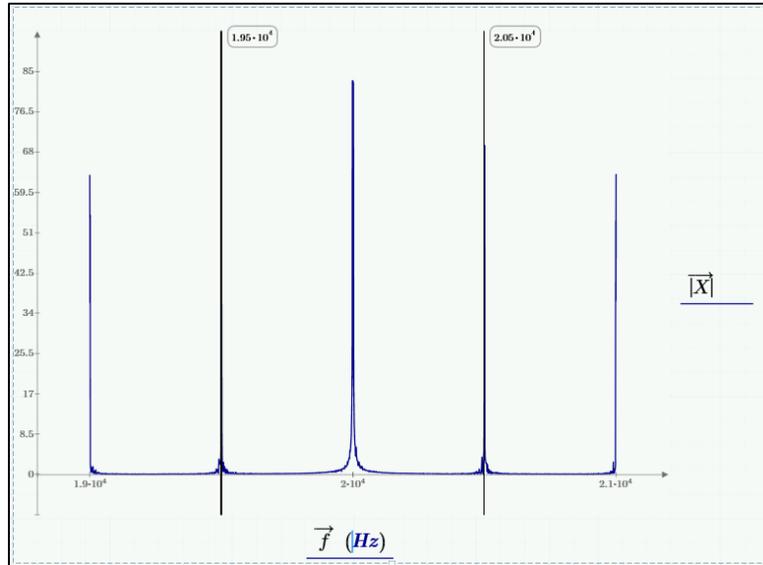


Figure 8. 0.5 psi input to the frequency modulation equation demonstrates a spectrum very similar to the ones observed during experimentation.

Conclusion

Quartzdyne pressure transducer responses to high frequency pressure signals were explored in two categories: electrical and mechanical. The electrical limitations were described as limitations due to counting a frequency output transducer. Sensing higher frequency pressure signals requires the user to sacrifice achievable resolution.

The mechanical limitations were well documented using experiment and simulation. The results lead Quartzdyne to assert that its analog pressure transducers can resolve pressure changes greater than 0.5 psi at a frequency of up to 1.5 kHz. However, the typical counting circuit would only have 14.3 psi resolution at this frequency requiring much larger signals than 0.5 psi. This demonstrates a situation where the mechanical components of a transducer are more than adequate, but the typical counting circuit is unable to resolve the observed pressure changes.

One could potentially resolve high frequency, small amplitude signals using an alternative circuit that is able to discriminate small frequency changes without counting, but that is beyond the scope of this report. Quartzdyne does not offer such circuits and encourages its customers to deploy such solutions if required.