MEASUREMENT OF GAS DAMPING IN AN ENERGY HARVESTER WITH NONLINEAR TRANSDUCTION

Svein Husa, Lars-Cyril Julin Blystad, Tao Dong and Einar Halvorsen

IMST, Faculty of Science and Engineering, Vestfold University College, Horten, Norway

Abstract: In this work we study how ambient gas gives rise to damping and thereby loss of performance in a vibration energy harvester. We use a purpose built setup to characterize an electrostatic harvester of the "shuttle" type at different vibration levels and at different frequencies. The device is kept in a small chamber where the ambient pressure may be varied between atmospheric and a few mBar. We are able to separate the damping effect of the gas from nonlinear effects in the harvester itself. We can thereby determine the mechanical loss as a function of gas pressure. At low pressure the loss is strongly pressure dependent while it seems to saturate at high pressure.

Key words: Gas damping, pressure dependent damping, nonlinear transduction

1. INTRODUCTION

It is obvious that gas present in the cavity protecting the movable parts of a MEMS structure will, in some way, affect its performance. In particular it will damp any resonant motion and therefore have a negative effect on the output power of an energy harvester. While hermetic bonding may give some residual pressure, polymer bonds are notoriously non-hermetic. Properly designed cavities can reduce the problem, but may have a size penalty. The effect of gas damping in this type of devices needs to be considered carefully.

In the present contribution we consider measurements of gas damping in an electrostatic harvester. It is of the "shuttle" type presented and analyzed by several authors [1]-[4], and will be described elsewhere. Many devices of this type, including ours, have nominally no linear response of output voltage to proof mass displacement. Instead, the response is quadratic or something more complicated. Gas damping is therefore not so easily determined from the frequency dependence of output power unless it can be observed as a deviation from a reference condition.

In the following we present a setup that allows us to do vibration measurements under controlled pressure. Using this setup, we investigate a method to extract the pressure dependence of damping without relying on linearity of transduction.

2. THE EXPERIMENT

2.1 The measurement equipment
To measure the effect of gas damping we built a test setup where the harvester was put into a small vacuum chamber mounted on a shaker. Since the device package is non-hermetic, we can control the pressure within the device and observe the effect of gas damping at different pressure values.

The harvester, a load resistor and a buffer amplifier is assembled on a small PCB. A buffer is inserted, since the capacitance of the connecting cables and measuring equipment would otherwise overload the device. The board is fixed to a carrier positioned in a small vacuum chamber. The chamber measures 30x30x40 mm and is mounted on an electromagnetic shaker. A reference sensor measures the acceleration of the chamber wall. The chamber is evacuated by a small mechanical pump and by the use of variable air bleed- and throttle valves we can adjust the pressure between 2 mBar and atmospheric pressure. Fig 1 is a photo of the device and the vacuum chamber. The shaker is powered by an analog amplifier that will take its input signal from a function generator or from a computerized control system. This system outputs analog signals from software generated test waveforms or from waveforms recorded in an operating environment.

2.2 A highly non linear device
Due to the nonlinear transduction, the shape of the generated waveform will continuously change when the amplitude of the translational movement of seismic mass and the associated electrodes increases. We may on the other hand expect the mass-spring system to be linear and insignificantly affected by transduction at low vibration levels. With atmospheric pressure in the cavity, the damping is high and the frequency response at a low vibration level has a typical linear, 2. order appearance with a broad, symmetric peak.
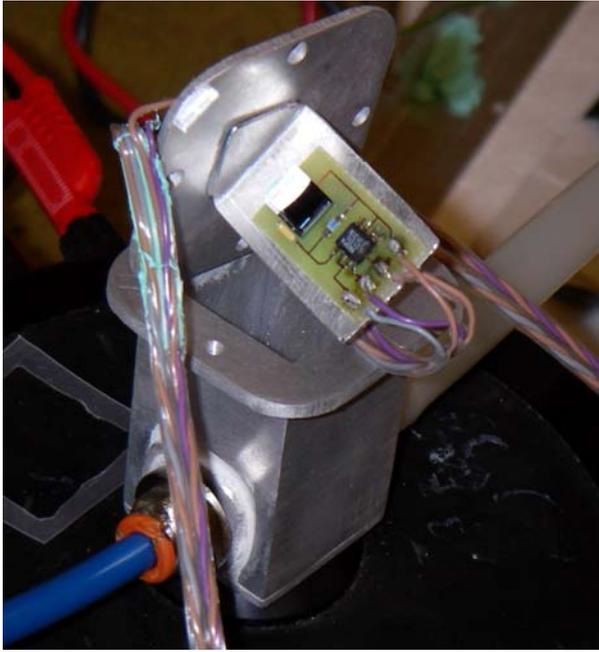
Fig. 1: MEMS device on PCB to be mounted in vacuum chamber.

Fig. 2: RMS output voltage as function of frequency at 5 different excitation levels. The pressure is 25 mBar.

Fig.3: RMS output voltage as function of excitation at low pressure, 25 mBar.

Fig.4: RMS output voltage as function of frequency at 4 different pressure levels. The excitation is 2.2g.

At low pressure and low damping, displacements may be large so that both transduction and mass spring system become nonlinear. This is shown in Figs 2, 3 and 4. Fig 2 shows the RMS output voltage of the harvester at different vibration levels. The pressure is 25 mBar and the damping is therefore low. The frequency is swept between 450 Hz and 700 Hz. Both the shape of the response curve and the max frequency depends on the excitation level. Fig 3 shows the output vs. excitation curve at 4 mBar and 25 mBar. The relation is clearly nonlinear.

Fig 4 shows the RMS output voltage of the harvester at different pressure levels. The excitation is 2.2 g. Both the max frequency and the shape of the response curve changes with pressure. When pressure increases from the low value of 25 mBar, the max frequency first increases, then decreases. The increase can be interpreted as a decrease of the effect of a softening spring as the motion becomes increasingly damped with increasing pressure and the displacement becomes small. The opposite effect, reduced max frequency at high pressure, is a normal consequence of increased damping in a linear, 2. order system.

Fig 4 shows very clearly that the pressure has a strong effect on the mechanical damping and thereby on the efficiency of the harvester. At a fixed vibration level of 2.2 g, the maximum output goes from 0.25 V to 2.0 V when pressure is reduced from 240 mBar to 25 mBar. It is of great practical value to know how the damping depends on pressure.
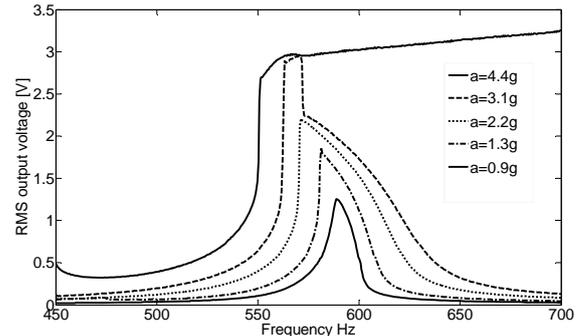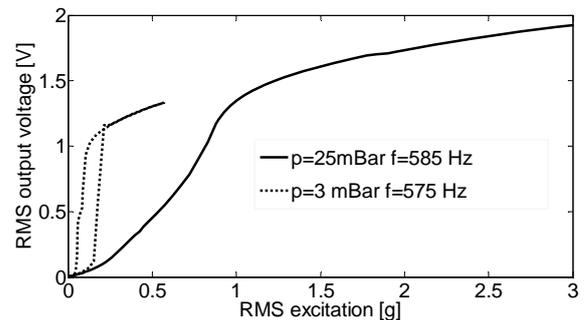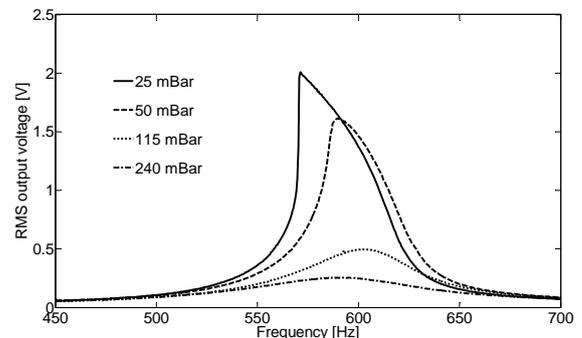
In a linear system, frequency response plots measured at different pressure values would give us this information. Both the Q value and the relative height of the response peaks are measures of the mechanical loss in the system. In our nonlinear system this method does not work. It is not possible to safely assign a Q value to the frequency plots of Fig 4 and the relative levels of the peaks are strongly influenced by the non linearity as shown in Fig 3.

2.3 An alternative approach

Our approach is based on an observation of the waveforms generated at two different pressure levels. Fig 5 shows a time plot of two waveforms. Both are

recorded at the peak of the frequency response but at two different pressure values, 25 mBar and 1000 mBar. During the recording the excitation level has been adjusted to give exactly the same RMS output voltage in both cases. From the figure we see that the waveforms are strikingly similar. This tells us that the mechanical motion and its amplitude must also be similar in spite of the different pressure and excitation. The displacement of the seismic mass cannot be read out of the plots. We will later estimate it from the loss measurements at high pressure.

Since 25 mBar and 1000 mBar are the limits our pressure range, we conclude that the amplitude at a nominal output voltage must also be the same at other pressure levels within this range. Since both records are done at resonance, and at the same amplitude, the inertial and spring terms cancel out. We are then left with the force caused by transduction and the force caused by gas friction. The transduction force is constant at a nominal output level. The observed difference in the external force

$$F_{ext} = m \cdot a_{excitation},\qquad(1)$$

acting on the mass, is therefore a direct measure of the difference in frictional forces between the gas and the vibrating system at the two pressure levels.
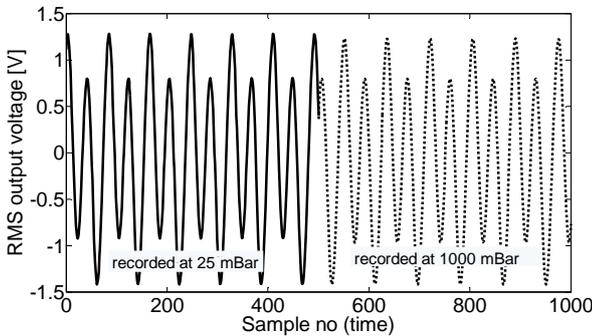

Fig.5: RMS output waveforms at low pressure and atmospheric pressure. The excitation has been adjusted to give the same RMS output voltage.

Based on this observation we recorded a series of input output relations of the type shown in Fig 3. We used an RMS output voltage of 0.8 V as reference and determined the acceleration needed to reach this value at different values of the pressure. This gives us a relation between gas pressure and acceleration shown in Fig 6. The acceleration ranges from a low value of 0.73 g at 25 mBar to 5.16 g at atmospheric pressure. In the figure we have also included a reference point at 3 mBar. The input output relation at this low pressure deviated from the other curves as shown in Fig 3.
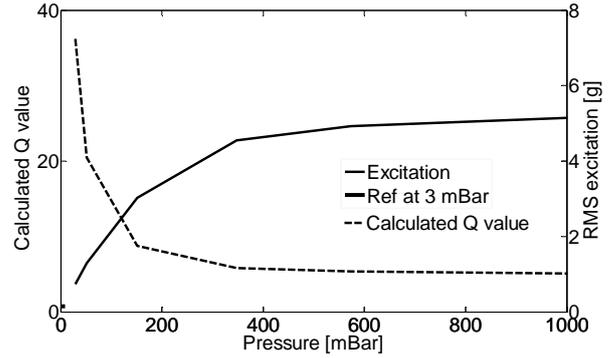

Fig.6: Excitation, a(p), needed to reach an RMS output of 0.8V and calculated Q value as function of pressure.

3. DISCUSSION

A MEMS structure made of Si has very low mechanic loss in the material itself. In an energy harvester the transduction from mechanical to electrical energy will act as an equivalent loss in the MEMS. This loss is not pressure dependent. At a given reference output it is constant, provided the output waveform also remains unchanged. At 3 mBar the curve in Fig 3 shows hysteresis. We observe the 0.8 V output at two input levels, 0.1 g and 0.2 g. In both cases the output waveform is the same as shown in Fig 5. From this we conclude that transduction loss represents less than 0.2 g vibration in all our measurements. At a pressure in the range between 25 mBar and 1000 mBar we can safely conclude that gas friction totally dominates the observed loss. The solid plot in Fig 6 represents for all practical purposes a loss vs. pressure relation.

While the curve very clearly shows how strong the pressure dependence is, the vibration level at 0.8 V output does not relate to a common measure of loss like the Q value. In section 2.2 we argued that a Q value cannot be extracted from the frequency traces for nonlinear operation. We may, if there is sufficient deviation from nominal behavior, extract a Q value from small amplitude motion at atmospheric pressure and low vibration level. Such measurements were done and resulted in a -3 dB bandwidth of 111 Hz at a resonance frequency of 562 Hz, giving a Q of 5.12. This is a reasonably well founded figure. We may now calculate a Q value at lower pressure if we scale according to eq 2. This is somewhat less well founded because it assumes that the device has a linear damping force under all the conditions that $a(p)$ is measured.

$$Q(p) = Q_{atm} \cdot \frac{a_{atm}}{a(p)} = 5.12 \cdot \frac{5.16}{a(p)}\qquad(2)$$

This calculated Q value is also plotted in Fig 6. It ranges from 5.12 at 1000 mBar to 36.2 at 25 mBar.

It may now be interesting to check the consistency between the calculated Q and the Q value based on the -3 dB bandwidth at a much lower pressure, where the response curve deviates from the symmetric shape of a linear, system. The -3 dB bandwidth at 50 mBar in Fig 4 is 28 Hz and the peak is at 591 Hz, which gives a Q value of 21.1. The Q(50 mBar) determined from eq 2 is 20.5. This close agreement indicates that down to this pressure the device behaves like a linear, 2. order system, even though the shape of the resonance peak is somewhat distorted. The same check at 25 mBar shows that the -3 dB bandwidth is the same as at 50 mBar and the calculated Q value will not have a sound physical basis.

We can also use this linear behavior at high pressure to estimate the RMS velocity and displacement of the seismic mass. In a 2. order mass spring system with viscous loss, characterized by f_0 and Q, we have a simple relation between the exciting vibration of the harvester frame and the resulting vibration of the seismic mass:

$$\frac{x_{mass}}{x_{frame}} = \frac{v_{mass}}{v_{frame}} = \frac{a_{mass}}{a_{frame}} = Q \qquad (3)$$

In section 2.4 we concluded that it was not possible to estimate the amplitude of the mass displacement from Fig 5. We are now in position to use the well founded Q value and measured excitation at atmospheric pressure to determine x_{mass} at 0.8 V. The result is 19.8 μm RMS or 56 μm peak to peak. This is the displacement of the mass at all pressure values as long as the output is 0.8V RMS. It is not affected by the fact that the linear, 2. order behavior seen at high pressure, is lost at low pressure.

The harvester that we tested needed 30times more driving acceleration to reach the reference output when the cavity was filled at 1 atmosphere compared with a low pressure of 3 mBar. It is clearly important to use bonding processes that are hermetic and that leave a low pressure after the process is completed. If it is not possible to have a very low remaining pressure in the device, the structural design needs to be optimized with respect to low sensitivity to gas damping by making appropriate cavities.

4. CONCLUSION

We have designed equipment and developed a test that can quantify the effect of gas friction in a highly non linear, electrostatic vibration harvester as function of the gas pressure in its cavity. In the range between atmospheric pressure and 50 mBar, we can use our experimental results to estimate a Q value, a linear system parameter, that describes the frictional loss. We also use the Q value at atmospheric pressure to determine the displacement of the seismic mass at a reference output, independent of the level of gas friction.

ACKNOWLEDGEMENTS

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