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Modeling Thickness Shear Mode Quartz Sensors for Increased Downhole Pressure & Temperature Applications

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Abstract: A quartz pressure sensor for downhole oilfield applications with an increased pressure and temperature range is discussed in this article. The proposed downhole sensor consists of a quartz piezoelectric resonator hermetically sealed between two quartz end caps. The end caps protect the resonator from harsh wellbore conditions and convey the pressure from downhole fluids to the piezoelectric resonator. As the resonator senses stress, its resonant frequency changes which can be used to calculate the pressure in the well. COMSOL software is being used by GRC to understand the shape and importance of the end caps on the resonator and to build a sensor that can withstand ultra high pressures and temperatures. Based on simulated results, an optimized new end cap is designed, manufactured and tested. This new design has the capability to accurately sense pressures greater than 20,000psi at temperatures greater than 200°C. Finite element results using COMSOL software is shown in this article.

Keywords: Downhole sensors, quartz, high pressure, high temperature.

1. Introduction

Modern wells entitled "ultra deep wells" involve drilling more than 30,000 ft and experience extremely high temperature and pressure gradients. According to DoE [1], approximately 185 trillion cubic feet (Tcf) of onshore and offshore deep gas exists in the US, at depths greater than 15,000 ft. Delivering 2 percent of this existing resource will provide an additional 17 percent supply of natural gas in the United States. Deep gas wells experience extremely high pressures and temperatures in addition to corrosive gases and hard rocks. The cost to bore the last 10 percent of a deep well is approximately 50 percent of the overall cost of drilling the well itself [1]. Hence drilling is pursued only in those areas which have proven oil/natural gas reserves. Quartz is the preferred means of sensing downhole pressures and temperatures due to its excellent long term stability, least overall accuracy errors, low creep and low hysteresis [2 - 4]. The design of sensors that can withstand ultra high pressures (>20,000psi) and temperatures (>200°C) is required to assist in efficient exploration of oil and natural gas. Quartz AT cut resonators have been used historically [3, 5] for downhole sensing.

GRC manufactures downhole gauges that are used worldwide for oil and natural gas production. One of GRC's product lines involves quartz based sensors which works on the principle of exciting a shear mode (c-mode) when an electric field is applied across the thickness of the resonator. GRC's quartz sensor has an overall accuracy of less than +/-0.02 percent full scale. This means that if a pressure of 20,000 psi is applied on the quartz sensor the maximum allowed overall accuracy error is less than +/- 4 psi. Such precise accuracy makes quartz a sought after tool for downhole application. Fig. 1 shows different components of GRC's quartz pressure sensor. The resonator and endcaps are made of quartz which is cut at an angle of 35°15' rotated clockwise about the x-axis. This type of cut is called an AT cut. An AT cut is preferred because it has the smallest temperature response compared to other available cuts. Hence, the change in frequency due to pressure is large compared to the overall change in frequency due to temperature. To eliminate the temperature dependence of the pressure sensor, another sensor isolated from the pressure is used to calculate the temperature of the pressure sensor. A commercially available glass tape is used to bond multiple quartz pieces (endcaps and resonator) together thus forming a quartz pressure sensor for downhole applications. The two endcaps and the resonator are hermetically sealed using a custom designed sealer with helium entrapped between the resonator and the hollow endcaps. The presence of helium allows the resonator to oscillate efficiently thus resulting in a decreased motional resistance and an increased quality factor. Quality factors greater than 1 million are a standard for GRC's quartz pressure sensors and result in a stable frequency.

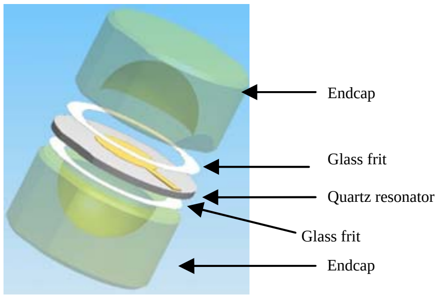

Figure 1. Components of GRC's quartz pressure sensor

1.1 Multiple Degrees of Freedom

Multiple degrees of freedom exist in the design of the quartz pressure sensor that enables the sensor to have an increased or decreased pressure range. A transfer function or an amplification factor (AF) is defined as

$$AF = \frac{\tau_r}{P_{ext}} \tag{1}$$

where τ_r is the stress in the resonator and P_{ext} is the externally applied hydrostatic pressure, both with units of psi.

The change in frequency (Δf) to the base frequency (f) of the piezoelectric quartz resonator due to the application of external hydrostatic pressure (P_{ext}) is

$$\frac{\Delta f}{f} = K * [\tau_r] \tag{2}$$

$$\frac{\Delta f}{f} = K * [AF * P_{ext}] \tag{3}$$

where K is the stress frequency coefficient and is dependent on the crystallographic orientation of the quartz substrate. In this application, since the resonator is an AT cut quartz the value is $K = 1.9 * 10^{-7} \frac{1}{psi}$. [6]. Sensitivity ($S$) of the device, with units of Hz/psi, can be calculated using

$$S = \frac{\Delta f}{P} = K * AF * f \tag{4}$$

Twinning, buckling and fracturing are the three primary modes of failure in a high pressure AT cut sensor. Buckling can be avoided by careful design of the sensor and is usually not seen for the geometric dimensions of interest in this article. Fracturing can be avoided by carefully polishing the sensor to its highest standard [7]. Twinning can be avoided if care is taken to design the sensor in a way that maintains the stresses in the resonator (τ_r) below the twinning stress (τ_{twin}), as shown in Eq 5. τ_{twin} , as a function of various temperatures, is shown in articles by Clayton et al [7] and Anderson et al [8].

$$\tau_r < \tau_{twin} \tag{5}$$

Since $\tau_r = AF * P_{ext}$, AF can be decreased to provide sufficient leeway for an increase in P_{ext}, thus allowing an increased pressure range for the quartz pressure sensor. This reduction in AF is achievable by varying the geometric dimensions of the endcap.

Multiple degrees of freedom exist that allow a decreased AF and an associated increase in the pressure range. These are (shown in Fig. 2):

(i) thickness of the resonator (h),
(ii) thickness of the top wall of the end cap (t),
(iii) thickness of the side walls of the endcap (w),
(iv) length of the endcap (L).

A thorough analysis using COMSOL was performed to understand the effects of each dimension. At the end of the analysis, an optimized endcap shape is identified that will result in a sensor with an increased pressure and temperature range.

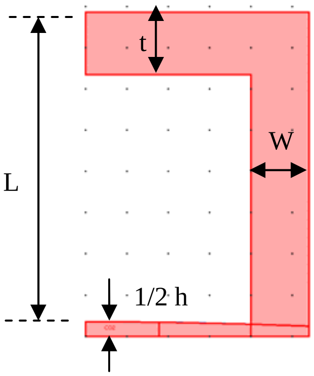

Figure 2. A 2D quarter section model of the quartz pressure sensor.

2. Variation of Each Degree of Freedom

Fig. 2 is revolved into 3D and the associated anisotropic stiffness, piezoelectric and dielectric material properties are provided as input to the model [9]. Fig. 3 shows the slice displacement plot of the resonator alone, indicating the 5th overtone. Only ½ the thickness and ½ the diameter of the resonator is modeled, with the appropriate boundary conditions. Figs. 3 and 4 indicate that the resonator designed is an energy trapped resonator. Fig. 5, shows a 3D quarter section model of the quartz pressure sensor with its associated boundary conditions. The external hydrostatic pressure seen by the sensor from downhole fluids is shown using arrows. As external pressure is applied, the endcaps bow/flex inward. The more the endcaps flex, the more pressure is transferred as stress onto the resonator. The key is to design the parameters of the endcap to keep τ_r less than τ_{twin}.

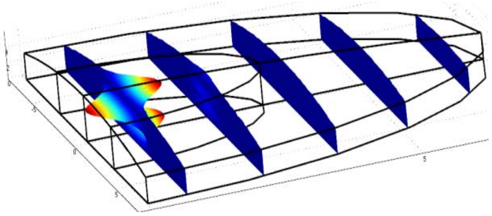

Figure 3. Slice plot of the resonator.

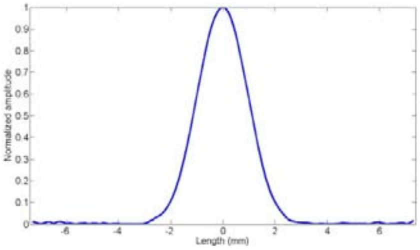

Figure 4. Total normalized displacement along the length of the resonator.

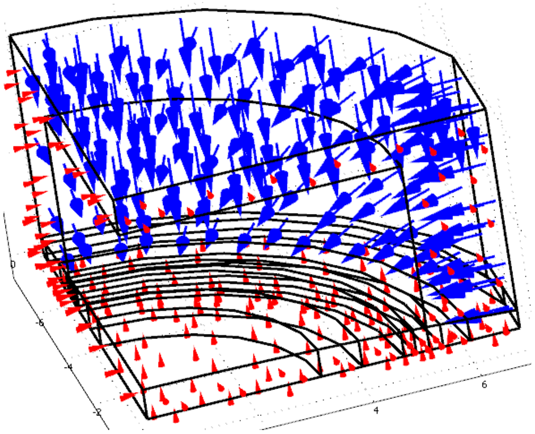

Figure 5. A 3D, quarter section model of the quartz pressure sensor.

2.1 Variation of thickness of resonator (h)

The thickness of the resonator determines the overtone and the frequency of operation. GRC's sensors are bi-convex and operate at 7.21MHz at the 5th overtone. The oscillation circuits that drive the crystal are designed for this frequency and overtone. Hence the choice was made not to vary the thickness of the resonator at this time. Nevertheless, a thick resonator would offer the maximum resistance for the endcaps to displace and flex under the influence of external hydrostatic pressure. Therefore a thick resonator should aid in increasing the pressure range of the quartz pressure sensor.

2.2 Variation of thickness of top wall of the endcap (t)

The variation of sensitivity as a function of top wall thickness (t) is shown in Fig. 6. There is an increased resistance for the walls of the endcap to flex under the application of external hydrostatic pressure as 't' increases. This causes reduced sensitivity thus resulting in increased pressure range. An experimental prototype was built and tested whose sensitivity is 1.42Hz/psi. This sensitivity of the built prototype is shown in Fig. 6, and compared against the predicted sensitivity using COMSOL modeling. We expect this prototype to withstand 70,000psi at an ambient temperature of 25°C as shown in Fig. 6.

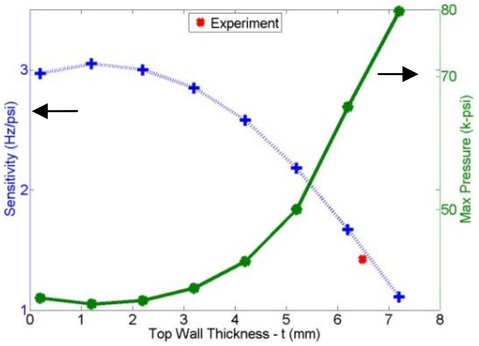

Figure 6. Variation of sensitivity as a function of top wall thickness. 'h=1.178mm', 'w=2.527mm', and 'L=7.62mm' are constant. Associated maximum external hydrostatic pressure range is also shown. Actual sensitivity data from an experimental prototype shows a good match.

2.3 Variation of thickness of the side wall of the endcap (w)

Similar to the variation of 't', an increase in the side wall thickness 'w' causes decreased sensitivity and thus an increase in the maximum pressure range as shown in Fig. 7.

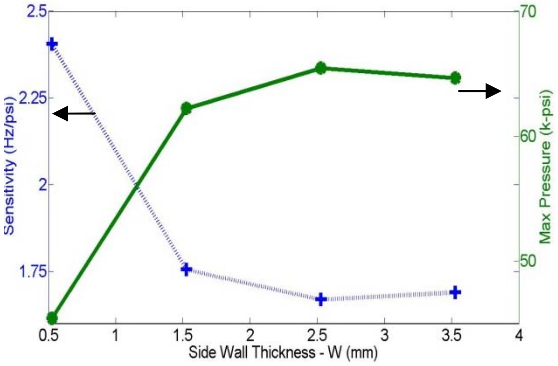

Figure 7. Variation of sensitivity as a function of side wall thickness (w). 'h=1.178mm', 't=6.209mm', 'L=7.62mm' are constant. Associated maximum external hydrostatic pressure range is also shown.

2.4 Variation of length of the endcap (L)

The variation of sensitivity as a function of the length of the endcap is shown in Fig. 8. As 'L' decreases, 't' also decreases as indicated in Table 1. The decreased 'L' and 't' cause the sidewalls of the endcap to resist flexing under the application of external pressure. This increased resistance lowers the sensitivity and thus increases the pressure range. The maximum pressure range achievable in an AT cut at 25°C is about 80,000 psi [10], beyond which twinning occurs limiting the usefulness of the developed pressure sensor. Hence beyond L=4.41mm and t=3.00mm there is no significant increase in the pressure range. However the sensitivity of the pressure sensor increases as L and t decrease because the top wall thickness becomes extremely thin limiting its capability to resist the flexing of the endcap.

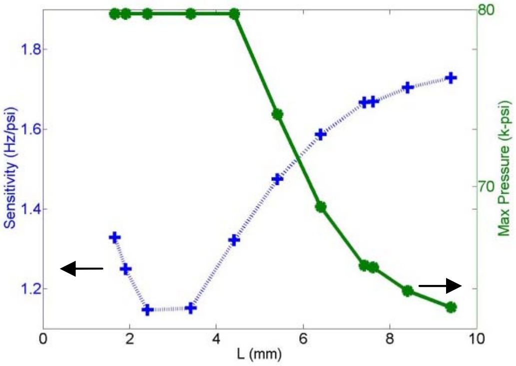

Figure 8. Variation of sensitivity as a function of ratio of length of endcap (L) and top wall thickness (t). 'h=1.178mm' and 'w=2.527mm' are constant. Associated maximum external hydrostatic pressure range is also shown.

Table 1. Comparison between L and t

L (mm)	t (mm)
9.41	8.00
8.41	7.00
7.62	6.21
7.41	6.00
6.41	5.00

5.41	4.00
4.41	3.00
3.41	2.00
2.41	1.00
1.91	0.50
1.66	0.25

3. Discussion

By varying the multiple degrees of freedom of a quartz pressure sensor, it is found that:

(a) a large top wall thickness 't', large side wall width 'w' and a short endcap length 'L' aids in increasing the pressure range.

(b) The maximum pressure range achievable in an AT cut pressure sensor is limited by twinning. At 25°C the maximum pressure range is about 80,000psi as shown by EerNisse et al [10].

All the results shown in this article are only valid at an ambient temperature of 25°C. At higher temperatures, the material properties of quartz vary, lowering the twinning stresses and hence the maximum pressure range. Nevertheless, an increase in pressure range at ambient temperature will also increase the pressure range at higher temperatures. Twinning determines the maximum upper limit of the developed pressure sensor. Testing of the built prototype (shown in Fig. 6) at GRC has shown that the sensor can withstand 200°C and 20,000psi without twinning. Further testing is currently in progress to build a sensor that can surpass this limit.

Current work also involves validating Figs. 6, 7 and 8 with more experimental data. Future articles in this regard will be published.

4. Conclusion

The design of a quartz sensor with an increased pressure and temperature range has been presented. With the aid of COMSOL software, a downhole sensor has been designed that is capable of withstanding pressures greater than 20,000 psi at temperatures of 200°C.

5. References

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6. Acknowledgements

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