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Analysis of metallic hemispherical shell vibration modes for coriolis vibratory gyroscope

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Abstract. Gyroscope is an instrument widely used in the navigation systems for sensing inertial angular motion. One of the principle of Gyroscope is Coriolis Vibrating Gyroscope (CVG), which is simple and easy to operate. It is realized during the development of the CVG that it is most suitable inertial sensor for aerospace applications. In this paper, a novel method for high reliable gyroscope application is demonstrated to verify the 'Mode 2' vibration pattern of vibrating hemispherical metallic shell. A parallel plate capacitor arrangement is made by placing discrete metallic plates around the metallic shell to study the vibration mode pattern. The shell vibrating at this particular mode, flexes along the axial direction of capacitor. The air gap of the parallel plate capacitor changes as the shell vibrates. The 'Mode 2' vibration pattern from the shell is confirmed by studying the phase relation at different capacitor locations.

1. Introduction

Gyroscope is an instrument widely used in the navigation systems for sensing inertial angular motion about its input axis without any external reference [1]. Over the last few decades, a host of physical laws were utilized to develop operational gyroscopes, which are currently in operation [2]. Development of Coriolis Vibratory Gyroscope (CVG) addresses all the aerospace applications needs like aircraft, satellite, deep space missions, launch vehicles, missiles and Submarine. In this type of gyroscopes, a vibrating hemisphere is excited to one of its resonant vibration modes at the prescribed amplitude. When the structure rotates about a particular fixed axis of its body, Coriolis forces act on the vibrating mass element and excites another resonant mode [3]. The rate of exchange of energy can be measured in terms of change of amplitude and phase of the capacitive signals at different locations around the hemisphere.

In the present work, a parallel plate capacitor arrangement is made by placing discrete metallic plates around the metallic shell to study the vibration mode pattern.

2. Working principle

In a CVG, one of the resonant modes also referred as driving mode is excited to a prescribed amplitude [4]. When the device rotates about a particular fixed axis, the resulting Coriolis forces acting on the vibrating mass excites a different resonant mode [5-6]. The rate at which the energy is transferred to this mode is used to measure the rotation rate about the sensitive axis. In most cases, the natural frequency of the second mode is identical to that of the first mode, like in vibrating string, hemispherical shell and in the Foucault pendulum. The arctangent of the ratio of the mode amplitude changes in response to the input rotation rate.

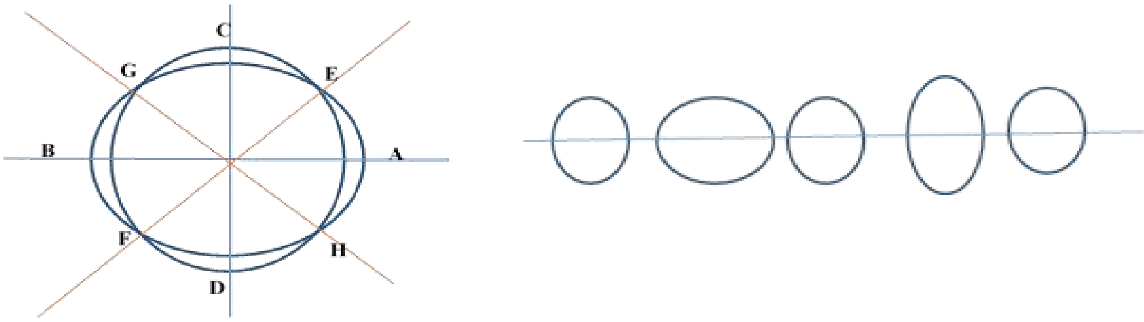
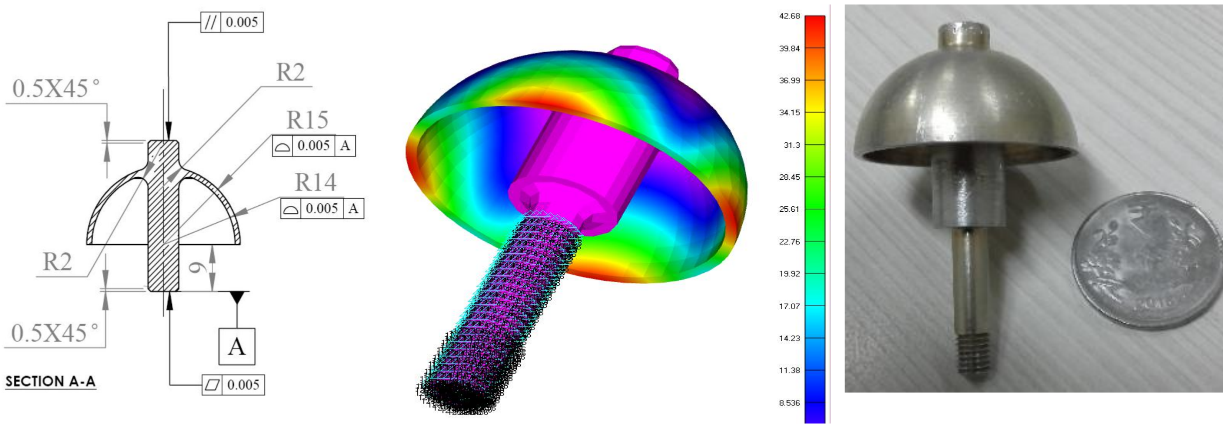


Figure 1. The mode pattern of the shell.

The CVG driven and readout mode amplitude satisfy coupled oscillator equations [7]. The equations are either same as two dimensional oscillator or they can be transformed in to desired two dimensional oscillator equations. When the hemispherical shell is excited to 'mode 2', the pattern looks as shown in the figure 1. The displacement of the shell is maximum at antinodal location and zero at nodal location. A parallel plate capacitor structure can be made with a shell and set of discrete metal pieces at nodal and antinodal locations.

A thin walled hemispherical shell is made to vibrate in its fundamental flexural mode by means of piezoelectric exciter. This mode pattern of the shell defines that in the first half cycle the shell deforms to its greatest ellipsoidal geometry and then returns to its spherical shape as shown in figure 1. In the next half cycle, a similar deformation takes place but spatially shifted by 90^{o} in azimuth. This mode of vibration leads to four antinodes (A, B, C, D) with maximum deflection of the shell and four nodes (E, F, G, H) with zero deflection.



(a) (b) (c)

Figure 2. Designed Vibration sensor Shell(a) Dimensions, (b) Simulated model and (c) Photograph.

A thin wall of approximately 1mm aluminium hemispherical resonator with 30mm diameter is designed with high geometrical tolerances (±5μm). The dimensions of the designed metallic hemispherical shell is shown in figure 2(a). NASTRAN simulation software is used to understand various modes, their coupling and material selection to get required resonant frequency. Figure 2(b) shows the stress pattern. High performance CNC machine is used to realize the metallic shell as shown in figure 2(c).

3. Experiment

To detect the nodes and the antinodes of the mode 2 vibration, at least 8 capacitors are required, which are to be placed around the metallic shell at equal angular difference as shown in figure 3. Eight no. of copper pieces of uniform dimension of 5mm x 2mm are used as the electrode to form a parallel plate capacitor along with the metallic shell with air gap of 30µm. The capacitance will not change in case of the metallic shell has no vibration. The static capacitance of all the capacitors under no vibration is of the order of 10 – 12pF. When the shell vibrates, its equatorial rim flexes up to a maximum of ±5µm along the A, B and C, D directions alternately. Under this condition the air gap changes by 30±5µm, thus results change in capacitance value at these locations. This dynamic change in capacitance is between 15 – 20 fF. This small change in capacitance will be added to the capacitance under no vibration state. Hence total change in capacitance across anti nodal locations ranges from ±10.015pf to ±10.02pf and 12.015pf to ±12.02pf respectively. As the shell vibrates at its natural frequency 6.279 KHz, the change in capacitance also corresponds to same frequency. An operational amplifier with very high input impedance, high band width with good gain linearity (AD4000-4) is used to detect the change in capacitance and boost the signal with the gain of 20.

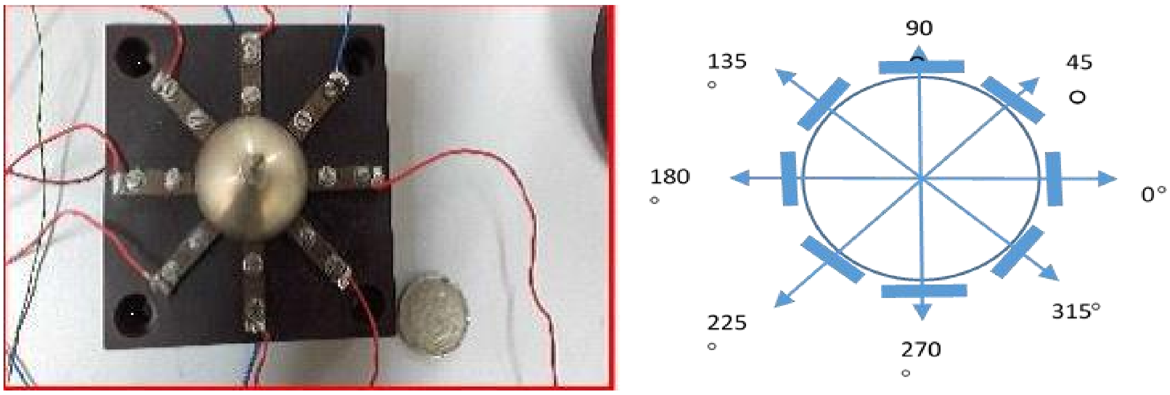


Figure 3. Arrangement of capacitors for designed shell.

4. Results and discussion

Figure 4(a) shows the electrical response of the vibrating shell at antinodal locations A, B, C, D. Since the Q factor of the aluminium shell is less (600-800), the signal damps rapidly. The vibration mode under investigation can be analysed by comparing the phase of the signals at these locations. When the mode under investigation is excited in the shell, capacitors at locations A and B experience a decrease in the air gap which leads to increase in the capacitance. At the same time capacitors at C and D experience decrease in capacitance as the air gap increases. These changes in the capacitances also result in similar change in phases at the locations A, B and C, D. These signals are recorded using the designed high input impedance ultra-low noise operational amplifier.

Mode 2 vibration on the hemispherical shell results in out of phase signal at A, C and B, D is shown in figure 4(b). From the phase information it is evident that the shell experiences a vibrational mode required for gyroscope operational applications. When the shell is under the vibration, maximum amplitude is experienced at antinodal locations and at the same time the nodal locations does not show any displacement, which results in no variation in capacitance. This can be seen by picking the capacitor signals at the locations E, F, G and H as shown in figure 4(c).

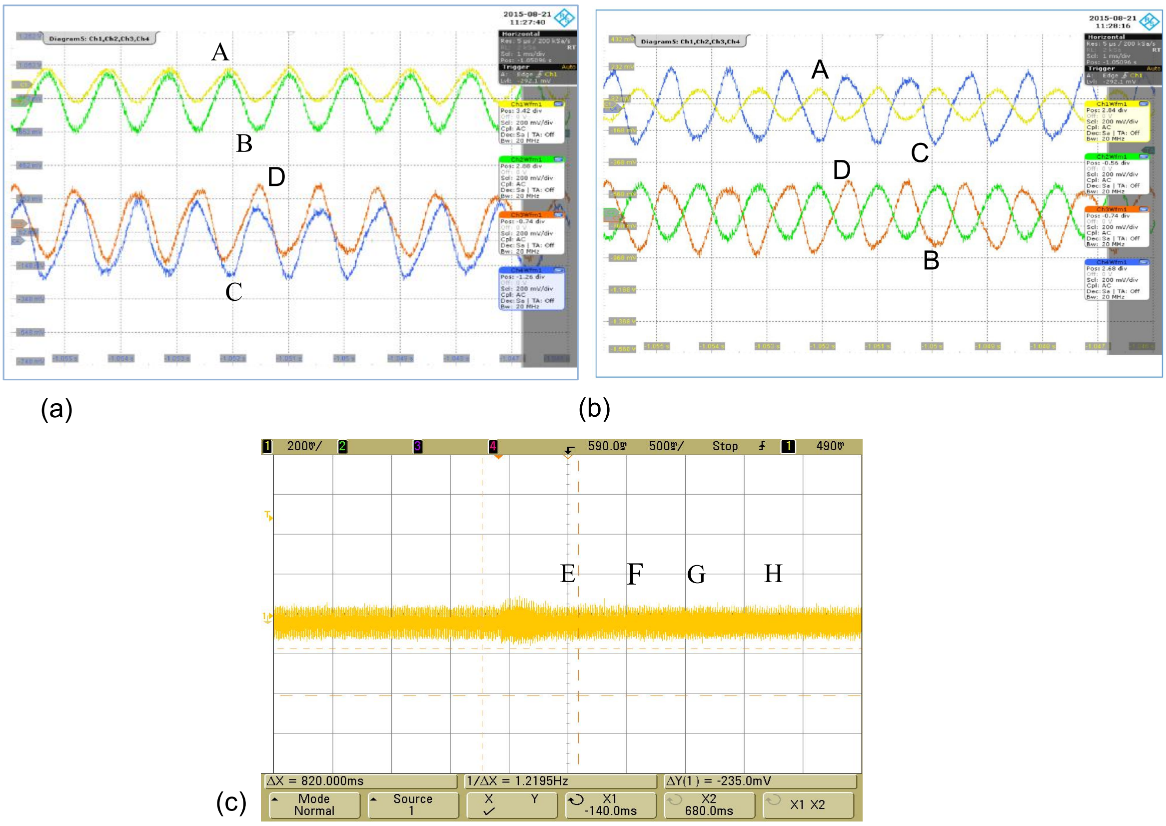


Figure 4. Capacitive response at anti nodal locations a) A, B & C, D b) A, C & B, D and c) E, F & G, H nodal locations.

5. Conclusion

A novel and low cost metallic hemispherical shell is designed and developed to measure and to analyse the vibrational modes for CVG. From the analysis of data, it is evident that the vibration mode imparted on to the shell is confined only at antinodal locations. Frequency and phase information of the signals reveal that the shell experiences 'mode 2' vibration. It is also clear from the data that the nodal locations do not show any vibration which implies that the shell is in the mode 2 alone.

Acknowledgments
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