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CHARACTERIZATION OF HEMISPHERICAL SHELL USING LASER DOPPLER VIBROMETER

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ABSTRACT

CVG Coriolis Vibratory Gyroscope is one kind of sensor in inertial sensors technology for navigation applications in aerospace field. Inertial Measurement unit requires accelerometer and gyroscopes for navigation aid. Navigation includes Guidance and Control and requires sensors to determine the present position and velocity of physical body. Gyroscopes are sensors which measures instantaneous rotation rate in navigation applications. Accelerometers are sensors which measures instantaneous acceleration in navigation applications. This paper presents overview of Hemispherical shell based Hemispherical Resonator Gyroscope HRG a kind of CVG. In this paper Q-factor measurement scheme is presented utilizing laser doppler vibrometer instrument of hemispherical shell. Different factors effecting Q-factor of hemispherical shell are analyzed. Different loss mechanisms are studied and ways to reduce them are presented in this paper. The aim of the research is to present an overview of realization and characterization of hemispherical shell using different fabrication techniques and pre-post processing experimental methods for Optimal Q-factor.

INDEX TERMS – Hemispherical Shell; Vibration loss; q-factor; Anchor loss; Laser doppler vibrometer.

I. INTRODUCTION

Navigation is a process of guiding safely and efficiently from one destination to another destination. Navigation in detail expands the process of "Where am I" and "How do I get to my destination" with "reference to What". Navigation can be defined broadly as the determination of physical body's position and velocity and guiding along the defined path relative to reference coordinate system so that destination is achieved. The process of navigation requires a) determination of present position and velocity of the physical body or vehicle in motion relative to known reference system, b) modifying the path or course of the physical body or vehicle in motion, c) stabilizing the vehicle or physical body so that it does not deviate from actual path, thus Navigation includes Guidance and Control and requires sensors to determine the present position and velocity of physical body or vehicle. Conventionally there are few types of Navigation techniques used traditionally which includes Celestial navigation, Inertial navigation, Radio Navigation, Satellite navigation and Integrated Navigation. In the field of Inertial Navigation, Inertial sensors like Gyroscopes and accelerometers are used to determine the present position and velocity of the physical body or vehicle.

Gyroscopes are sensors which measure instantaneous rotation rate in navigation applications. It is applicable to several areas such as aircraft, aviation, sailing, satellite, and oil drilling-exploration and so on. However, classical gyros are composed of many mechanical moving parts which can cause the operation failure. In that sense, vibratory gyroscope is a relatively effective sensor since it has no moving parts which mean that it has longer operation time compared to classical mechanical gyros. The vibratory gyros working principle is based on the Coriolis Effect. Due to the external rotation of the platform, while the vibratory gyro is at its resonance, this external rotation causes the precession of the stress wave in gyros. By measuring the precession angle, one can measure the amount of external rotation.

Gyroscopes are operated in a wide range of dynamic applications that demand navigation, guidance, stabilization, orientation capabilities in transportation, space explorations, military systems, mining operations and consumer electronics. Despite significant advancements in the technological level of gyroscope industry, persistent demands for enhanced sensitivity, low cost, miniaturization, GPS/GNSS independent navigation requirements makes way for continuous

novel research and development efforts in this sensor technology field.

The hemispherical resonator gyro HRG has several advantages in comparison to the other gyroscopes in terms of high reliability, long life time span, natural radiation or solarization redundancy, small size and low bias drift errors. M/s Delco researched and realized practical gyroscope in 1960's applying Bryan's discovery [1]. The working phenomenon of CVG is based on the forces arising from Coriolis acceleration. The effect was first observed by Gaspard-Gustave Coriolis. [2]. A solid hemispherical shell shows high resistance to extension and compression, maintaining a constant total circumferential length at its rim during resonance vibrations. The thin shell walls undergo periodic deformations into specific shapes defined by standing wave patterns and associated vibrational modes. Due to mechanical stress and external force in hemispherical shell the wave pattern with two maxima and two minima at rim is formed. This wave pattern consists of two nodes and two antinodes. CVG sensor senses this standing wave pattern precision due to wave inertia property of hemispherical shell upon external rotation in this vibration pattern. When the hemispherical shell in case is rotated externally about the stem or rotation axis and the standing wave pattern generated at rim due to mechanical stress and inertia nodes and antinode's location on rim of hemispherical shell precess w.r.t. fixed location on the hemispherical shell by a factor 0.3 or depending upon the shape of resonating element. The angular rotation about the rotation axis of the CVG sensor is evaluated by detecting the change in the locations of nodes and antinodes of vibration pattern at rim in hemispherical shell.

This paper presents characterization methodology of thin-walled resonator shell using Laser vibrometer instrument in high vacuum chamber test facility. This paper studies on effect of surface machining errors and assembly errors in joining resonator shell with matching forcer-pickoff, different boundary conditions and metallization layer nonuniformity. In this paper Q-factor measurement scheme is presented using laser doppler vibrometer. This scheme helps in developing Quartz resonator and identifying the sources of errors at different stages of development as compared to electrical methods.

II. DESIGN AND CHARACTERIZATION

A. Design

Due to mechanical stress and external force in hemispherical shell the wave pattern with two

maxima and two minima at rim is formed. This wave pattern consists of two nodes and two antinodes. CVG sensor senses this standing wave pattern precision due to wave inertia property of hemispherical shell upon external rotation in this vibration pattern.

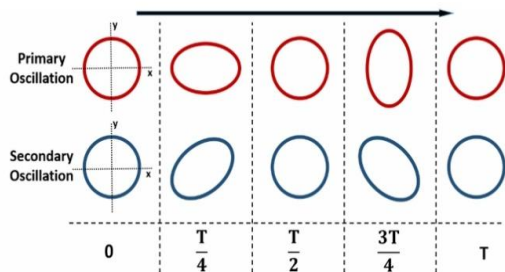


Fig.1 Illustration of vibrating shell shapes during stress cycle

When the hemispherical shell in case is rotated externally about the stem or rotation axis and the standing wave pattern generated at rim due to mechanical stress and inertia nodes and antinode's location on rim of hemispherical shell precess w.r.t. fixed location on the hemispherical shell by a factor 0.3 or depending upon the shape of resonating element. The angular rotation about the rotation axis of the CVG sensor is evaluated by detecting the change in the locations of nodes and antinodes of vibration pattern at rim in hemispherical shell.

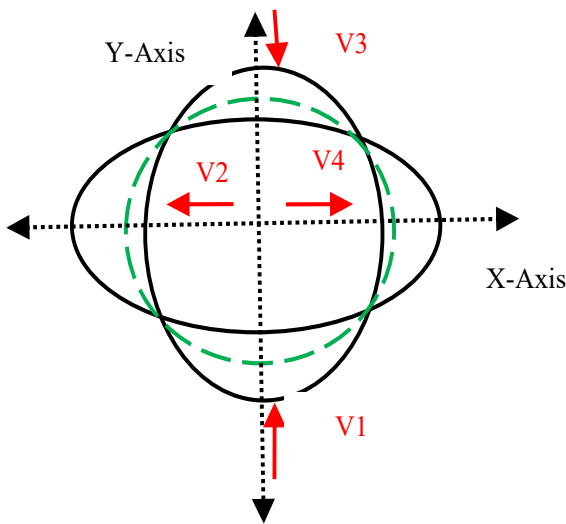


Fig. 2. Standing wave pattern

The HRG consists of mainly hemispherical shaped thin-walled resonator shell, forcer-pickoff parts for excitation and vibrating signal detection. These two are made up of high purity, isotropic, low intrinsic loss fused quartz. These are bonded each other with

low outgassing glue or specialty solder preform and sealed hermetically maintaining high vacuum in housing.

Hemispherical Resonator Gyro (HRG) consists of Hemispherical shaped shell as per the geometry parameters of the resonator are shown in fig.2. The un-coated shell is excited electrostatically with high voltage from pulsed power source. It sets up in $n=2$ vibration mode, 2 nodes and 2 antinodes as shown in fig.2. The high Q-factor and minimal frequency mismatch decides the sensor accuracy and high reliability. In this paper Q-factor measurement scheme is presented using laser doppler vibrometer. Factors affecting Q-factor of thin-walled mushroom design are analyzed.

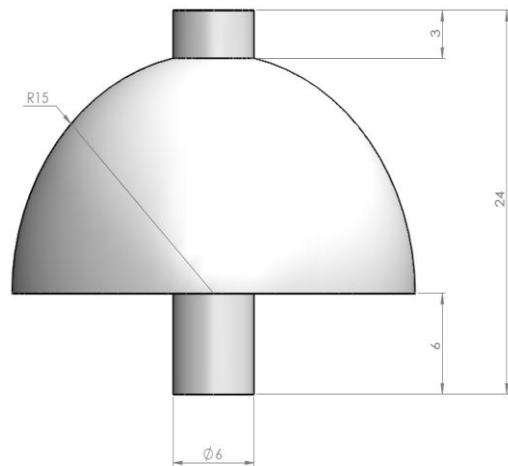


Fig. 3. Depiction of shell's geometry parameters

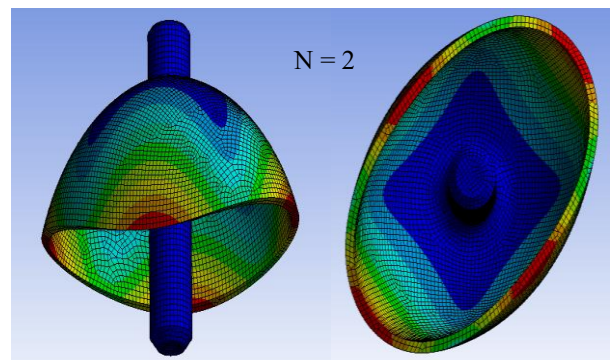


Fig. 4. Illustration of shell's n=2 mode

A. Factors affecting Q-factor of thin-walled resonator shell

The Total Q-factor of the resonator shell can be evaluated from each factor contributing in loss mechanism [8] as listed below:

$$Q^{-1}_{total} = Q^{-1}_{air\ damping} + Q^{-1}_{assembly} + Q^{-1}_{material} + Q^{-1}_{surface} + Q^{-1}_{etc.}$$

In order to obtain the Optimal Q-factor, all different types of loss mechanisms affecting the CVG sensor need to be individually optimized:

1) Air damping, $Q_{\text{airdamping}}$ affects Q-factor significantly up to 1000 times due to ambient conditions. It can be reduced to large amount by keeping the CVG sensor in high vacuum of $1\text{e-}6$ mbar or better. In vacuum conditions the viscous damping caused due to collision of atoms is reduced. By creating vacuum, the mean free path is increased and significantly reduces collision among atoms. Suitable selection of pumping system and usage of getter materials or gas absorbers can significantly improve the life span of the CVG sensor and minimize the air damping.

2) Assembly losses, Q_{assembly} are mainly caused by acoustic losses into resonator during assembly. It can be minimized by decoupling the resonator and assembling the resonator to pick-off by different boundary conditions. Suitable selection of low damping adhesive-glue or joining material like indium solder or low melting solder preform of customized shaped producing minimal stress upon curing and low outgassing can minimize the assembly losses.

3) Material Based Intrinsic Losses, Q_{material} mainly due to in elastic collision of atoms due to vibration oscillations and temperature fluctuation which causes damping and also due to the presence of material defects which causes damping. This kind of losses can be minimized by using raw material with low thermal expansion. Material losses are caused by surface contamination in resonator and lattice defects generated during surface polishing or nanomachining due to stress. These effects are reduced by using an isotropic, low internal loss quartz glass material.

4) Surface losses, Q_{surface} are mainly caused by unevenness in the surface texture of hemispherical shell which is generated during machining and metallization processes. These effects are minimized

through atomically smooth surfaces of thin-walled resonator by grinding or ultrasonic fabrication techniques of thin-walled resonator and utilizing uniform thin film metallization process like RF-DC magnetron sputtering techniques with epicyclic rotation mechanism for uniform metallization and minimal residual stress.

5) Additional loss mechanisms, Q_{etc} are mainly due to presence of residual stresses in thin-walled resonator during fabrication and machining processes. These effects can be minimized by controlled heat treatment and removal of defect layer at submicron level by ion beam-based plasma etching and chemical treatment procedures.

III. CHARACTERIZATION AND TEST RESULTS

A. Experimental Test Setup

The un-coated Resonator shell is placed in Vacuum chamber consisted of Turbo molecular pump backed by dry scroll pump as shown in fig.4. The resonator is excited electrostatically which forms capacitance between resonator and Forcer-pickoff using high voltage of 400V square wave using pulsed power source. The Polytec laser doppler vibrometer instrument is used to detect vibration pattern and measure natural frequency, damping time and displacement amplitude of resonator shell in frequency and time domain as shown in fig.5. The test result as captured in Polytec software is shown in fig.7. The result shows the change in phase from -90° to $+90^\circ$ at resonance peak of resonator shell. The test results of hemispherical shell machined in conventional Turning-Grinding process and Ultrasonic machining process is tabulated in Table I. The results obtained shows Q-factor obtained by 3 dB bandwidth formulation is better in Ultrasonic machining process as it induces minimal residual stress in resonator shell during machining.

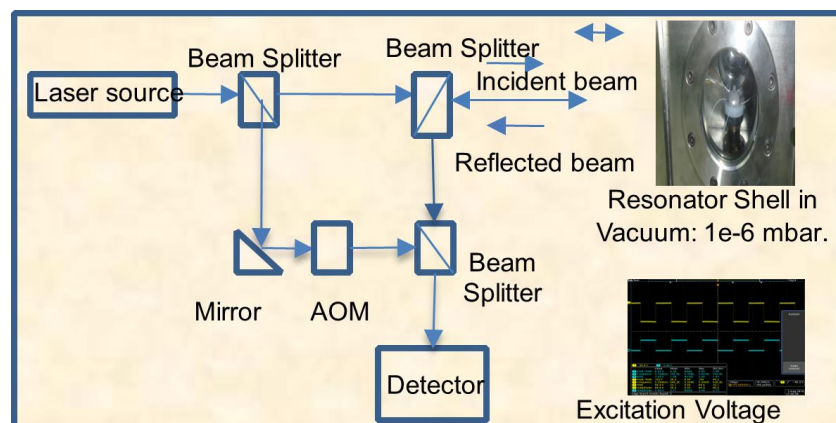


Fig. 5. Q-factor Measurement Scheme using Laser Doppler Vibrometer

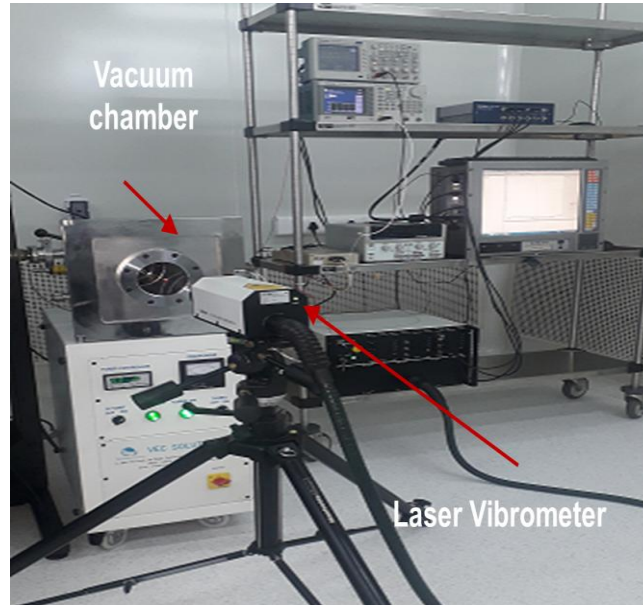


Fig. 6. Q-factor Measurement Test Set-up

The Q-factor is calculated as

$$Q = \frac{f_c}{FWHM}$$

Where,

f_c is the resonant (centre) frequency

FWHM is the Full Width at Half Maximum

The results of Q-factor are tabulated in Table I of resonators machined using different machining techniques. The graph in Fig 8 shows evaluation of Q-factor utilizing Gaussian fit data from Polytec Laser vibrometer measured data.

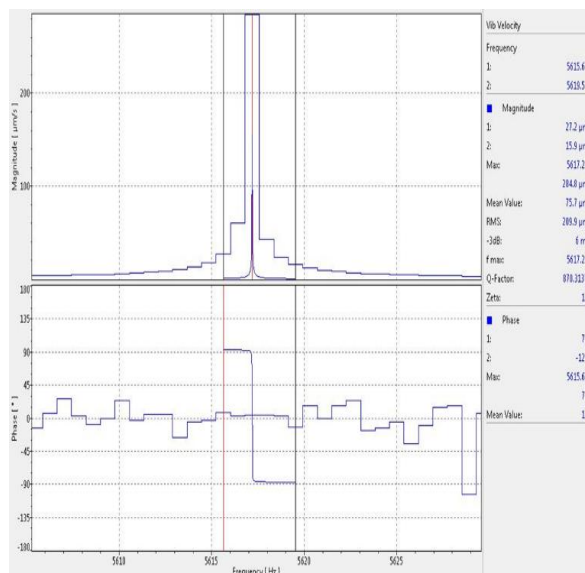


Fig. 7. Screenshot of Polytec software test result graph

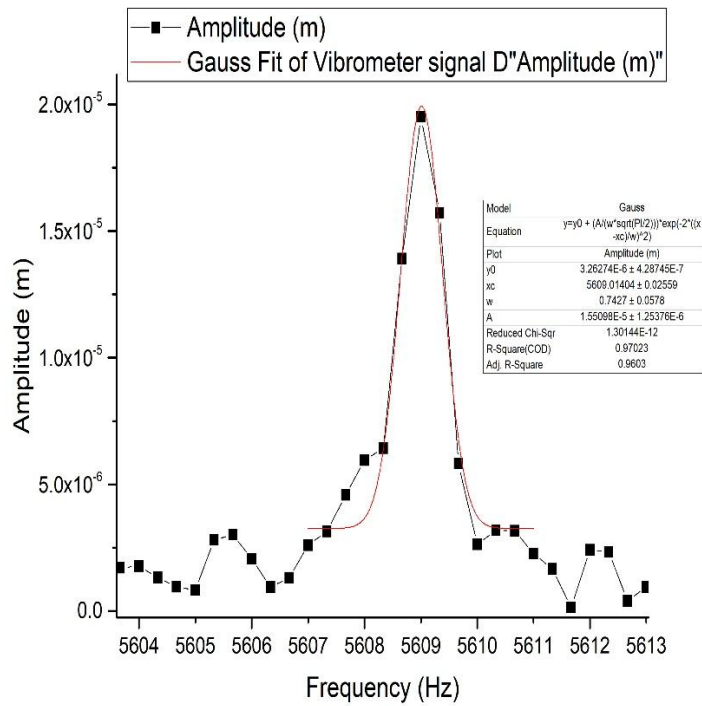


Fig. 8. Gaussian Fit of Laser Vibrometer Results

TABLE I Test Results

S. No	Parameter	Ultrasonic Machined	Turning /Grinding
1	Test Voltage	400V Square Wave	400V Square Wave
2	Q-Factor	8.73 e5	1.8 e5
3.	Natural frequency	5.6172 KHz	5.622 KHz

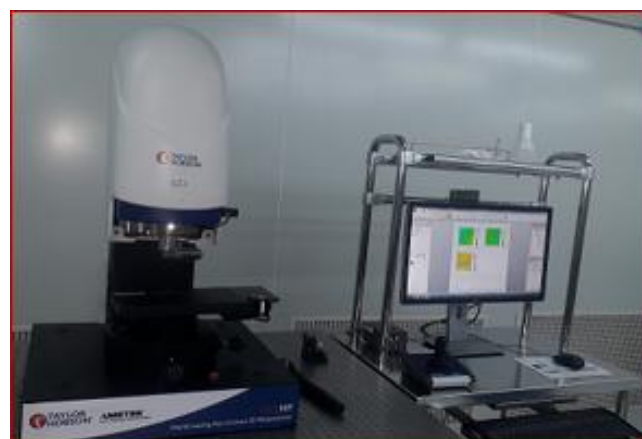


Fig. 9. 3D surface Profiler

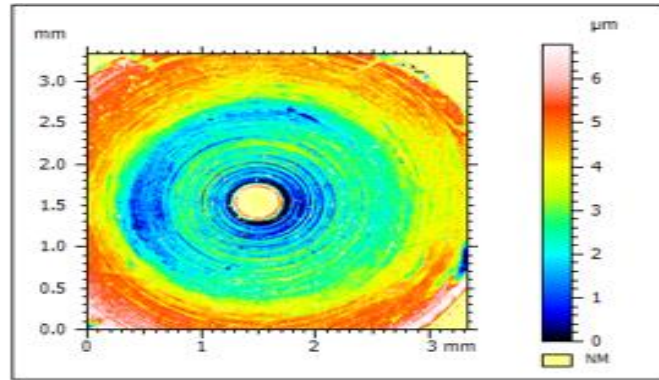


Fig. 10. Surface Analysis of Resonator Top surface

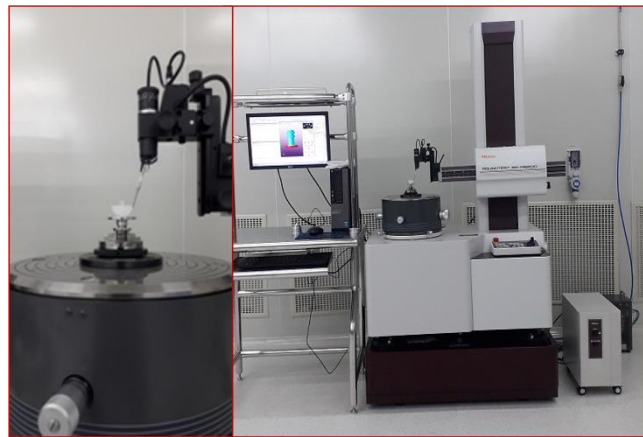


Fig. 11. Roundness Tester

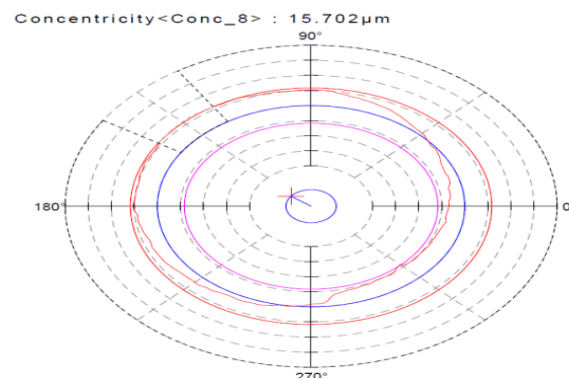


Fig. 12. Concentricity measurement between ID and OD of resonator using Roundness Tester.

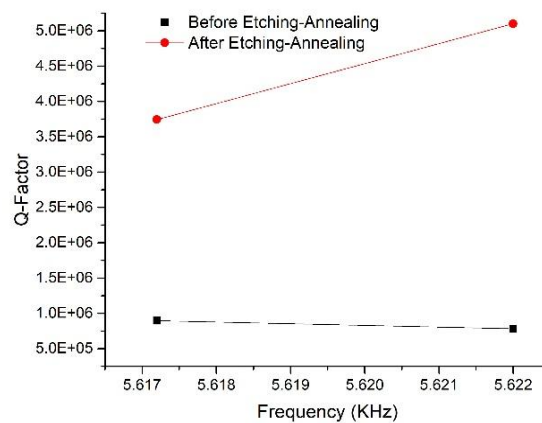


Fig. 13. Test Results

The graph in fig.13 shows the measurement of Q-factor of Quartz resonator. After Vacuum annealing in the set-up as shown in fig14. around 1150°C for 6 hrs. with controlled heating and cooling cycle the Q-factor improves significantly.



Fig. 14. Annealing Furnace

IV. CONCLUSION

This paper investigates the vibrational loss mechanism affecting the Q-factor of the hemispherical shell. Based on FEM analysis the hemispherical shell of fused quartz material is selected for optimal Q-factor. Utilizing the Laser Doppler Vibrometer methodology the Q-factor evaluation scheme of hemispherical shell is presented. The main advantage of this scheme over electrical methods is to evaluate the Resonator shell performance at different stages during machining, finishing, residual stress removal stages of fabrication as electrical method requires finished Quartz Pick-off and complex electronics with signal processing. During development stages this method help in optimizing the different process involved in the realization of hemispherical resonator shell. The

effect of shell's surface finish parameters, viscous air damping on the Q-factor of resonator shell is investigated.

The analysis in this paper about Q-factor improvement by suitable choice of low loss and low CTE fused quartz material may be useful in the development of Hemispherical Shell for optimal Q-factor and in the analysis of source of error in performance evaluation.

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