Influence of the instability of angular velocity of the rotating carrier itself on the stability of silicon micromachined gyroscope

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Abstract: In order to find out the influence of the instability of angular velocity of the rotating carrier itself on the stability of silicon micromachined gyroscope, the digital models for relative error of the high and low damping gyroscope's output signal are given respectively, based on the motion equations of the silicon micromachined gyroscope. Theory proves that the output signal error of the silicon micromachined sensor is mainly caused by the instability of damping factor and the angular velocity of the rotating carrier itself. The experiment result indicates that the error of proportionality coefficient of output voltage which is caused by the instability of the angular velocity of the rotating carrier itself reaches to 4.1 %. Theoretical demonstration and experimental verification show that the instability of angular velocity of the rotating carrier itself has an important effect on the stability of low damping silicon micromachined gyroscope.

Key words: gyroscope; micromachined; angular velocity

1 Introduction

There are many kinds of micromachined angular velocity gyroscope, which include driven and non-driven frames distinguished by the principle and construction. Nowadays, micromachined angular velocity gyroscope with non-driven frame is only reported by China and Russia researchers[1-4], and others are driven frame[5,6]. At present, there is no particular report about the gyroscope's performance test with no driven. The paper reports the influence of the instability of angular velocity of the rotating carrier itself on the proportional coefficient of the output signal[7].

2 Principle

The gyroscope consists of the rectangular silicon plate, which is suspended in case by the elastic torsions. About the case, the plate has one degree of freedom determined by relative angle of rotation (Fig. 1).

Angle α is measured by the differential capacitive pick-off, whose two coats are mounted on the moving plate and two others on the case. The gyroscope elements comprise the plate and the torsions and which are made of silicon by etching.

The gyroscope is installed on the carrier, rotating with the speed $\dot{\varphi}$ about the axis, perpendicular to the plane of the gyroscope element, and is intended for measuring its speed of rotation Ω about a fixed axis in the carrier lateral plane.

Such manufacturing technology is considered perspective at present that gives certain advantages to mass production of the gyroscope.
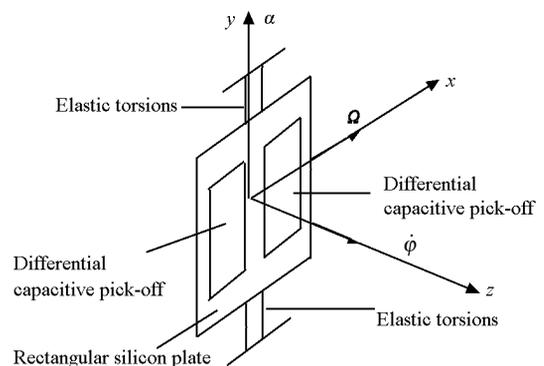

Fig. 1 Cinematic scheme of the silicon micromachined angular velocity sensor

Cinematic scheme of the gyroscope need taking the torsions elastic factor K_T into account and that the information output is realized by angular speed and the rotation angle of the gyroscope. That allows using in this case equation of motion of the gyroscope element, the equation being written in the coordinate system xyz rotating together with the gyroscope element and in addition the torsions rigidity is taken into account and in

the preliminary analysis all the angular velocities of the carrier except the measured one are omitted.

$$B\ddot{\alpha} + D\dot{\alpha} + \left[\left(C - A\right)\dot{\varphi}^2 + K_T\right]\alpha =$$
$$\left(C + B - A\right)\dot{\varphi}\Omega\sin\dot{\varphi}t \qquad (1)$$

Where, A, B, C are the moments of inertia of the gyroscope element about x, y, z axes correspondingly, D is the aerodynamic damping factor.

This differential equation solution in steady mode has the following form

$$\alpha = \frac{\left(C + B - A\right)\dot{\varphi}\Omega}{\left[\left(C - A - B\right)\dot{\varphi}^2 + K_T\right]^2 + \left(D\dot{\varphi}\right)^2}\sin\dot{\varphi}t \quad (2)$$

and the amplitude α_m of the gyroscope element oscillations during the measuring is defined by the expression:

$$\alpha_m = \frac{\left(C + B - A\right)\dot{\varphi}}{\left[\left(C - A - B\right)\dot{\varphi}^2 + K_T\right]^2 + \left(D\dot{\varphi}\right)^2}\Omega \quad (3)$$

In the denominator of this expression there is the torsions' elastic factor K_T. That does not allow excluding dependency of the output characteristic on a very unstable parameter.

So another strategy of the gyroscope parameters choice to ensure measuring accuracy is offered.

First, we will note that physical characteristics of silicon and technology of its fabrication predestine such a correlation of moments of inertia values and the torsions elasticity, that in real design

$$\left(C - A - B\right)\dot{\varphi}^2 \ll K_T \qquad (4)$$

Then note that during the choice of parameters in Eq. (3). It is not to tend to the following condition in the denominator

$$K_T < D\dot{\varphi} \qquad (5)$$

Because stability of the damping factor D is lower than stability of torsions' elastic factor K_T. Besides, that is difficult to obtain, as for increasing of D it is necessary to reduce the gap between the gyroscope element and the case that reduces the maximum angle of deflection and accordingly the output curve tangent.

For this reason it's desirable to make the design as

$$K_T > D\dot{\varphi} \qquad (6)$$

In this case the denominator value in the Eq. (3) will define the most stable elastic factor K_T for the silicon gyroscope element.

However, in this case the output signal of gyroscope will be directly proportional to the carrier speed of rotation and very unstable. For eliminating of this disadvantage in the present development it is offered during the working process to calculate constantly $\dot{\varphi}$ by measuring of frequency of the output signal of the differential angle pick-off. That is possible to be carried out by introducing a microprocessor in the gyroscope

(or using the carrier calculator). From the aforesaid it also follows that in gyroscope there is no need to tend to the resonance mode, but in order to avoid additional dynamic errors the pre-resonance mode should be chosen.

3   Principle errors

The stable elastic moment of the silicon torsion spring is considered the basic one for balancing of the measured gyroscopic moment. It provides certain advantages on condition that the carrier rotation rate $\dot{\varphi}$ is determined by the device output signal frequency measuring by electronics. But it requires considerable reduction (several orders) of the damping moment that causes certain difficulties in the prototype manufacturing and finishing. The matter is that the damping factor dependence on the pressure of the gas filling the case is very feeble and deep vacuum creation is required to obtain the damping low enough (the vacuum being at the level of 10^{-3} mmHg (1 mmHg = 133.3224 Pa) or lower). At such a rarefaction level, electronic elements inevitably emit gas molecules that change the reached vacuum level. This fact requires placing the electronics in an individual case that is impossible because the device overall size will exceed the limits of the technical requirements.

On this basis, not excluding in principle such a device manufacturing possibility, it is decided to fill the device prototype case with gas (nitrogen) at the standard atmosphere pressure in order to cut the manufacturing cost and to reduce the device overall size.

Expression for the amplitude U_m of the output voltage oscillations of the angle α pick-up is

$$U_m = \frac{K_{TS}\left(C + B - A\right)\dot{\varphi}}{\left[\left(C - A - B\right)\dot{\varphi}^2 + K_T\right]^2 + \left(D\dot{\varphi}\right)^2}\cdot\Omega$$
$$(7)$$

Where, K_{TS} is the angle pick-up transmission factor.

Approximate expression for the error ΔU_m at the change of the following parameters: $\dot{\varphi}$—the carrier rotation rate, K_T—the torsions' elastic factor, D—the damping factor, K_{TS}—the angle pick-up factor, has the following form

$$\Delta U_m = \frac{\partial U_m}{\partial\dot{\varphi}}\Delta\dot{\varphi} + \frac{\partial U_m}{\partial K_T}\Delta K_T +$$
$$\frac{\partial U_m}{\partial D}\Delta D + \frac{\partial U_m}{\partial K_{TS}}\Delta K_{TS} + \cdots \qquad (8)$$

During this expression, for the real silicon rate gyroscope designs

$$K_T \gg \left(C - A - B\right)\dot{\varphi}^2 \qquad (9)$$

We can get the relative error of outputting signals through having calculated partial derivative and trans-

formed the previous expression. The relative error of outputting signals for high damp gyroscope (shown in Eq. (5)) is:

$$\frac{\Delta U_m}{U_m} = \frac{K_T^2}{D^2 \dot{\phi}^2} \cdot \frac{\Delta \dot{\phi}}{\dot{\phi}} -$$
$$\frac{K_T}{D^2 \dot{\phi}^2} \cdot \frac{\Delta K_T}{K_T} - \frac{\Delta D}{D} + \frac{\Delta K_{TS}}{K_{TS}} \qquad (10)$$

Likely, the relative error of output signal for low damp gyroscope (shown in Eq. (6)) is:

$$\frac{\Delta U_m}{U_m} = \frac{\Delta \dot{\phi}}{\dot{\phi}} - \frac{\Delta K_T}{K_T} - \frac{D^2 \dot{\phi}^2}{\left[K_T^2 + D^2 \dot{\phi}^2 \right]} \frac{\Delta D}{D} + \frac{\Delta K_{TS}}{K_{TS}} \qquad (11)$$

It is known from Eq. (10) and Eq. (11) that the error of output signal of silicon micromachined gyroscope is mainly caused by the instability of damping factor and the angular velocity of the rotating carrier itself.

4 CJS–DR–WB01 silicon micromachined angular velocity gyroscope tests

Five pilot-models of CJS–DR–WB01 have been tested. The tests are held on dynamic stand controlled by personal computer. The gyroscope rotation rate is set in the range 5 ~ 25 Hz by a rotation simulator. The tested gyroscopes prove the total efficiency on all the conditions of the carried tests.

The variation of proportional coefficient and output signals voltage of the gyroscope caused by the instability of the angular velocity of the rotating carrier itself is detailed in Table 1. Dependence of the gyroscope output signal on the measured angular velocity at different rotation frequencies of simulator is shown in Table 2 and Fig 2. Dependence gyroscope output signal from input rate is shown in Table 3. Dependence gyroscope output signal from simulator frequency is illustrated in Fig. 3.

Table 1　The variation of proportional coefficient and output signals of the gyroscope caused by the instability of the angular velocity of the rotating carrier itself

No.	0639	0640	0879	0880	0888
$\Delta U/U$	30.4 ~ 33.3	29.6 ~ 31.85	30.1 ~ 31.77	32.74 ~ 34.62	30.59 ~ 32.65
$\Delta K/K$	2.3 ~ 2.6	2.64 ~ 3.85	1.75 ~ 3.4	1.5 ~ 2.3	2.12 ~ 4.05

Table 2　CJS–DR–WB01-0639 dependence of the sensor output signal on the measured angular rate at different rotation frequencies of simulator

$\dot{\phi}$/Hz	$\Omega/(\circ) \cdot s^{-1}$									
	100(CW)	100(CCW)	200(CW)	200(CCW)	300(CW)	300(CCW)	400(CW)	400(CCW)	500(CW)	500(CCW)
5	703.4	697.6	1 405	1 499	2 107.2	2 101.6	2 808.4	2 800.4	3 511.2	3 503
11	1 426.8	1 428.4	2 845.4	2 853.6	4 263.6	4 279.8	5 697.4	5 716.4	7 145.6	7 159.2
17	1 802.8	1 809	3 567.6	3 598.6	5 360.4	5 385.8	7 094.6	7 172.2	9 119.4	9 048.2
25	1 922.4	1 896.4	3 760	3 751.2	5 621	5 632.2	7 641.6	7 645.8	9 590.2	9 947.6
Stability/%	±32.49	±32.4	±31.96	±30.4	±31.9	±32.1	±32.2	±32.4	±32.6	±33.3

Note: CW—clockwise; CCW—counter clockwise

Table 3　CJS–DR–WB01-0639 dependence sensor output signal from input rate

$\dot{\phi}$/Hz	$\Omega/(\circ) \cdot s^{-1}$										Stability/%
	100(CW)	100(CCW)	200(CW)	200(CCW)	300(CW)	300(CCW)	400(CW)	400(CCW)	500(CW)	500(CCW)	
5	7.034	6.976	7.025	7.495	7.024	7.005	7.021	7.001	7.022	7.006	2.4
11	14.268	14.284	14.227	14.268	14.212	14.266	14.243	14.291	14.291	14.318	2.3
17	18.028	18.09	17.838	17.997	17.868	17.953	17.986	17.936	18.239	18.096	2.5
25	19.224	18.964	18.8	18.765	18.737	18.774	19.104	19.114	19.18	19.895	2.6

5 Discussion

The influence of the rotate speed $\dot{\phi}$ of the rotating substrate on proportional coefficient and output signals of the gyroscope is significant (up to 4.1 %), because output signals of silicon micromachined gyroscope is proportional to the rotate speed of the aircraft (shown in Eq. (7)) under low damp situation (shown in Eq. (6)). To avoid the disadvantage, the rotate speed error caused by electron circuit makes output signals out of stability, the microprocessor in gyroscope modifies the rotating frequency achieved by measuring different angular velocity, then the influence is decreased.

The instability of outputting damping coefficient D is mainly caused by varying of aerodynamic viscosity
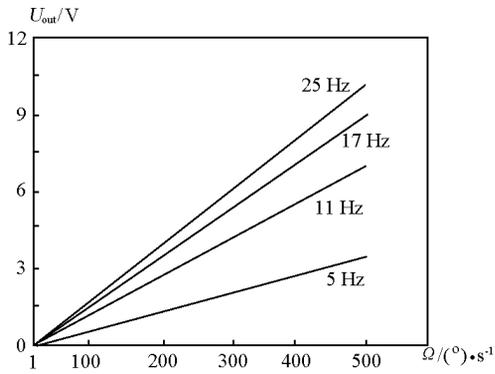
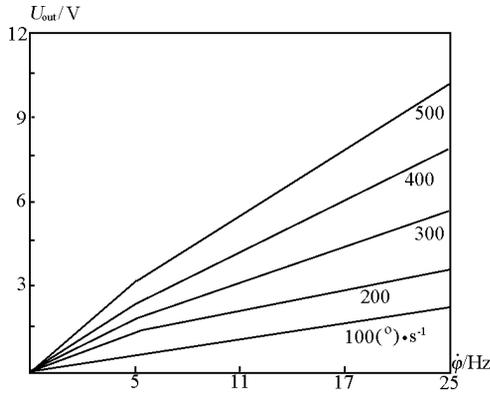**Fig. 2   CJS-DR-WB01-0639 dependence gyroscope output signal from input rate**

Fig. 3   CJS-DR-WB01-0639 dependence gyroscope output signal from simulator frequency

coefficient μ of gas in the case of the gyroscope according to temperature. For nitrogen, $\Delta\mu = 29.3\ \%$ (100 ℃), The variety of damping factor D because of varying temperature is $\pm 17\ \%$. For low damp gyroscope

(shown in Eq. (11)), the main factor is the angular velocity of the rotating carrier itself $\dot\phi$, not damping coefficient.

6   Conclusions

Because of the instability of the angular velocity of the rotating carrier itself, the output voltage error reached to 30 %, so that the error of proportionality coefficient reached to 4.1 %.

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