THE PROBLEMS OF CHARACTERISTIC STABILIZATION FOR MICROMECHANICAL GYROSCOPES

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1. Design concepts of micromechanical gyros

The idea to use microelectronics group technology to manufacture a gyroscope with low weight, size, and cost apparently belongs to experts from the Draper lab from USA. For the first time, they developed IC gyroscope prototypes and published their results. At the present time many firms produce silicon micromechanical gyros of their own design. The prime market for such gyros is civilian applications. Those micro gyros are used in car stability and braking automation, for optical axes stability, and in medical equipment, Ref. 1, 4-6.

All microgyros have low accuracy because of a natural frequency vacillation and Q-factor of the device mechanical part. Analytical calculations and experimental data display, that improvement of characteristics of microgyros may be reached only at usage of an autotuning systems and stabilization of the device main parameters, Ref. 2. Such parameters are frequency and oscillation amplitude of an oscillator. Except for that it is necessary to steady a difference of natural frequencies of axial and equatorial oscillations, and also damping of equatorial oscillations with high accuracy.

For all known designs of microgyros the oscillating mass in elastic suspension is common. Angular rate of an instrument case results in appearance of Coriolis forces which determine origin of an additional oscillating motion. Measurement and the analysis of this motion parameters allows to determine of the basis motion.

By the form used movings of sensing weights divide microgyros into four subclasses. In the scheme LL sensitive element during excitation of primary oscillations makes parallel-plane motion and the same motion in other plane at origin of Coriolis forces. In devices of scheme RR - both vibration modes of a sensitive element angular.

Two vibration modes of a countermeasure feeler are realized in schemes LR and RL. A classical example of construction of the micromechanical gyro such as LL is widely known scheme with divided weights of the sensing element, designed in Draper Laboratory, Ref. 3. Later technicians of laboratory have licensed and have published the symmetrical scheme of the microgyro with sensing weight as a ring. This scheme on adduced classification concerns to RR type. In the scheme the system of the elastic suspension of a countermeasure feeler (Fig.1), consisting of four main radial

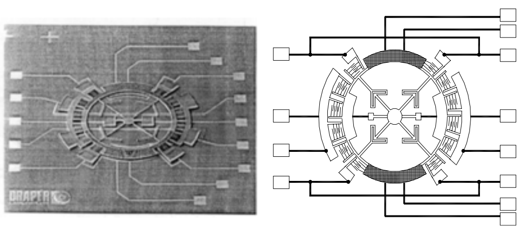

Fig.1. SEM- Photo and the Scheme of the Gyro

and two additional torsion bars is used. This system provides necessary suspension elastic properties on an axis of excitation of primary oscillations, an output axis and maximum rigidity on the third not informative axis.

Excitation of primary oscillations in the microgyro implements with the help of the comb structure electrostatic driver of force. Measurement of secondary fluctuations is carried out with the help of the capacitor transducer which one plate is the case of the device, and other plate a sensitive element. For creation of additional control efforts concerning a measuring axis the electrostatic driver of force on a design similar on capacitive an angle transmitter of turn of a countermeasure feeler is stipulated. Scheme RR-of the gyro in variations in the last years became the basis for many developers.

2. Metrology characteristics of micromechanical gyros

The major metrology characteristics of microgyros are sensitivity and working frequency band. As a first approximation movement of a sensitive element in RR-microgyroscope at influence of angular speed of the basis ω_y can be described the equation Ref. 2

$$\ddot{\alpha} + 2\xi\omega\dot{\alpha} + \omega^2\alpha = \chi\gamma_0\nu\cos\nu t \cdot \omega_y , \qquad (1)$$

where ω - own frequency of fluctuations for a sensitive element on output coordinate α, ξ - factor of attenuation, γ_0, ν - amplitude and frequency of raised fluctuations, I, I_x - the axial and equatorial moments of inertia for a sensitive element, $\chi = I / I_x$.

The solution of the equation (1) for compelled component under condition of allocation quadrature a component results movements in expression for a steepness of the characteristic of the device (device sensitivity).

$$k = \frac{\chi\gamma_0(1+\delta)^2 - 1)}{\nu[(1+\delta)^2 - 1)^2 + 4\xi^2(1+\delta)^2]} \cdot 3600,$$

second of arc/deg/s, (2)

where $\delta = \frac{\omega - \nu}{\nu}$ - relative frequency off-tune of primary and output (secondary) oscillations.

The efforts created by the electrostatic engine during excitation of microgyro oscillations are insignificant. For this reason for reaching oscillation frequency about 1 - 3 °, the instrument case is used usually vacuumization up to value no more than 10^{-3} millimeter of mercury. In these conditions the parameter ξ has a small (10^{-4}-10^{-5}) and instead of the formula (2) for obtaining an estimation of sensitivity of the device it is possible to use approximated expression

$$k = \frac{10\chi\gamma_0}{\Delta}, \text{second of arc/deg/s}, \qquad (3)$$

in which the oscillation frequency γ_0 should be substituted in degrees, and $\Delta = \omega - \nu$ - in hertz.

Thus, sensitivity of the microgyro such as RR on mechanical parameter α as a first approximation does not depend on the sizes of a countermeasure feeler, and is determined only by a ratio of moments of inertia, amplitude of excited oscillations and an absolute value of a frequency off-tuning of primary and output oscillations.

At the same time dynamic responses of the microgyro depend on the last parameter (a frequency off-tuning) in a large degree and, in particular, its passband. Really, supposing $\omega_y = \sin \Omega t$, for the description bending envelope forced vibrations of a countermeasure feeler it is possible to receive a transfer function

$$W_{\alpha_{oc}}^{\omega_y}(s) = \chi\gamma_0\nu \cdot \frac{s^2 + 2\xi(\nu+\Delta)s + (\nu+\Delta)^2 - \nu^2}{[s^2 + 2\xi(\nu+\Delta)s + (\nu+\Delta)^2 - \nu^2]^2 + 4\nu^2(\xi(\nu+\Delta)+s)^2} \qquad (4)$$

Amplitude frequency characteristics of the microgyro, according to expression (4) at ξ = 0,0001 (Fig.2) display, that the working area of frequencies of the device proportionally extends with increase of value of a frequency off-tuning. However, as follows from expression (3), sensitivity of the device to input angular rate accordingly drops and the oscillation of transients increases.

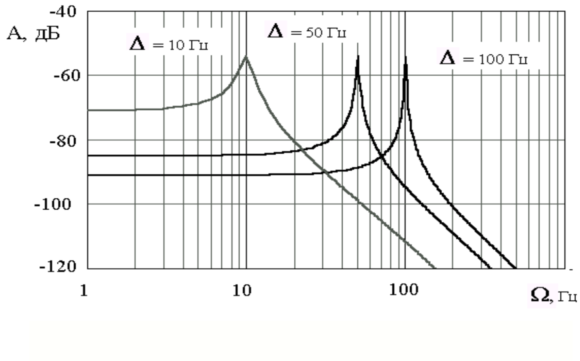

Fig. 2. Relation of an amplitude logarithmic frequency characteristic (LFC) on bending of output signal from a frequency off-tuning

3. Excitation and stabilization of primary oscillations characteristics

For reliable excitation of primary oscillations the scheme with the reference generator which frequency is automatically set up on frequency of a mechanical resonance of a countermeasure feeler on an axis of excitation is used. The best outcomes are reached in versions when the contour

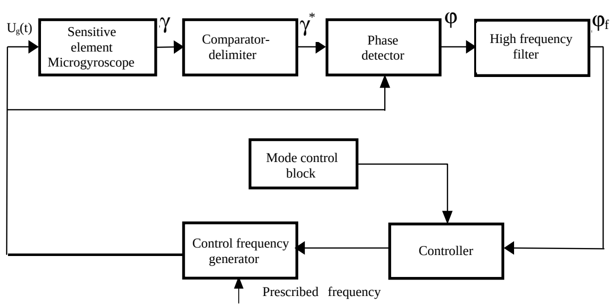

Fig.3 Functional diagram of selftuning of a frequency reference generator

of selftuning of a stable reference frequency is under construction on the basis of a phase detector, detecting a phase shift between assigned and excited oscillations of a sensitive element (Fig.3).

Sensitivity of a phase method of measurement of a frequency off-tuning can be estimated, using the simplified model of dynamics of motion of a sensitive element under effect of the harmonic moment created by the engine on a signal of the reference generator

$$\ddot{\gamma} + 2\xi\nu\dot{\gamma} + \nu^2\gamma = k_d \sin\omega_g t \qquad (5)$$

where ν - frequency of own not damped oscillations of a sensitive element,

ξ - a relative damping ratio, k_d - a power factor of the electrostatic engine.

The solution of an equation (5) can is copied in the form

$$\gamma = A(t)\cos(\omega_г t + \varphi(t)), \qquad (6)$$

where A(t), φ (t) - amplitude and a phase of an output signal concerning a quadrature equivalent of a signal of the reference generator.

After the termination of transient the constant value of a phase shift $\varphi(t) = \varphi_{уст}$ is established (Fig.4) which value depends on quantity of a frequency off-tuning and it is determined by a particular solution of an equation (5). Sensitivity of a phase way reliably allows to fix value of a frequency off-tuning up to the 100-th shares of a hertz at resolution of a phase detector of 1-2 degrees.

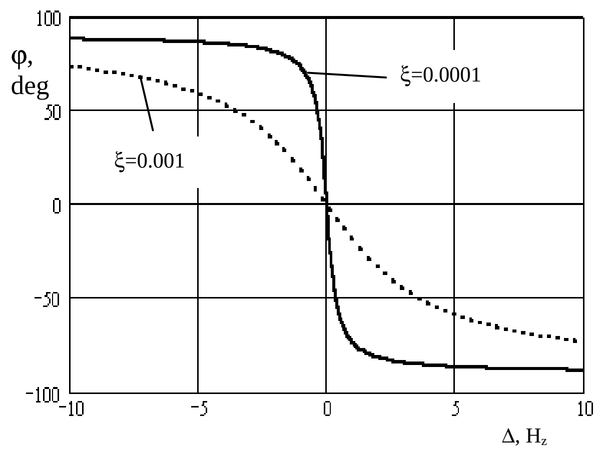

Fig.4. Dependence of values of a phase shift to a frequency off-tuning

The signal of the reference generator on phase relations represents mean model of motion of a countermeasure feeler on angular rate and, means, may be used as reference in the scheme of demodulation of an output signal of the microgyro.

At a choice of the circuit of the phase detector it is necessary to take into account time assigned on process of synchronization of frequencies of the basic generator and a mechanical resonance of a sensitive element, and as efficiency of suppression of the second harmonic in its output signal. The best results as have shown researches, the circuit using algorithm of calculation of mutual correlation function between signals of position of a sensitive element and the basic generator shows. The session of calculation of correlation function is carried out on one period of a signal of the basic generator. After its termination the estimation of phase shift is remembered and used in a contour before the subsequent updating. For real designs of a microgyroscope application of correlation algorithm allows to reduce time of synchronization in a contour up to ~ 1 s (Fig. 5).

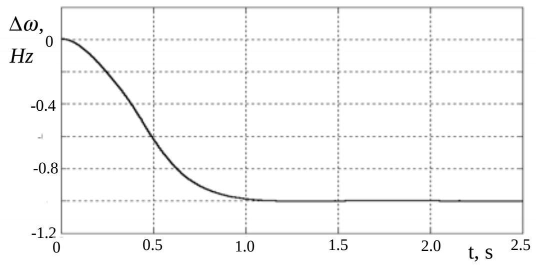

Fig.5. Process of synchronization of the basic generator on freguency

The simple version of construction of a contour of stabilization of amplitude of excited oscillations of a countermeasure feeler is adduced on Fig.6.

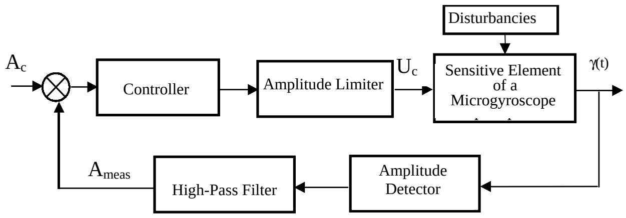

Fig. 6. A functional diagram of a amplitude righting system

It provides measurement of oscillation frequency with the help of an amplitude detector. On the basis of these measurements the stress intensity, given on the electrostatic engine is shaped. For maintenance of an astatism of a contour by mistake of stabilization in the control unit the integral law of regulation is realized. Changing a goodness of circuit it is possible to control a transient period (fig.7) and sensitivity to exposures.

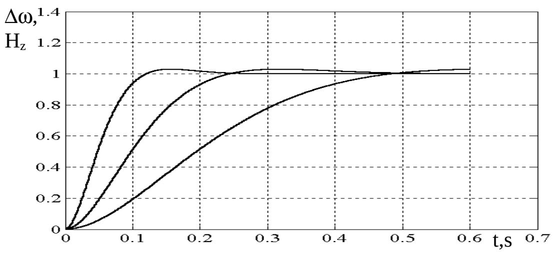

Fig. 7. Transients in a contour of amplitude stabilization

4. Synchronization of frequencies for primary and secondary oscillations

As it was shown, for maintenance of required metrology characteristics the certain difference of frequencies of primary and secondary oscillations of a countermeasure feeler should be supported during activity of the device. At a small index of attenuation as show researches, changes of amplitude of secondary oscillations occur under the harmonic law to frequency, an equal difference frequency of a frequency off-tuning of primary and secondary oscillations. This attribute may be used for construction of an appropriate meter. The detector of a frequency difference is formed on the basis of phase measurements between a signal of the reference generator of a difference frequency and the detected signal of a measuring channel of the microgyro. As the reference generator of a difference frequency should be synchronized with the reference generator of excitation, in practice it may is realized on the basis of frequency dividers. The selected signal of a difference frequency is used or for rectification in an output signal of the microgyro, or used for change of suspension rigidity on a measuring axis by an electrical way.

5. The conclusion

The problem of improvement of metrology characteristics of the micromechanical gyro demands realization of significant researches on development of contours and systems of an autotuning and stabilization of main parameters of the device and development by results of these researches of the specialized signal processor.

References

1. **Kumar K., Barbour N., Elwell J.** Emerging Low Cost Inertial Sensors // Trans. 2nd St.-Petersberg Intern. Conf. Jn Giroscopic Technology and Navigation, May 24-25, 1995. St.-Petersburg: CSRI “Electropribor”, 1995. Pt.1. P. 3-15

2. **Severov L.A., Ponomarev V.K., Panferov A.I. Kucherkov C.G., Sorokin A.V.** Micromechanical gyros: designs, characteristics, technologies, paths of development. News of High Schools. Instrument making. Vol.41, # 1-2, 1998. p. 57-72.

3. **Barbour N. et al.** Micro-Electromechanical Instrument and Systems Development at Draper Laboratory // 3rd Saint Peterburg International Conference of Integrated Navigation Systems. –SPb.: CSRI «Electropribor», 1996.- Part 1.-P.3-10.

4. **Geiger W. et al.** Improved Rate Gyroscope Designs Designated for Fabrication by Modern Silicon Etching // Symposium Gyro Technology, Germany. –1997.-p. 2.0-2.8.

5. **Evstifeev M.I.** A condition of developments and perspectives of micromechanical gyros development//Navigating and mission control.-SPB.: Research Institute "ELEKTROPIBOR", 2000.p..54-71.

6. **Yazdi N. et al.** Micromachined Inertial Sensors // Proceedings of the IEEE, vol.86, #. 8, AUGUST 1998.- P.1640-1658.