MICROMECHANICAL GYROSCOPES: DEVELOPMENT AND PERSPECTIVES

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Abstract

There is a short overview of design and principle of operation of vibrating beams gyroscopes and vibrating ring gyroscopes. Principal disadvantages of such constructions are revealed. The short description of design and principle of operation of autooscillation (self-oscillation) micromechanical gyroscope are adduced. Showed that this principles allow to solve a lot of problems those are connected with described problems.

Index Terms: overview, micromechanics, gyroscope, construction, principle of operation, vibrating beam, vibrating ring, vibrating plate, autooscillation (self-oscillation).

I. INTRODUCTION

Researches of far-reaching importance are connected with the development of micromechanical gyroscopes (MMG) those are based on the vibrating elements and waves. They are fabricated by using the Micromachined Electro-Mechanical System's (MEMS) techniques in silicon or piezoelectric materials. In these gyroscopes Coriolis force produced by the rotation (because of a resonant primary excited mode) leads to a secondary resonant mode.

Such sensors are widely used at present in motor car construction, electronics, medicine and communications. Huge potential of the micro-mechanical devices is recognized by many companies, for instance Draper Laboratory, Analog Devices, British Aerospace etc.

Micromechanical gyroscopes can be used for inertial navigation purposes as a part of a navigation system or stand alone and be used in other applications where rotation rate needs to be measured. Examples of these are automotive applications, such as traction control systems, ride stabilization and rollover detection, some consumer electronic applications, such as stabilization of pictures in digital video camera, inertial mice in computers, and robotics applications [1].

II. SAW-GYROSCOPES

A principle of MMG' construction could be based on the converters of surface acoustic waves (SAW). Such gyroscopes could be named as SAW-gyroscopes. The scheme of such converter are represented in Fig. 1.

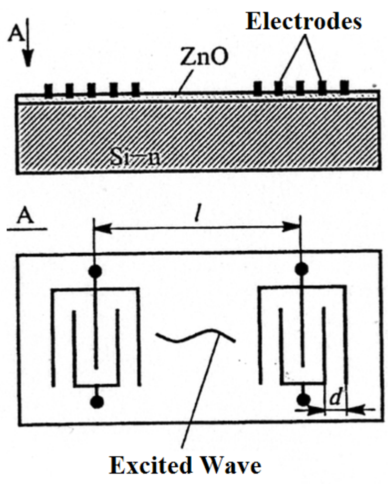

Fig.1. SAW-Converter

If electrodes are energized then SAW will appear. *d* is equal to the length of excited wave.

Some connected with creation of SAW-gyroscopes experiments are described in papers [2] and [3]. Principally it is possible to create SAW-gyroscope with distributed mass that represents the complex of elementary masses or "points". If gyroscope rotates with some angular rate round the sensitivity axis then it leads to occurrence of Coriolis force. Owing to action of Coriolis force the "points" make some secondary SAW. And these SAW allow to measure rotation's angular rate.

SAW-gyroscopes are built on the base of acoustoelectric elements. The backing is Y-oriented $LiNbO_3$.

The experimental researches [2], [3] show that sensitivity of SAW-gyroscopes is very low. So research was ceased.

III. VIBRATING RING MMG

The principle of micromechanical solid-state wave gyroscopes operation is based on inert properties of elastic waves [4]. The kinematic scheme of a vibrating ring gyroscope is shown in Fig. 2. A sensitive element of a gyroscope is the elastic thin-walled ring 1. This ring connected with the case 3 of the device by the system of elastic elements. The basic requirement to this suspension system is transfer of the case rotation to the ring at an angular rate of Ω [5]. But also resistance to the radial elastic deformations of a ring should be minimal. Electrostatic drivers 4 are evenly surround the ring 1 [1].

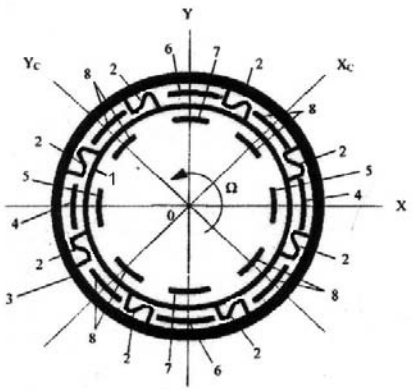

Fig. 2. Kinematic scheme of a vibrating ring gyroscope

External and internal capacitor plates of drivers rigidly connected with the case of the device, and they are located in four zones that coincide with axes of case X and Y in Fig. 2. Existing schemes of excitation systems can differ both in the number of driver zones and in the presence either only external, or only internal driver capacitor plates. If some high-frequency voltage will be applied to the electrodes 4 then periodic radial forces will appear. These forces lead to high-frequency elastic fluctuations of the ring. For MMG the basic form of fluctuations is fluctuations with form factor (mode) k = 2. The ring form is close to the elliptic form when the condition is deformed. The form of fluctuations when there's no rotation of the device case (Ω=0) is shown on the left side of the Fig. 3. The radial movings of a ring are close to zero on the points 1, 2, 3 and 4. This points located on the axes that is turned through the angle $\varphi=\pi/4$. If to assume that there is no radial damping forces then the form of the fluctuations that is shown on the left side of the Fig. 3 will exist infinitely long.

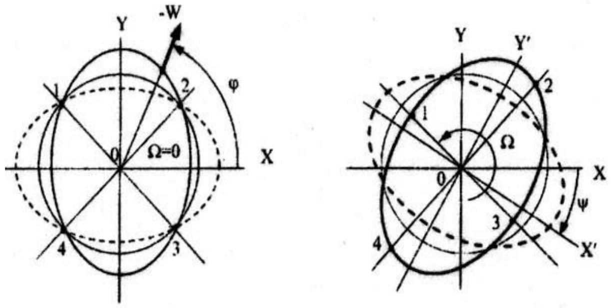

Fig. 3. Vibrations of a wave micromechanical gyroscope when there is no rotation of sensor (left) and when sensor is rotating (right)

One of the first vibrating ring MMG was created in Michigan University in 1994. It's diametr is 1mm. It is represented in Fig. 4 a) [6, 7]. The Q factor of this MMG is approximately 2000, the dynamic range is ±100°/s, the nonlinearity of translation characteristic is 0,2%.

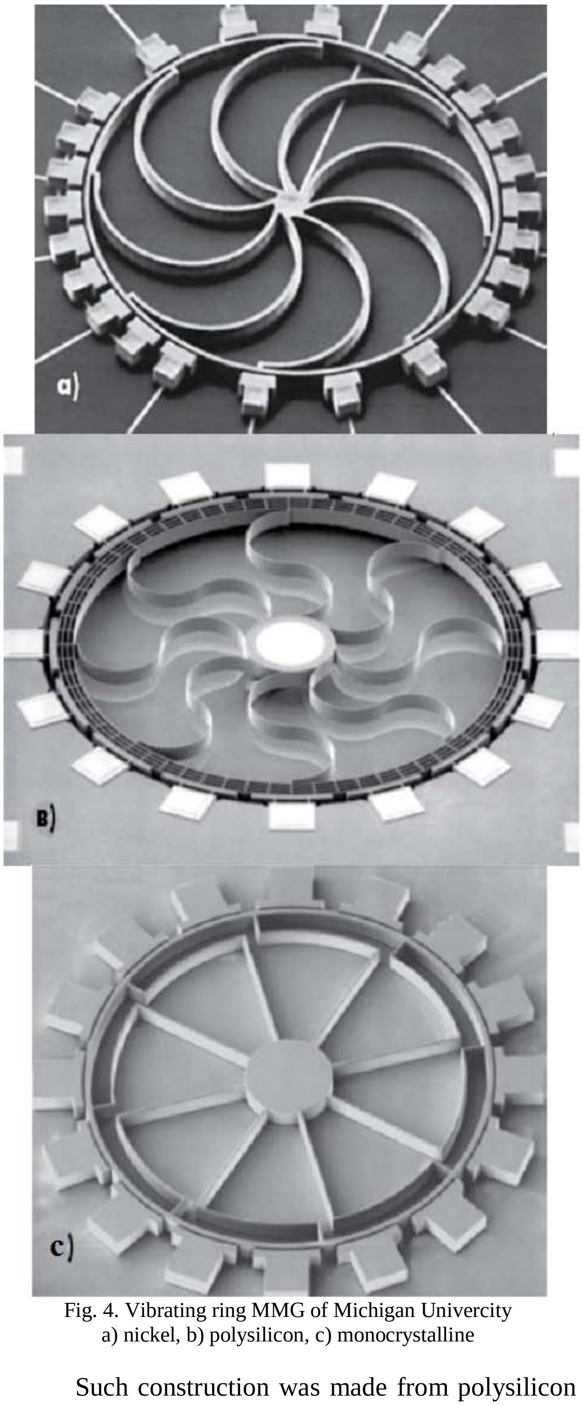

Fig. 4. Vibrating ring MMG of Michigan Univercity
a) nickel, b) polysilicon, c) monocrystalline

Such construction was made from polysilicon little bit later (Fig. 4 b)). The diametr is 1,1 mm, the thickness of disk is 80 μm, the width of the ring and the spokes is 4 μm, the Q factor is approximately 1200 (in the high vacuum) [8].

Made from monocrystalline silicon ((111)-orientation) vibrating ring MMG was glass. The diametr of disk is 2,7 mm, the thickness of disk is 150 μm, the Q factor of the resonator is 12000. Because of such value of the Q factor the accuracy is

0,002 °/s, the nonlinearity of translation characteristic is 0,02%, and the zero drift is 1 °/s (in 10 hours without temperature compensation) [8].

Some types of vibrating gyroscopes are designed with absolutely different shape of the resonator. SEM view of star-shaped vibrating gyroscope is shown in Fig. 5 [5]. Star-shape allows providing better electronic balancing of the resonator. As a result the Q factor of such resonator is from 25000 to 115000 [8].

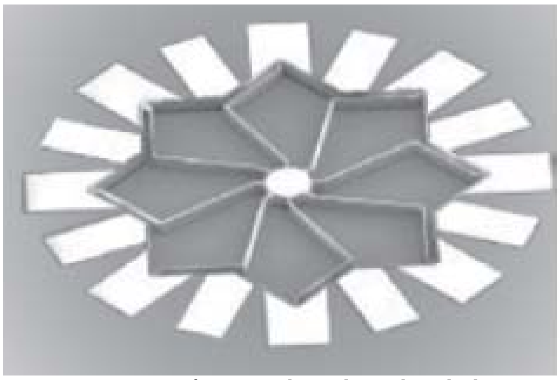

Fig. 5 SEM view of micromechanical star-shaped vibrating gyroscope

The next stage of vibrating ring gyroscopes is the line of devices GYRO-SiRRS01B that are designed by the English company British Aerospace Systems. SRC03 и SRC05 are disigned by it's subsidiary companies Sumitomo Precision Products Company and British Aerospace Systems and Equipment [8]. All these devices are very resistant to vibratory influence - they function even if the linear acceleration is 100g-200g. The main difference from previous devices is the transition from the capacitive excitation system to the inductive excitation system. And the transition of output system is the same too [9]. The permanent magnet (samarium- cobalt) is situated under the vibrator. The diametr of the vibrator is 6 mm. If the current is impressed in the serpentine circuits then the primary oscillations will be excited and the ring will become an oval. Another operational points are the as in the vibrating ring MMG those were written before.

The appearance of SRC03 MMG is represented in Fig. 6. The overall dimensions of device's case are 29 mm × 29 mm × 18,4 mm [8].

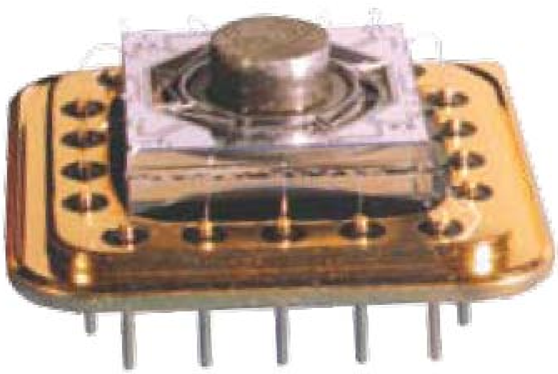

Fig. 6. The appearance of SRC03 MMG

IV. DISTRIBUTED MASS MMG

Another type of MMG is construction with distributed mass that was designed in MicroSystems Laboratory of University of California in Irvine [10]. There are several resonators those are symmetrically situated with respect to the center of construction. These resonators radially oscillate with the same phase and frequency. The construction of distributed mass MMG is represented in Fig. 7. The rotation around vertical axis with angular rate Ω_z leads to the appearance of Coriolis force F_C that is directed tangentially. This force causes torsional oscillation that will be registered by the capacitive position sensors [8].

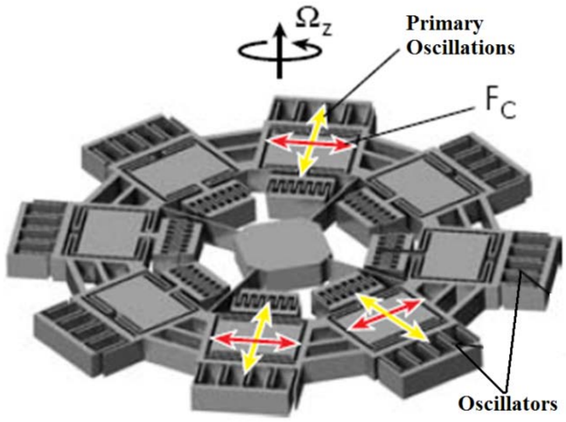

Fig. 7. The construction of distributed mass MMG

Such construction of distributed mass MMG has a lot of advantages. Oscillations of the inertial masses occur along several directions. These directions are symmetrical with respect to the center of construction. Thereby influence of counterbracing is much less. Owing to this fact the level of output signal noise falls and the stability of zero-signal rises. In addition all exciting forces are opposite in pairs and equal, so the total sum of these forces practically is equal to zero in the point of anchoring of the vibrator and the back. Therefore exciting oscillations nearly have no any influence on the back. Besides multiaxial structure minimizes influence of various manufacturing defects, internal stresses, and anisotropic properties of the material [10]. All these factors allow increasing sensitivity of MMG and measurement range [8].

V. BASIC DISADVANTAGE OF EXISTENT MMG

The basic disadvantages of existent MMG become clear after discussion of various MMG' constructions.

Firstly it is essential loss of input sensitivity, extend of influence of various noises, and loss of measuring accuracy as a result of extreme enthusiasm about the minimization of devices' dimensions. Efforts to reverse the situation at the expense of toughening of technological requirements have not given desired effect. As a result the improvement of metrological characteristics was insignificant but the cost have risen a lot.

Secondly inertial masses should be less and resonant mod should be applied because of using of capacitive transducers those have extremely small force characteristics. Moreover evacuation and encapsulation of sensor's interior content should be implemented to ensure high Q of device's oscillating system. These are rather complicate manufacturing operations.

Thirdly the problem of high-accuracy measurement of capacity and its increment appears because of small size devices' sensitive elements. The displacement of sensitive elements is parts of nm and the variation of capacity is fF.

There is no any sense to discuss measurement of such values with the possible appraisal of errors at the moment. The error could reach 100%. Practically the appraisal of position sensor's sensitivity is at stake. And the limitation of sensitivity is connected with either fluctuating processes of converter or such processes in electronic modules' electric circuits [11].

In addition capacitive method of measurement demand complicated schemes of signal conditioning and its noise immunity is bad. The signal-noise ratio becomes much worse because of appearance of spurious capacitance in the circuits of connection of position sensor and unit of useful signal's conversion. And the output signal of position sensor contains quadrature and in-phase components except the useful signal. These components should be eliminated some way.

Fourthly capacitive position sensors and electrostatic compensating force transducers have nonlinear conversion response. It demands to inject additional compensating devices into the devices' circuits to linearize its characteristics.

It is necessary to find some fundamentally new circuit and constructive solutions. It helps to make a breakthrough of creation of high-precision and highly sensitive MMG. However it requires a new thinking, a refusal of stereotype construction, and an application of new elements.

Especially it is clear when the topic is the micromechanical devices those are able to rival the fiber-optical sensors.

New ways of creation of precision digital space-saving devices should be found because of the considerable enhancement of control and navigation tasks. Another reason is the toughening of requirement that the metrological characteristics of the device should be better and the size of the device should be less. One of the most perspective direction of researches is the designing of devices with processing control that are essential because of its operation's entity. It advance facilities to improve the efficiency of getting information either because of the engineering implementation and the choice of operation mode or the soft control.

VII. AUTOOSCILLATING GYROSCOPES

The creation of the autooscillating MMG (AMMG) allows solving many of the aforementioned problems. Such devices are described with more details in paper [12]. The kinematic scheme of AMMG is presented in Fig. 8.

Two inertial masses (IM) (1, 10) are monocrystalline silicon plates with rectangular optical gaps (4, 7). These plates are fixed onto the elastic suspension elements (16, 11) between the magnets. IM can make linear moving on two orthogonally related coordinate axes: longitudinal axis (excitative axis) and lateral axis (output axis). Conducting paths (2, 9) are dusted on the surface of each IM. Light sources (3, 5, 6, 8) and photodetectors (15, 14, 13, 12) are fixed along excitative axis and output axis of each IM.

It is established in the paper [13], that application of magnetoelectric principle of transformation in micromechanical drivers allows substantially increasing its power characteristics in comparison with power characteristics of electrostatic drivers.

Conversion to the autooscillating mode with low frequency of oscillations (below resonance) allows improving the sensitivity by order of magnitude greater. Also it allows refusing of using electrostatic elements with low technical characteristics. Sensitivity and accuracy of measurement increase because of bigger IM. Electrical circuit of the device and signal processing circuit become simpler. And digital output could be realized too. Analysis of AMMG characteristics is represented in paper [14].

The principle of dynamic balancing is used in AMMG as a force-balance device. It allows solving some of the aforementioned problems.

Realization of autooscillating mode enables to solve number of "dead-ended" problems:

- The structure of devices becomes easier because of using of direct current circuits.
- The new for MEMS elements (magnetoelectric drivers and optoelectronic position sensors) could be used [14].
- Inversely proportional connection between bandwidth and accuracy of the position sensor is usual for the devices with linear control circuits. This connection is broken in AMMG.

Analysis of autooscillating systems' properties discloses another advantage that is the most essential. Autooscillating systems are very widely-spread in the natural, biological, and physical objects because of it. This advantage consists in the much better characteristics of energy conversion. It allows getting more information quantity when the energy costs (consumption) are much less [12].

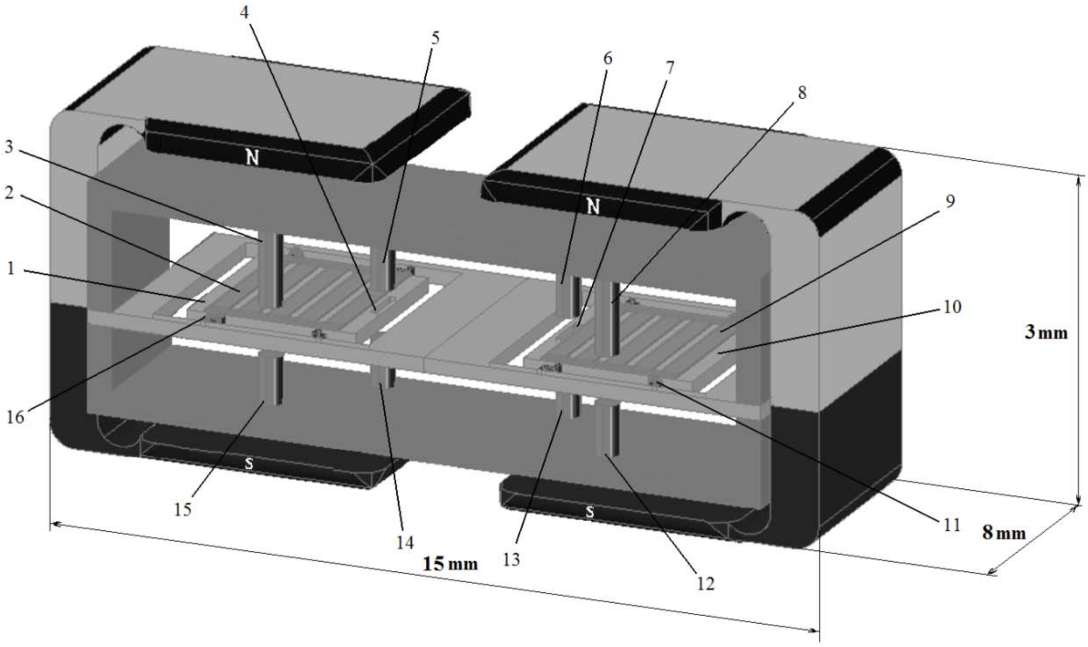

Fig. 8 Scheme of AMMG (it is not proportioned to make it more demonstrable)

VIII. CONCLUSIONS

There are a lot of problems those should be solved in the modern engineering of MMG. These problems are mostly connected with the search of new technological methods of micromechanical structures' formation with a necessary size. Another task is research of position sensor that persistently functions even if movement of sensitive element will be very small. And the ensuring of necessary sensitivity in the low-frequency area is very important too.

The results of solving these problems by scientists, engineers, and technologists will determine the future of MMG and whole micromechanical devices. One of the ways of making metrological characteristics of MMG better is the use of new principles of construction and new elements.

The next purpose of science in this region is the creation of MMG with a wider measurement range and bigger accuracy in comparison with the micromechanical devices existing today. Projecting sensors should be close to the fiber-optic gyroscopes in accuracy characteristics. Creation of such a device will allow the expansion of an application area of MMG.

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