Justification of the Scheme of Ultrasound Processing of Inner Spherical Surface of Quartz Resonators of Solid-State Vibratory Gyroscopes

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Abstract. the scheme of final processing of thin-walled spherical surface` details of navigational instruments made of quartz or fused quartz using ultrasound oscillations, which amplitude and frequency provides a uniforn cutting speed at the sphere surface without using complex kinematics of tool movement is justified.

Keywords: navigational instruments, fused quartz, ultrasound, resonator, precision

INTRODUCTION

Among the perspective tools of flying objects` navigation, including spacecraft, there are solid-state vibratory gyroscopes (SSVG). The main unit of SSVG is resonator. It has such constructional peculiarities as the usage of fused quartz or quartz; presence of cylinder stem on inner and outer surfaces of hemispherical forms; small thickness of the walls (1–2 mm); high demands to the precision of the form and to the quality of the surface (form`s deviations are not more than 0.3 μm, roughness Ra ≤ 0.04 μm). The most complicated technological operations in the process of making the resonator are morphogenesis and final polish of the inner and outer spheres which are bounded in central part by cylinder stems.

Processing of spherical surfaces by already known methods is multioperational grinding and succeeding polish with special tools. Herewith high firmness and fragility of the material lead to fractures formation which length exceeds the abrasive grain of the tool by 3 sizes. This layer disturbs the stable work of SSVG and decreases the set resource. The layer with fractures is removed by multi transitional polish. the mentioned above demands the increasing of the allowance for polish and causes the growth of technical cycle` duration. Kinematics of sphere grinding and sphere polish includes the combination of rotary and reciprocating movements of the tool [1].

The change of the speeds and velocities sign causes dynamic loads, and presence of the stem in the center of inner hemisphere makes the exclusion of tool`s hit almost impossible. It leads to the appearance of overvoltages, which lead to early damage of the resonator. There also exists a danger of stem trimming by the tool. The exclusion of tool swinging leads to unevenness of surface taking off because of the difference of speeds at resonator`s sections.

The usage of casting, stamping or additive technologies which don't demand dimensional accuracy. The usage of free ball grinding which makes chaotic movements when it is influenced by the energy of ultrasound oscillations of the pressed waveguide which is effectively used in final processing of stamps` surfaces in bearing manufacturing, for example, is almost unperformable to the SSVG resonator because the center of hemisphere is occupied by the stem.

Thereby the existing technological methods don`t allow a stable receiving of the demanded characteristics of resonator in mass production conditions.

RESULTS AND DISCUSSION

We have performed the research [2], where we have found the dependence of the length and concentration of fractures on the surface layer of fragile materials to the amplitude of ultrasound oscillations of the tool and we have shown the ability of high-performance processing with minimal defectiveness at the expense of decreasing the amplitude by the criterion of fractures' length acceptable and increasing oscillation frequency to the level which provides the necessary taking off intensity.

Taking into consideration the research data for solving the SSVG resonator processing task with the demanded quality and precision we offer to use the following approach.

It is offered to perform the processing only with rotation of the product at the minimal speed without tool swinging, which excludes the hitting loads and the danger of the resonator`s stem trimming. The offered scheme of SSVG resonator processing is shown at the Fig. 1.

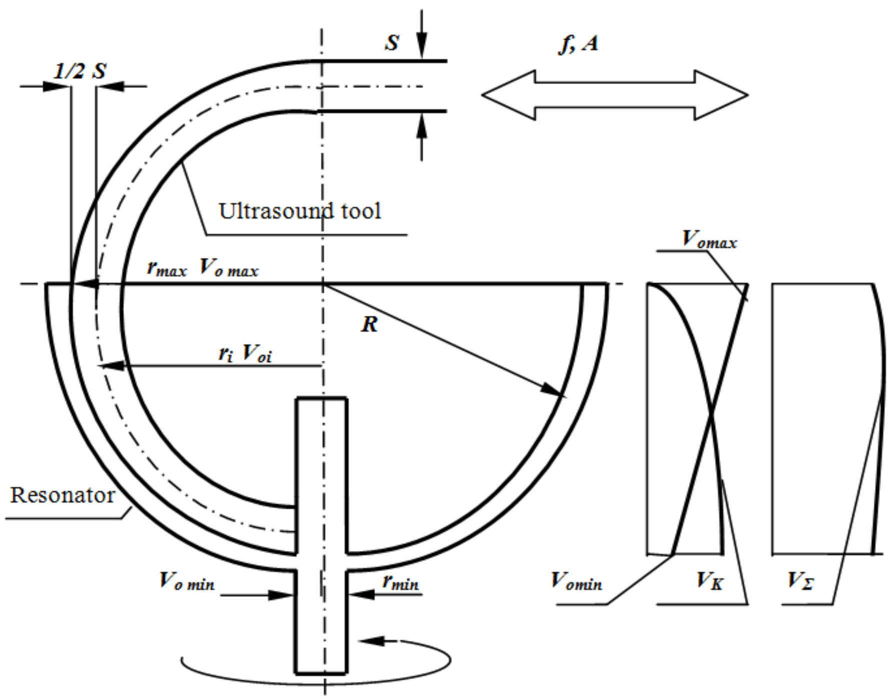

Figure 1. Scheme of SSVG resonator ultrasound processing:
V_0 – speed of resonator rotating; V_K – speed of tools oscillations; V_Σ – total speed; R – radius of the resonator sphere; r_i, r_{min}, r_{max} – current, minimum and maximum rotation radiuses; S – thickness of the tool; f and A – frequency and amplitude of oscillations

For alignment of speeds diagram, and consequently- taking the material off the surface, it is offered to give the tool a special profile of ultrasound oscillations, which amplitude and frequency are chosen according to the conditions of non-excess, which was defined by specifications, of the fractured layer’ depth. The shape of the tool provides the distribution of speed oscillation which in combination with speed rotation diagram provides the alignment of speed on the whole processed surface and, consequently, stabilizes the taking off.

To make the distribution of the tools oscillation speed at resonator sections, perpendicular to its axis of rotation, reverse to the distribution of peripheral speed at the surface of the inner sphere of the resonator, which length of generatrix is obviously equals the quarter of sphere circumference radius *R*, a quarter of ultrasound oscillation wavelength i.e. 1/4λ should be put on it. This is a necessary condition of performing an equal taking off the material and accuracy of processing without swinging movements and tool's rotation. In this case there will be followed the condition: at $V_0 = max \rightarrow V_K = min$ and at $V_0 = min \rightarrow V_K = max$. The diagram of total speed at the sphere surface will be comparatively uniform, i.e. the total speed at the generatrix length is approximately equal. This will provide the uniformity at different sections of the processed surface. Herewith it is necessary to view the oscillations wavelength at the medium section of the tool, which curvature radius will be different from the radius of resonator`spherical surface in a half of tool`s thickness.

To find the ultrasound frequency which provides the given condition, we'll use a known formula [3]:

$$f = \frac{C}{\lambda}, \tag{1}$$

where *f* – resonance frequency of ultrasound oscillations; *C* – velocity of sound in the tool's material, λ – oscillations wavelength.

Considering the mentioned above, we have an equality:

$$\frac{1}{4}\lambda = \frac{1}{4} 2\pi R_t, \tag{2}$$

where R_t – radius of tool’s curvature.

In the calculation it is necessary to consider the distribution of ultrasound at the axis of the tool which has the length *S.* I.e. the radius of curvature R_t will be 1/2*S* smaller than sphere radius. Considering this after transformation we`ll get the formula for finding the tool's wavelength of oscillations:

$$\frac{1}{4}\lambda = \frac{\pi}{4}(R - S)_t. \tag{3}$$

If inside the resonator there is a cylinder stem with radius r_{min}, then in calculating the wavelength in the tool it is necessary to consider decreasing of sphere generatrix’ length at Δl, which owing to comparative smallness of the stem radius can be equal: $\Delta l = r_{min}$, i.e. the formula (3) transforms into:

$$\frac{1}{4}\lambda = \left[\frac{\pi}{2}(R - S) - r_{\min}\right]. \tag{4}$$

After transformations and substitution (4) in (1) we'll get a formula for finding the tool’s oscillations frequency depending on the sizes of the main parts of resonator:

$$f = \frac{C}{2\pi(R - S) - 4r_{\min}}. \tag{5}$$

Based on joint viewing of the known dependencies of finding peripheral speed of the product through its diameter and the number of turnings and also the average speed of ultrasound oscillations, equalling $V_0 = V_K$ in all the sections of resonator perpendicular to axis of its rotation, we'll get a formula for finding the number of resonator turnings at its ultrasound processing:

$$n = \frac{1200 fA(1-\frac{r_{\min}}{R})}{\pi R \,\mathrm{Cos}(arc\,\mathrm{Sin}\frac{r_{\min}}{R})}, \tag{6}$$

where A – amplitude of tool's oscillations.

As the task of final formation of SSVG resonator consists not only of providing the accuracy of the shape and decreasing the dynamic loads, as mentioned above, but in decreasing the sizes of fracture formation area as well, in formula (6) it is necessary to consider maximum meaning for oscillations amplitude at the criterion of fracture formation.

In formula [3] we`ve got the formula for maximum meaning of oscillations amplitude causing fracture formation in amorphous materials:

$$A_M = \frac{[\sigma]e^{\delta x}}{E}, \tag{7}$$

where δ – coefficient of ultrasound wave attenuation; E – elastic modulus; [σ] – breaking point of the material's compression; x – depth of fracture distribution.

After substitution of (7) into (6) we'll finally get a formula for the resonator's number of turnings:

$$n = \frac{1200 f[\sigma](1-\frac{r_{\min}}{R})e^{\delta x}}{\pi RE \,\mathrm{Cos}(arc\,\mathrm{Sin}\frac{r_{\min}}{R})}. \tag{8}$$

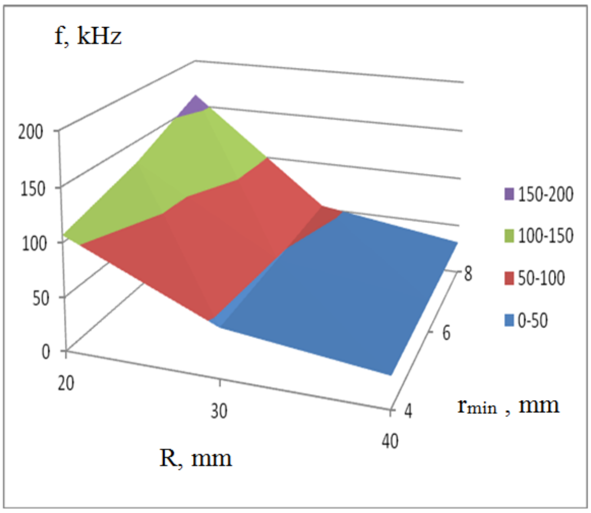

Figure 2. Dependence of tool's oscillations frequency f from sphere radiuses R and resonator's stem r_{min}

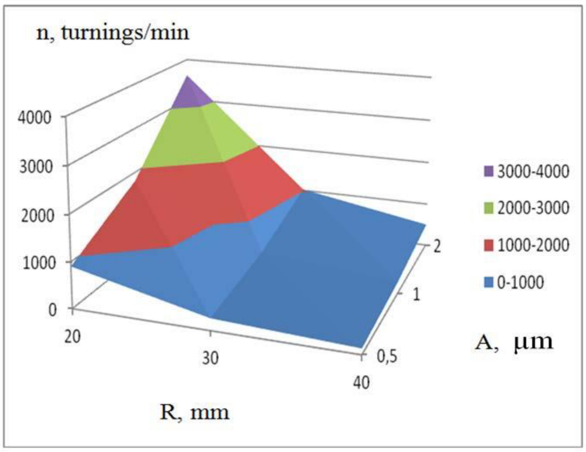

Figure 3. Dependence of tools number of turnings *n* from its oscillations amplitude *A* and resonator's sphere radius *R* at r_{min} = 6 mm

Below at Fig. 2 and 3 there are the results of the calculations of the demanded tool frequencies *f* and the number of resonator`s turnings *n* for its different sizes. As the basic material of the tool the alloy D16T was taken. the velocity of sound distribution in it is C = 5000 m/s. For different conditions of fracture formation the meanings of oscillations amplitude *A* 0.5; 1.0 and 2.0 µm were defined.

It can be seen that resonator's sphere radius influences on the tool oscillations frequency mostly. The stem`s radius influences significantly less, especially at big sizes of sphere.

At small sphere radiuses transverse sizes of stem mostly decrease the sphere generatrix' length, and so the tool's oscillations wavelength. With sphere radiuses less than 40 mm, the demanded oscillations frequencies get further the range of ultrasound technological frequencies. That is why, in case of making compact resonators, for manufacturing them according to the offered technology it is necessary to make special ultrasound generators. Thus for developing SSVG at present time, which has the resonator sizes bigger than 30 mm, it is possible to use serial generators with the frequency of output signal 22 and 44 kHz. Some frequency deviation from the calculated frequencies in this case will lead to a non-significant decrease of processing performance, which is allowed in the conditions of experimental producing SSVG for working off the resonator's construction and its production technology, and also for its subsequent small-scale and mass production.

For justifying the rational processing scheme, regimes and construction of the tool we have performed solid-state modeling of resonator's vibratory stability at different schemes of processing final-cell analysis of stress-strain state of resonator and the tool, the shape of the tool has been optimized.

Conclusion

Experimental working off the offered scheme has shown that, comparing to the existing schemes of sphere grinding, the number of resonators which have the deviation from sphericity less than 0.3 µm after processing, increased almost in 1.4 times (75–80 % binstead of 54–60 %). Herewith the depth of fractured layer decreased by 35-50 %. It has decreased the time of final polish for its excretion by more than 2 times. It will allow a stable receiving of SSVG with drifting indicators of heightened accuracy and to provide the demanded output of valid products and products' lifetime specified.

Thereby we generally have proved the principal possibility of SSVG resonators processing by the simple kinematic scheme with product`s rotation and corresponding ultrasound oscillations of definite dependences of frequency and amplitude mentioned above.

For processing most of the known resonators with sphere radius more than 30 mm the following regimes can be recommended: rotational frequency of 200–500 turnings/min, tool's oscillations frequency 0.5–1 µm. Herewith the existing ultrasound generators production models with output voltage frequency of 22–44 kHz can be used.

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