

UDC 535.2

PACS: 42.60.-v, 42.62.-b, 42.81.Pa

EDN: COGSET

Investigation of the ring laser perimeter stability to vibration overloads

A. O. Sinelnikov^{1,2*}, P. S. Romanov², N. V. Tikhmenev², and A. A. Ushanov²

¹ RUDN University, Moscow, 117198 Russia

² JSC «State Research Institute of Instrument Engineering», Moscow, 129226 Russia

* E-mail: mr.sinelnikov.a@mail.ru

Received 29.12.2025; revised 17.02.2026; accepted 5.06.2026

The paper presents an experimental study of the perimeter sensitivity of a helium-neon ring laser to external dynamic impacts. The laser under investigation had a generation wavelength of 633 nm and a resonator perimeter of 28 cm. A quantitative dependence of perimeter detuning on the overload along the axis of the movable piezo-mirror was experimentally established. It was determined that the operational stability threshold of the laser corresponds to an overload of 56g, at which the critical detuning of 222 nm is reached. Exceeding this threshold disrupts the single-mode generation regime in the laser, leading to a significant error in the output signal. The sensitivity of the laser perimeter to dynamic impacts was calculated to be 3.75 nm/g. The obtained results define the applicability limits of this type of ring laser under vibration load conditions.

Keywords: ring laser, perimeter detuning, dynamic effect, vibration, overload.

DOI: 10.51368/2949-561X-2026-3-87-92

For citation: Sinelnikov A. O., Romanov P. S., Tikhmenev N. V., and Ushanov A. A., Applied Physics, No. 3, 87–92 (2026).

Introduction

Ring lasers have found wide application as high-precision angular rate sensors in modern navigation and control systems [1]. Their operating principle is based on the Sagnac effect, which results in a frequency difference Δf between counter-propagating waves that is proportional to the rotation rate of the device Ω : $\Delta f = K\Omega$, where K is the scale factor of the ring laser [2, 3]. Excluding the active medium, this factor is determined by the resonator geometry: the optical path length L , the area S enclosed by the contour, and the generation wavelength λ . A key condition for the stable and accurate operation of a ring laser is maintaining the resonator length (perimeter) with an accuracy of a few nanometers [3, 4]. During operation, external impacts (temperature, vibrational accelerations) can cause mechanical deformations of the resonator, leading to its detuning ξ – a change in

the effective perimeter ΔL [5, 6]. This phenomenon causes a shift of the generation frequency from the center of the gain line of the active medium, which impairs key laser parameters, resulting in a decrease in radiation intensity, an increase in the lock-in threshold, and the instability of the scale factor.

To compensate for thermal deformations, the ring laser is equipped with a perimeter control system (PCS) that actuates movable piezomirrors [6, 7]. However, rapid oscillations of the piezomirrors caused by vibration may not be compensated by the system in time [8]. In this case, perimeter detuning ξ causes the laser to exit the optimal generation mode. Moreover, changes in the optical path of the resonator caused by mirror movement can induce an error signal interpreted as rotation [4].

The problem of dynamic impacts becomes particularly relevant when ring lasers are used under conditions of increased mechanical loads,

for example, in the geophysical equipment or control systems for moving objects [1, 9]. As shown in prior studies [10, 11], the ring laser design has its own resonant frequencies (up to 2000 Hz), at which vibration accelerations on the resonator housing can reach tens of g. The element most sensitive to overloads is the movable piezomirror, whose displacement directly affects the resonator perimeter. Thus, a quantitative assessment of the stability of the ring laser perimeter against vibrations is an important task that determines the reliability and application range of these high-precision devices.

The aim of this paper is to experimentally study of the ring laser perimeter's sensitivity to external dynamic impacts and to determine the physical mechanisms behind the vibration influence on its output characteristics.

Theoretical part

The operation of the ring laser as an angular rate sensor is based on maintaining a stable single-mode generation regime at the center of the gain line of the active medium. As noted in the introduction, external dynamic impacts cause perimeter detuning ξ , which leads to a change in the resonator's optical length ΔL and a shift in the natural frequency of the longitudinal mode, as determined by the expression [2, 12]:

$$v = q \frac{c}{L + l(n_a - 1)}, \quad (1)$$

where q is an integer (mode order); c is the speed of light; l , n_a are the length and refractive index of the active medium, respectively.

The dependences of generation intensity I on the resonator length L have been well studied [5, 2]. When the perimeter changes by ΔL , the intensity I will change, and it is convenient to choose the perimeter change (detuning) ξ as the argument of the intensity function, which is defined as $\xi = \Delta L = L - L_0$, where L_0 is the resonator length corresponding to the maximum intensity ($I = I_0$). The relationship between the perimeter detuning ξ and the generated radiation intensity I is key to understanding the stability of device operation. Near L_0 , the dependence $I(\xi)$ is approximated by a parabola [5, 11]:

$$I_\xi = I_0 (1 - a \cdot \xi^2), \quad \text{with } |\xi| \leq \pm \xi_f, \quad (2)$$

where a is a constant coefficient; ξ_f is the boundary of the stable single-mode regime region. As detuning continues to increase, a transition to the mode competition zone occurs.

$$\begin{aligned} -I_\xi &= I_0 \left[1 - a \cdot (\xi \pm 1)^2 \right], \\ \text{with } -\xi_f \pm 1 &\leq |\xi| \leq \pm \xi_f \pm 1, \end{aligned} \quad (3)$$

followed by a transition to the irregular regime described by the random function $SQR(\xi)$ [11]. Thus, the threshold detuning value ξ_f is a critical parameter that defines the boundaries of the ring laser operating mode.

Under vibrational impact conditions, the overload P_g arising at the structure's resonant frequencies f_B causes a force applied to the piezomirror, leading to its displacement and perimeter modulation. This process can be described by the dependence:

$$\xi(t) = P_g(f_B) \cdot \xi_g \cdot \sin(2\pi f_B t), \quad (4)$$

where ξ_g is the sensitivity of the perimeter detuning to the projection of vibrational acceleration onto the normal to the piezomirror surface. The overload coefficient P_g , which depends on the impact frequency f_B can be expressed in a linear approximation through the natural frequencies of the resonant modes f_{Bi} with excitation amplitudes a_{Pi} and quality factors Q_{Pi} [8]:

$$P_g(f_B) = \frac{a_{Pi}}{\sqrt{(f_B^2 - f_{Bi}^2)^2 + \left(\frac{f_B \cdot f_{Pi}}{Q_{Pi}}\right)^2}}. \quad (5)$$

Thus, the theoretical model establishes a direct relationship between the external vibrational impact described by the frequency f_B , the overload P_g , and the resulting perimeter detuning ξ , which directly determines the radiation intensity I_ξ and, consequently, the stability of the ring laser output characteristics. Experimental verification of these dependences allows for a quantitative assessment of the laser stability threshold.

Experimental Study and Results

The object of study was a helium-neon ring laser with a four-mirror resonator, a perimeter of 28 cm, and a lasing wavelength of $\lambda = 633 \text{ nm}$ [9]. The schematic of the experimental setup is shown in Fig. 1. The laser resonator consists of two movable (3) and two fixed mirrors (4). Thermal deformations of the ring laser housing were controlled and compensated by a perimeter control system acting on the piezocorrectors (5) of the movable mirrors via a control voltage U_{PC} . Information on the resonator state was recorded by two intensity monitoring

photodiodes (1), whose signals I_{M1} , I_{M2} carried data on the intensity of the counter-propagating waves. The measurement of the difference frequency Δf of signals $U_{\sin}$ and $U_{\cos}$, proportional to the angular velocity Ω , was performed using an information photodiode (2). The laser housing (6) was mounted on a mechanical dither (7) fixed by screws to a movable plate (8) of a vibration shaker to ensure the rigid transmission of mechanical impacts in the specified direction (9). Accelerometers were mounted on the housing (6) to record the overloads P_g along three axes of external impacts.

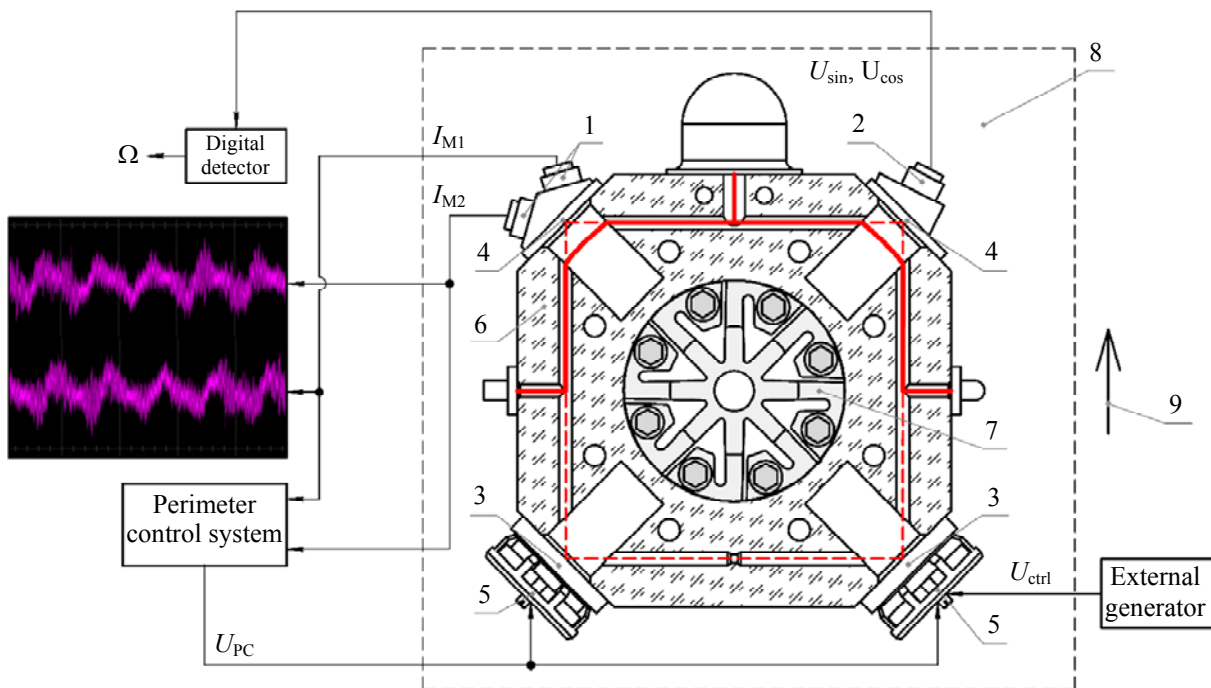


Fig. 1. Experimental setup schematic: 1 – intensity monitoring photodiodes; 2 – information photodiode; 3 – movable mirrors; 4 – fixed mirrors; 5 – piezocorrectors; 6 – ring laser housing; 7 – mechanical dither; 8 – vibration shaker plate; 9 – external dynamic impact direction

The first stage of the experiment studied the dependence of the output signal Ω on the controlled perimeter detuning ξ created by applying a voltage U_{ctrl} to the piezocorrector, with the PCS disabled. The signal Ω was found to remain stable in the range of ξ from 0 to 222 nm and to correspond to the projection of the Earth's diurnal rotation rate ($\sim 12.45 \text{ deg/h}$). When the threshold of 222 nm was exceeded, a sharp, fivefold increase in the readings was observed, indicating that the ring laser had exited the operating single-mode regime. Additionally, the

intensity modulation I_M under a sinusoidal detuning at a frequency of 2 kHz was investigated. The amplitude of the signal modulation was recorded to grow linearly with ξ increasing up to 222 nm, after which characteristic nonlinear distortions appeared in the signal. The second stage was devoted to the impact of an external harmonic vibration in the frequency range f_B from 20 to 2000 Hz at an acceleration amplitude $P = 4g$. The ring laser with the mechanical dither was mounted on a dynamic shaker. After a preliminary warm-up of

the laser, the PCS was switched to manual mode (the voltage across the piezocorrectors was fixed) to exclude its influence on the modulation of signal I_M and to enable the recording of the detuning ξ caused exclusively by external vibration. A significant increase in the modulation amplitude of the intensity signal I_M was observed only in narrow frequency bands (675–690 Hz, 720–750 Hz, 1010–1045 Hz) that correspond to the regions of mechanical

resonances of the ring laser structure. Figure 2 shows a fragment of the signal I_M at a vibration frequency f_B of 920–1120 Hz.

The accelerometer readings recorded along three axes (in the direction of impact, the ring laser sensitivity axis, and the movable piezomirror axis) confirmed the occurrence in these spectral frequency ranges of significant overloads P_g directed primarily along the axis normal to the movable piezomirror surface (Fig. 3).

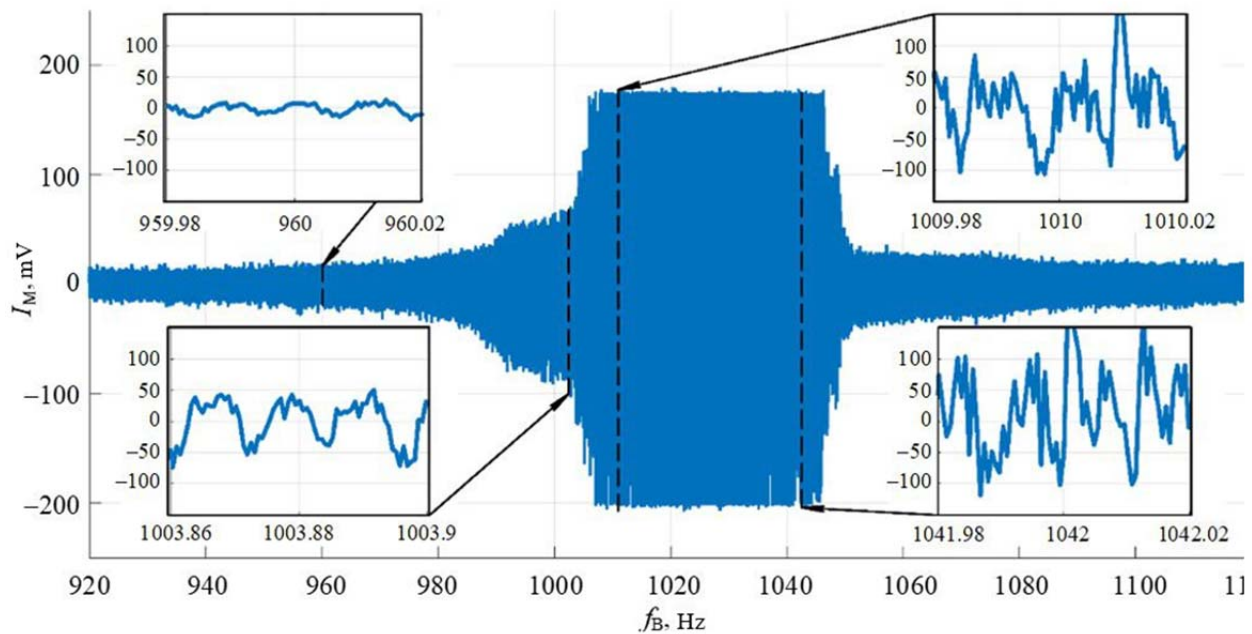


Fig. 2. Modulation of the intensity signal under an external dynamic impact

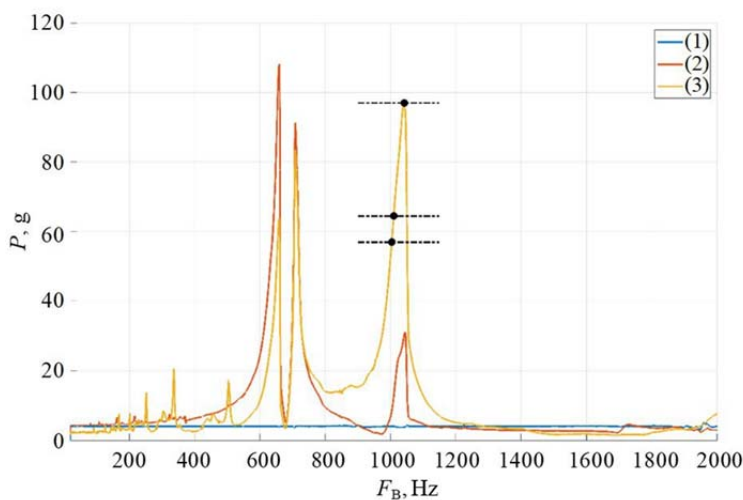


Fig. 3. Overloads along the ring laser axes: (1) – along the impact axis (driving action), (2) – along the ring laser sensitivity axis, (3) – along the ring laser piezomirror axis

A comparison of the modulation pattern of the optical signal I_M under vibration with the calibration dependence obtained at the first stage

of the experiment allowed establishing a quantitative relationship between the overload P_g along the mirror axis and the induced perimeter

detuning ξ . An approximation of the experimental data (Fig. 4) yielded the following dependence:

$$\xi(P) = 0.057P^2 + 0.789P. \quad (6)$$

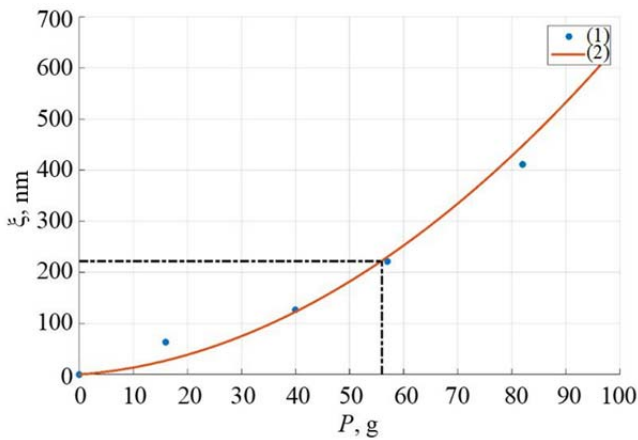


Fig. 4. Dependence of the ring laser perimeter detuning on the overload along the movable mirror axis

It follows from this dependence that the critical detuning value $\xi \approx 222$ nm is reached at an overload $P \approx 56$ g. A linear approximation in the operating range determines the sensitivity of the perimeter of the investigated ring laser to dynamic impacts as equal to 3.75 nm/g.

Discussion of the Results

The obtained experimental data allow concluding that the investigated ring laser exhibits high dynamic stability and establishing a quantitative correlation between mechanical impacts and changes in its optical parameters. The critical threshold established for the perimeter detuning, which is equal to 222 nm, corresponds to the theoretical boundary of the stable single-mode lasing regime. Exceeding this value leads to a transition to the zone of longitudinal mode competition, which fully explains the fivefold increase observed in the output signal error of the device. This result confirms the basic principle that the stability of the ring laser scale factor is determined by maintaining the condition $\xi < \xi_f$.

The revealed selectivity of the laser output signal response to vibration, which is expressed as a significant modulation of the radiation intensity only in narrow frequency ranges, indicates the resonant nature of the impact. This agrees with the data on the intrinsic resonances of the ring laser structure existing within the

frequency range up to 2000 Hz. The prevailing overload specifically along the axis normal to the surface of the movable piezomirror experimentally proves that this element is the main channel for transmitting dynamic perturbations to the optical path of the resonator.

The quadratic nature of dependence (7) likely reflects the nonlinearity of the elastic properties of the piezomirror mount to the laser housing at large deflection amplitudes. The calculated perimeter sensitivity of 3.75 nm/g and the determined stable operation threshold of 56g are key quantitative characteristics for assessing the applicability of the device. These values indicate that at overloads below 56g, the PCS is potentially capable of compensating for the resulting detuning, as it remains within its operating range and does not exceed the critical value ξ_f .

A comparison with known studies [8, 10] confirms the general mechanism of vibration influence through the excitation of structural resonances. At the same time, the obtained specific numerical characteristics (3.75 nm/g, 56g) for a laser with a perimeter of 28 cm contribute new insights into the operational limitations of such devices as part of inertial measurement systems and expand the understanding of their applicability under moderate vibrational loads.

Conclusion

An experimental study of the influence of external dynamic impacts on the stability of the ring laser perimeter has been conducted in this paper. Quantitative estimates of the device stability have been derived from the analysis of the relationship between vibrational overloads, perimeter detuning, and the output characteristics of the device.

The results confirm the theoretical model, according to which the stability of the single-mode lasing regime critically depends on the perimeter detuning value. The experimentally established detuning threshold of 222 nm corresponds to the boundary of the stable single-mode lasing zone. Exceeding this threshold results in a transition to the mode competition regime and a significant increase in the measurement error.

A direct relationship has been established between the overload acting along the axis of the movable piezomirror and the induced perimeter detuning. It has been found that the critical detuning is reached at an overload of 56g, which sets a clear operational limit for devices of this type. The calculated sensitivity of the perimeter to dynamic impacts is 3.75 nm/g.

The obtained results are of practical significance for the development and application

of ring laser gyroscopes under vibrational loading conditions. They show that as long as overloads remain below the specified threshold, the perimeter control system can ensure the normal operation mode of the device, thereby expanding its potential applicability. This study contributes to the understanding of vibration influence mechanisms on the accuracy of inertial measurement systems and provides specific quantitative criteria for assessing their stability.

REFERENCES

1. Sinelnikov A. O., Tikhmenev N. V., Ushanov A. A., and Medvedev V. M., *Photonics of Russia* **18** (6), 450–466 (2024). <https://doi.org/10.22184/1993-7296.FRos.2024.18.6.450.466>.
2. Lukyanov D. P., Raspopov V. Ya., and Filatov Yu. V. *Applied Theory of Gyroscopes*, St. Petersburg: GSC RF OJSC Concern TsNII Elektropribor, 2015 [in Russian].
3. Aronowitz F. *Optical Gyroscopes and Their Applications*, **339**, (1999).
4. Lee J. I., *International Journal of Precision Engineering and Manufacturing* **13** (8), 1439–1443 (2012).
5. Grushin M. E., Kolbas Yu. Yu., and Medvedev A. A., *Photonics* **14** (2), 150–159 (2020) [in Russian]. <https://doi.org/10.22184/1993-7296.Ot.2020.14.2.150.157>
6. Fenercioglu T. O. and Yalçinkaya T., *International Journal of Applied Electromagnetics and Mechanics* **61** (3), 429–443 (2019). <https://doi.org/10.3233/JAE-190019>
7. Lee S. H., Shon W. H., Suh S. W., Yu S. N., and Han C. S., *International Journal of Precision Engineering and Manufacturing* **12** (1), 91–96 (2011). <https://doi.org/10.1007/s12541-011-0011-1>
8. Bolotnov S. A., Nazarov S. I., Sinelnikov A. O., Tikhmenev N. V., and Ushanov A. A., *Gyroscopy and Navigation* **15** (3), 215–225 (2024). <https://doi.org/10.1134/S2075108724700317>
9. Kuznetsov A. G., Molchanov A. V., Izmailov E. A., and Chirkin M. V., *Quantum Electronics* **45** (1), 78–88 (2015). <https://doi.org/10.1070/QE2015v045n01ABEH015420>.
10. Tikhmenev N. V., Nazarov S. I., Ushanov A. A., and Sinelnikov A. O., *Management of Large Systems: Collection of Papers*, № 109, 293–309 (2024) [in Russian]. <https://doi.org/10.25728/ubs.2024.109.13>.
11. Sinelnikov A. O., Tikhmenev N. V., Ushanov A. A., and Nazarov S. I., *Nanoindustry* **18** (S11–1 (135)), 380–387 (2025) [in Russian]. <https://doi.org/10.22184/1993-8578.2025.18.11s.380.387>
12. Liu J., Guo L., Weng J., Liu W., Yang Y., Zhao K., and Zheng Y., *Optics Express* **31** (22), 36314 (2023). <https://doi.org/10.1364/oe.503255>.

About authors

Sinelnikov Anton Olegovich, Ph.D. of Technical Sciences, Head of Laboratory RUDN University (6 Miklukho-Maklaya Ulitsa, Moscow, 117198, Russia); JSC «State Research Institute of Instrument Engineering» (125 Prospekt Mira, Moscow, 129226, Russia). E-mail: mr.sinelnikov.a@mail.ru SPIN code: 2442-7507, AuthorID: 887339, ORCID 0000-0002-5579-3509

Romanov Pavel Sergeyevich, assistant engineer JSC «State Research Institute of Instrument Engineering» (125 Prospekt Mira, Moscow, 129226, Russia). E-mail: romanov_p7274@mail.ru SPIN code: 2329-2940, AuthorID: 1306982, ORCID 0009-0006-3309-0657

Tikhmenev Nikolay Vadimovich, Candidate of Physical and Mathematical Sciences, head of department JSC «State Research Institute of Instrument Engineering» (125 Prospekt Mira, Moscow, 129226, Russia). E-mail: nvtikhmenev@mail.ru AuthorID: 602152

Ushanov Aleksandr Aleksandrovich, Lead Electronics Engineer JSC «State Research Institute of Instrument Engineering» (125 Prospekt Mira, Moscow, 129226, Russia). E-mail: a.a.ushanov@mail.ru SPIN code: 1666-3279, AuthorID: 1211000, ORCID 0009-0009-3703-9981