Increasing the uniformity of distribution of the oscillations of the disc ultrasound radiators for gas media

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Abstract. The article is dedicated to the research of the influence made by secondary modes of oscillations on the uniformity of distribution of the oscillations produced by the ultrasound disk radiators. The article considers the reasons for emergence of the secondary oscillation modes and the ways of mitigating the influence of the secondary modes on the final distribution of the oscillations of the ultrasound disc radiator. It is pointed out that the difference between the working mode frequency and the secondary flexural mode should be 500 Hz or above, and the minimum difference between the working mode and the secondary radial mode frequencies should be 2 kHz. The article also presents the results of the studies of the disc radiators with anisotropic mechanical properties. It suggests a method for modernization of the disc radiators featuring anisotropic mechanical properties in various ways.

1. Introduction
At the present time, the use of ultrasound oscillations for intensification of various technological processes occurring in the gas media is one of the promising ways of increasing their performance. The most common processes that occur in the gas media are coagulation of particles, drying and atomization of fluids [1-6]. To improve the efficiency of the mentioned processes it is necessary to intensify the ultrasound impact on the media; at that, to maximize the performance of the intensified technological processes, a certain type of the ultrasound wave radiated into the gas media needs to be provided. For this reason, it is necessary to create the ultrasound radiators capable of maintaining the required ultrasound field distribution in a gas medium [7]. The analysis of the ultrasound radiator designs made for gas media revealed the ultrasound oscillatory system (USOS) with a disc radiator presented in figure 1 [8] to be the most efficient and promising one.

The disc-shaped radiators are the optimal ones for creating an ultrasound effect with the given properties. However, the structures existing at the present moment do not comply with the set requirements and are not sufficient to intensify the technological processes at the industrial scale for the little radiation surface and the insufficiency of the sound pressure value. This is why the researches of the large-sized (over 350 mm) ultrasound disc radiator design still remain relevant. At that, the difficulty of large-diameter radiator design is associated with the non-uniformity of the radiator oscillation range, which causes the high mechanic tensions in the material that may result in destruction. The non-uniformity of the distribution for disc radiators with the diameter over 350 mm is normally caused by the emergence of a big number of the secondary modes; therefore, for the larger diameters, the probability of a secondary mode getting close to the working circular flexural
oscillating mode is higher, and the working mode oscillation distribution pattern may be deformed. Moreover, one of the main factors influencing the uniformity of oscillations is the anisotropy of the mechanical properties of the material the disc radiator is made of. Therefore, the objective of the research is optimization of the ultrasound disc radiator structure for the improvement of the uniformity of oscillations.

![Figure 1. Ultrasound oscillatory system (USOS): 1 – disc radiator; 2 – concentrator; 3 – waveguide; 4 – piezoelectric transducer; 5 – pins.](image)

2. Influence of the secondary modes of oscillations on the resulting distribution of the disc radiator oscillations

Due to the occurrence of the additional resonance phenomena, some secondary adjacent modes of the oscillations may occur in practice. In this situation, the coincidence of the frequencies of a secondary mode of oscillations and the frequency of the working circular flexural oscillating mode may cause the decrease of the oscillation uniformity and the increase of the maximum tensions, which, in their turn, make an impact on the radiation performance of the disc radiators. This way, the oscillation form of one of the secondary modes would overlap the form of the working oscillation mode. Figure 2 presents different oscillation modes of a disc radiator, including the secondary ones.

![Figure 2. Different ways of distribution of the disc radiator oscillations: (a-c) – secondary flexural modes; (d) – circular flexural mode.](image)

To explain the effect produced by the overlap of the oscillation modes on each other, the distributions presented in figure 3 are studied. Figure 3a presents the oscillation form of the circular flexural oscillating mode (frequency 24056 Hz); figure 3b presents the oscillation form of the secondary mode (frequency 24127 Hz); figure 3c presents the resulting oscillation form (frequency 24210).
Figure 3. Forms of oscillations produced by a disc radiator: (a) – circular flexural mode; (b) – secondary flexural mode; (c) – resulting mode.

Analysis of the computer simulation results leads to the conclusion that the secondary mode of a close frequency (difference under 100 Hz) reduces the uniformity of the circular mode distribution. As we can see, the circular mode oscillation form (figure 3a) is overlapped with the secondary mode oscillation form (figure 3b); this is how the resulting oscillation distribution is formed (figure 3c). The analysis of the results of the computational experiment showed that to ensure the uniform distribution of the oscillation range, the frequency difference between the working circular flexural oscillating mode and the adjacent secondary flexural oscillating modes must not fall below 500 Hz. Otherwise, the form of oscillation of the adjacent secondary mode and that of the working circular mode may overlap, and the uniformity of the oscillation range distribution may fall.

This way, in order to increase the difference between the frequencies of the sought mode and the secondary one, it is necessary to determine the nature of its occurrence and the way of measuring its resonance frequency (the structural property or geometrical dimensions of a certain element of the radiator, making a material influence on the frequency of the secondary mode). The resonance frequency of various secondary modes may materially depend on the geometrical dimensions of this or those circular areas, the change of which may insignificantly influence the resonance frequency of the working circular mode of the disc radiator as a whole. Therefore, the difference between the working circular mode frequency and that of the circular mode may be increased by introducing some changes into the radiator structure. Along with the secondary flexural and oscillating modes of great quality, the reduction in the uniformity of the disc radiator oscillation ranges and the deformation of the circular lines of the oscillation "zeros" is caused by the combination of the forms of the working flexural and oscillating circular mode and the radial oscillating mode. This way, a part of the disc radiator begins oscillating, predominantly, in the radial direction. As the radial mode overlaps the circular flexural and oscillating mode (at the frequency differences between the modes of 50-100 Hz), it becomes impossible to detect the radial or the circular flexural and oscillating mode separately from the other. However, the resulting mode may be determined through the changes of the diameter of some parts of the disc radiator in the oscillation process. Figure 4 demonstrates the distribution of the oscillations of the disc radiator at the radial oscillation mode with the phase 0° (figure 4a) and 180° (figure 4b). Figure 4(c-d) demonstrates the distribution of the oscillations of the disc radiator, working at the resulting (circular flexural and oscillating mode and the radial mode) at the oscillation phases 0° (figure 4c) and 180° (figure 4d).

Analysis of the distributions of the disc radiator (figures 4a and b) reveals that the central circular bulge oscillates predominantly in the radial direction, at the same time deforming the peripheral elements of the disc radiator (radial oscillation range of the central circular bulge constitutes not less than 80% of the axial oscillation range). At that, the analysis of the circular flexural and oscillating mode reveals (figures 4c and d) that predominantly all the system elements oscillate in the axial direction with a minor partial displacement of the first ring elements in the radial direction (not more than 30% of the radially directed oscillation range).

The analysis of the computational experiment results revealed that the radial oscillating mode has a low Q-factor, and its presence makes an impact on other modes in a wide frequency range. To reduce the impact of the radial oscillation mode on the circular mode, the differences between the frequencies of the flexural oscillating and the radial mode need to be 2 kHz or above.
3. Impact of anisotropy of the mechanical material properties on the resulting distribution of the oscillations of the disc radiator

It is a known fact that the material anisotropy is related to their structural non-uniformity and the significant difference of their elastic and strength properties in various directions. For design of the plate-based US disc radiators, the relevant material properties are the Young's modulus value in the longitudinal and latitudinal directions, as they influence the uniformity of distribution of the oscillations in various circular flexural and oscillating modes. Therefore, at the next stage, the impact of the anisotropic mechanic properties on the resulting distribution of the disc radiator oscillations was studied. For this purpose, the work of the ultrasound disc radiator at various anisotropy values in the longitudinal and latitudinal directions was simulated. Figure 5 demonstrates the oscillation forms at different values of the Young's modulus in the longitudinal direction; at that, in the latitudinal and vertical directions, the Young's modulus was set as a constant value.

![Figure 5](image)

Figure 5. Distribution of the disc radiator oscillations depending on the Young's modulus values in the longitudinal direction.

The darker areas in the 3D models presented in figure 5 show the lower values of the oscillation ranges, the "oscillation zeros".

As a result of the computation, the ratio shown in figure 6 was formulated.
The analysis of the collected data reveals that the greater the difference in the Young's moduli in the longitudinal and the latitudinal directions, the lower is the uniformity of the disc radiator oscillation distribution.

4. Experiment results
After that, to validate the theoretical conclusions, a US disc radiator of a titanium plate featuring the anisotropy of the mechanical properties was produced. Figure 7a presents the picture of the radiator and the locations of the oscillation "zeros"; figure 7b shows the photograph of the enlarged central part of the radiator.

As we can see, the oscillation zero form in the central part has the shape of an ellipsis, which matches the theoretical expectations. The analysis of the oscillation "zero" picture and comparison to the theoretical distribution pattern drew the conclusion that the radiator material features a 4.5% anisotropy, which is comparable to the previously completed values of radiator material Young's modulus. After the radiator is manufactured, the same methods may be used to determine the direction of the anisotropic mechanical properties of the radiator material. Therefore, the direction parallel to the lesser axis of the ellipsis, is the area of the appropriate improvement of the radiator.
Further studies were intended to optimize the disc radiator structure by improving the initial product in order to increase the uniformity of the oscillation range. For this purpose, a number of simulation computations was made for various improved structures. The analysis of various improvement options revealed the most efficient one. The optimal way of the radiator modification is through reduction of the thickness of certain areas. Thus, the hardness of the radiator is reduced in the direction with the greatest Young's modulus. Figure 8a presents the draft of the reverse side of the radiator with the improved areas (shaded areas with reduced thickness) and the photo of an improved radiator is shown (figure 8b).

![Figure 8](image)

**Figure 8.** Improved ultrasound disc radiator: a – draft of the radiator with improved areas; b – radiator photo.

As a result of the modernization, the oscillation distribution has changed. Figure 9a presents the picture of a modernized radiator and the locations of the oscillation "zeros"; figure 9b shows the photograph of the enlarged central part of the radiator.

![Figure 9](image)

**Figure 9.** Oscillation "zeros" patterns on the improved disc radiator surface.

As we can see, the oscillation zeros have got the shape of the circular areas. Analysis of the oscillation zero shapes on the radiator surface and the oscillation range value data analysis showed that the non-uniformity of the oscillation ranges within each circular area did not exceed 10%.
5. Conclusion
As a result, it has been found that to ensure the uniform distribution of the oscillation range, the frequency difference between the working circular flexural oscillating mode and the adjacent secondary flexural oscillating modes must not fall below 500 Hz. At that, to reduce the impact of the radial oscillation mode on the circular mode, the differences between the frequencies of the flexural oscillating and the radial mode need to be 2 kHz or above. In order to increase the difference between the working flexural mode and the secondary one, it is necessary to determine the nature of its occurrence and the way of measuring its resonance frequency (the structural property or geometrical dimensions of a certain element of the radiator, making a material influence on the frequency of the secondary mode). The resonance frequency of various secondary modes may materially depend on the geometrical dimensions of this or those circular areas, the change of which may insignificantly influence the resonance frequency of the working circular mode of the disc radiator as a whole.

The completed research provided the base for optimizing the structure of the disc radiator featuring the anisotropic mechanical properties in order to ensure the uniformity of the oscillation ranges.

It has been concluded that the optimal way of improving the radiator in order to increase the uniformity of the oscillation ranges is to reduce the thicknesses of certain parts of the radiator in the direction featuring the greatest Young's modulus value.

Acknowledgements
The study was carried out by a grant from the Russian Science Foundation. (project №19-19-00121).

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