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ON THE RESONANCE CHARACTER OF NONLINEAR WAVE PROCESSES IN CLOSED CYLINDRICAL TUBES

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The results of investigation of nonlinear resonance pressure oscillations excited using a flow-type hydrodynamic oscillator in closed cylindrical tubes that are arranged perpendicularly to the waveguide and are filled with liquid have been given. It has been shown that the amplitude of oscillations in them can be an order of magnitude larger than the amplitude of exciting oscillations in the wave guide.

Keywords: *wave technology, nonlinear oscillations and waves, resonance oscillations in liquid-filled tubes, hydrodynamic oscillator.*

Introduction. Different nonlinear effects resulting from the interaction of waves and owing to which a number of physicochemical processes may be accelerated tens and hundreds of times are frequently used in wave technology, which is based on the theory of nonlinear oscillations and waves in multiphase gas-liquid-dispersion media [1].

In wave technology, a special role is attached to resonance phenomena due to which one can raise the efficiency of generation of nonlinear oscillations and waves and hence the technological processes based on them [2–7].

Formulation of the Problem and Experimental Procedure. In the literature, there are a number of publications in which the role of branched acoustic resonators is studied with the aim of using them to damp out pressure oscillations in waveguides [8–10]. At the same time, excitation of large-amplitude pressure oscillations and waves in multiphase media is a challenge to wave technology. In this work, we present results of experimental investigation of the excitation of resonance pressure oscillations in tubes built in perpendicularly to a working chamber (waveguide) along which nonlinear waves propagate.

The experiments have been carried out with a wave device consisting of a generator of nonlinear oscillations and a working chamber. A flow-type hydrodynamic oscillator was used as the oscillation source [11, 12]. Tap water whose flow circulated through the oscillator and the working chamber served as a medium in which nonlinear waves were excited and propagated. The working chamber represented a cylinder with rigid walls of inside diameter 28 mm and length about 300 mm. The water from the chamber was discharged through an orifice of diameter 14 mm. Tubes of length 50, 100, and 150 mm in which oscillations were recorded had a cylindrical cross section with an inside diameter of 12 mm. Transducers recording variable-pressure oscillations were installed on their ends. In the chamber, there was installed a transducer whose membrane was arranged on the chamber's interior surface. Signals from Kistler 701A-type transducers were recorded with a Classic 6000 electron oscilloscope which simultaneously enabled us to record oscillation spectra. The total error of measurement and recording of the discrete components of the spectrum in amplitude amounted to ±2.5% for frequencies to 100 kHz. To eliminate the influence of the medium we carried out experiments more than once with the same water successively with tubes of different lengths. The results of repeat experiments were virtually identical. The experimental diagram is shown in Fig. 1. The experiments were carried out according to both it and the diagram where the inlet and outlet of the working chamber were interchanged. In this case the instrument transducer in the chamber was arranged at its inlet, and the tube was at the outlet. The water pressures at entry into the hydrodynamic oscillator and in the working chamber were held constant in the process of the experiments.

Results and Discussion. The experiments have shown that the oscillation spectra of pressure waves, which are observed in the tubes, do not fundamentally differ as the position of the chamber changes.

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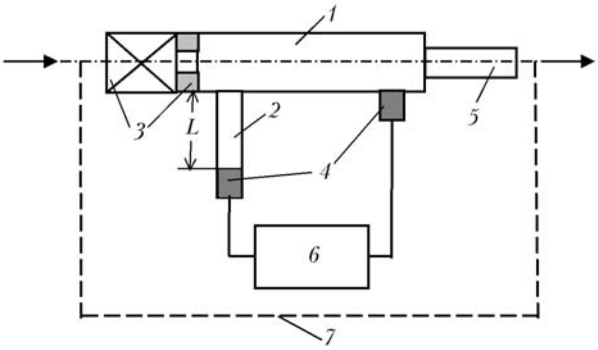

Fig. 1. Experimental diagram: 1) working chamber; 2) plug-in tube for measurements; 3) hydrodynamic wave oscillator; 4) instrument transducers; 5) discharge pipe; 6) oscilloscope with electronic memory; 7) water-circulation line.

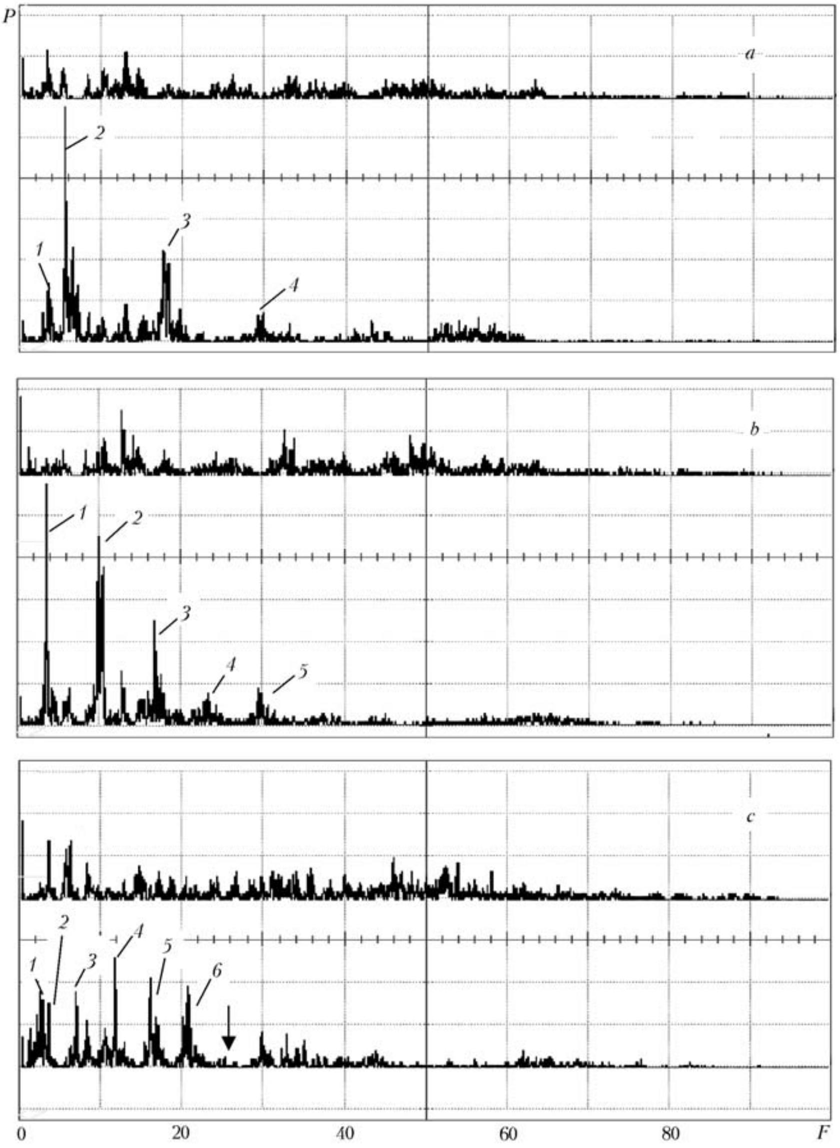

Fig. 2. Spectra of pressure oscillations in the chamber (upper rows) and in tubes of different lengths L (lower rows): a) L = 50, b) 100, and c) 150 mm. The scale reads to 34.53 mV along the P axis. F, Hz.

TABLE 1. Numerical Characteristics of the Peaks of the Oscillation Spectrum in the Tube with L = 50 mm

Characteristics of the peaks	Peak of the initial spectrum	Peak numbers			
		1	2	3	4
Frequency, Hz	5380	3330	5380	17,260–18,010	29,010–29,720
Amplitude, mV	20.7	50.6	200	66.8–78.3	23–25.3

TABLE 2. Numerical Characteristics of the Peaks of the Oscillation Spectrum in the Tube with L = 100 mm

Characteristics of the peaks	Peak numbers				
	1	2	3	4	5
Frequency, Hz	3270–3300	9570–10,220	16,550	23,090	29,260
Amplitude, mV	198	154	80.6	25.3	29.9

Figure 2 gives typical oscillation spectra of pressure P, which have been obtained in tubes of different lengths and in the working chamber. The oscillation spectra in Fig. 2a and b are given for the 50- and 100-mm-long tubes arranged at entry into the chamber, whereas the spectrum of oscillations in the 150-mm-long tube with its arrangement at exit from the chamber is given in Fig. 2c.

The hydrodynamic oscillator emits pressure waves in a wide frequency range; the position of individual peaks of the frequency spectrum (Fig. 2c, top row) and their amplitude distribution are nearly random (the exception is provided by a few peaks on the initial portion of the frequency spectrum). At the same time, we observe pronounced resonance peaks (lower rows) with amplitudes much larger than the amplitudes of the oscillator's spectrum in all tubes.

We emphasize that for a velocity of sound of 1500 m/sec in water, the working chamber in the device, which has a maximum diameter, is a "narrow" tube in the frequency range 0–65 kHz at $a \le 0.61\lambda$ [13], i.e., the wave amplitude is constant in any cross section of the chamber (plane wave), and the geometric dimensions of the chamber exert no influence on the phase velocity of the waves.

Let us consider oscillation processes* in a short tube of length 50 mm. The most characteristic resonance peaks are marked in Fig. 2a, and the data on their frequencies and amplitudes are given in Table 1. The peak contained in the initial spectrum of oscillations of the working chamber is denoted by 1. They are virtually identical. Peak 2, the peak of the largest amplitude, is also contained in the initial spectrum, but its amplitude is nearly an order of magnitude larger than that of the initial peak. It represents the first (quarter-wave) resonance in a tube closed by a rigid wall (transducer's membrane) on one side and open on the other [13]. The velocity of sound calculated from the formula $F_1 = V/4L$ for the first (quarter-wave) resonance turns out to be equal to 1076 m/sec. The reason for its reduction can be gas bubbles that are formed at the outlet of the hydrodynamic oscillator [7].

Higher-frequency peaks (3 and 4) observed in the oscillation spectrum of this tube can be represented as a combination of the first two peaks: the peak of the lowest frequency (external action) and the first resonance peak of eigenmodes in the tube. Then the frequencies of the third and fourth peaks will be equal to

$$F_3 = F_1 \cdot 2 + F_2 \cdot 2 = 3330 \cdot 2 + 5380 \cdot 2 = 17{,}420 \text{ Hz},$$

$$F_4 = F_1 \cdot 4 + F_2 \cdot 3 = 3330 \cdot 4 + 5380 \cdot 3 = 29{,}460 \text{ Hz}.$$

It is seen that the calculated data are in good agreement with experimental ones (see Table 1).

Let us consider analogously oscillations in tubes of length 100 and 150 mm. Figure 2b gives the spectral characteristics of oscillations in the 100-mm-long tube, and Table 2 gives the values of the frequencies and amplitudes of the principal peaks. If we assume that the first peak in the spectrum is the first (quarter-wave) resonance, the rough value of the velocity of sound will be ~1320 m/sec. This pressure peak is the sharpest with a bandwidth of ~100 Hz taken at the level 6 dB. At the same time, the second peak, as is seen in Fig. 3 on a scale increased along the fre-

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* Standing pressure waves are excited in tubes closed on one end, and the presence of the standing-wave resonance can be judged from the maxima in the oscillation spectra.

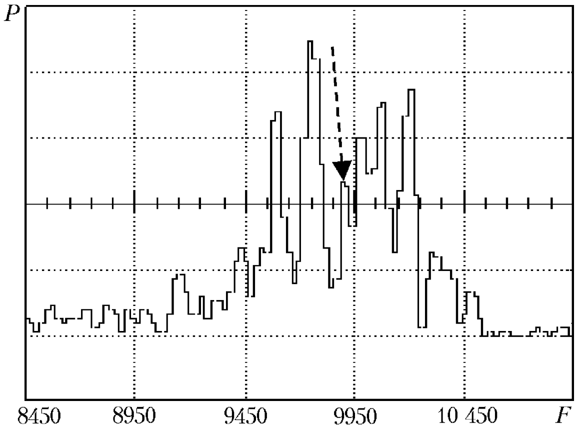

Fig. 3. Second peak of Fig. 2b. The arrow shows the third harmonic of the first peak. The scale reads to 34.53 mV along the P axis. F, Hz.

TABLE 3. Numerical Characteristics of the Peaks of the Oscillation Spectrum in the Tube with L = 150 mm

Characteristics of the peaks	Peak numbers					
	1	2	3	4	5	6
Frequency, Hz	2290–2310 2580–2600	3340–3450	6660–6770 6810–6900	11,550–11,560 11,590–11,610	15,720–15,810 15,870 15,940–15,960	19,960–20,220 20,450–20,640
Amplitude, mV	62.1 55.2	52.9	62.1 50.6	89.8 64.4	57.5 62.1 73.7	52.9 66.8

quency axis, consists of a few peaks with one of which the third harmonic of the first peak is coincident. The third peak corresponds to the fifth harmonic. The last two peaks (4 and 5) correspond to the seventh and ninth harmonics respectively. The remaining peaks of the spectrum are, apparently, determined by the nonlinear interaction of waves of higher order. The presence of such interaction is also demonstrated by the high value of the amplitude of the second peak.

The spectrum of oscillations in the tube of length 150 mm is presented in Fig. 2c, whereas the values of their frequencies and amplitudes are given in Table 3. Furthermore, a number of intermediate peaks located on the frequency axis for F = 8100–8210 Hz, 10,280 Hz, 12,630 Hz, 15,180 Hz, and 16,540 Hz are additionally contained in the spectrum of pressure oscillations in the tube of length 150 mm.

As in the previous cases, the first peak of the spectrum corresponds to the first (quarter-wave) resonance of a tube whose one end has a rigid wall, and the other is open. The calculated value of the velocity of sound in water is equal to

$$V = 4F_1L = 4\cdot 2300\cdot 0.15 = 1380 \text{ m/sec} .$$

The second peak corresponds to the conditions of manifestation of the first (half-wave) resonance of a liquid column confined between the rigid end wall of the tube and the opposing wall of the chamber. We have

$$F_2 = \frac{V}{2\,(L + D)}\,, \quad \text{where} \quad D = 28 \text{ mm} .$$

The velocity of sound determined from this relation is

$$V = 2F_2\,(L + D) = 2\cdot 3400\cdot 0.178 = 1210 \text{ m/sec} .$$

Apparently, the difference in the velocities of sound is due to the presence of a larger number of gas bubbles in the cavity confined between the tube's end and the opposing wall of the working chamber than that in the cavity of the tube.

The third harmonic of the first peak falls within the region of frequencies of the third peak. The fourth peak corresponds to the fifth harmonic of the first peak with a fairly high degree of accuracy:

$$F_4/F_1 = 11{,}550/2310 = 5\ .$$

The fifth and sixth peaks are the seventh and ninth harmonics of the first peak respectively. Furthermore, overlapping of the harmonics of the quarter-wave and half-wave resonances is possible. In particular, the third peak is additionally coincident with the second harmonic of the second peak, whereas the eleventh harmonic of the first peak is coincident with a certain harmonic which is in antiphase. This results in a pronounced crevasse on this spectral portion (it is shown by an arrow in Fig. 2c). Moreover, there can also be nonlinear resonances of the $F_1 \cdot m + F_2 \cdot n$ type yielding intermediate peaks at 12,530 Hz, 15,180 Hz, and others which may also fall within the frequency region of the above peaks. As a result many peaks turn out to be split into a few adjacent peaks.

The performed analysis of the spectra in the tubes shows that with increase in the tube length the resonance maxima in the oscillation spectra of standing waves become broader and split into a few narrower peaks. The character of variation in their amplitudes changes, too. Whereas a nearly exponential monotonically decreasing dependence of the peak amplitude on the frequency is observed for tube of length 50 mm, the resonance peak of higher order (fourth peak), not the first peak, has the maximum amplitude for the tube of length 150 mm. The amplitude level of the maximum peak decreases with increase in the tube length, too. Also, we must note that the velocity of sound calculated from the formula for the quarter-wave resonance in the shortest tube (50 mm) is smaller than that for the tubes of length 100 and 150 mm. In our opinion, the main reason for this difference is that the relative volume concentration of the gas bubbles entering the short tube is higher than that of the bubbles in the longer tubes. The computational evaluations performed with the data of [7] have shown that the volume gas content in water for velocities of sound of 1076 to 1300 m/sec amounts to less than 0.02%. Nonetheless, even at this level of gas content, its influence on the oscillation spectra of nonlinear waves is quite appreciable.

The spectrum of pressure oscillations in the working chamber, on passage of the waves through it (Fig. 2a and b), changes compared to the spectrum at entry into the chamber (Fig. 2c) mainly in the high-frequency region: broad-band peaks with amplitudes exceeding their mean value 2 to 3 times are formed in it. This is the manifestation of the nonlinear character of the generated waves and their nonlinear interaction in propagation along the chamber [14].

Conclusions. The investigations carried out have shown that nonlinear waves generated by the hydrodynamic oscillator excite resonance oscillations with amplitudes nearly an order of magnitude larger than the initial ones in cylindrical tubes that are closed on one side and are arranged perpendicularly to the waveguide. As has been established by calculation, quarter-wave resonances of standing waves and their harmonics and nonlinear resonances at combination frequencies are realized in these tubes.

The obtained experimental results show the possibility of creating new wave devices for generation of high-power oscillations in a wide frequency range. Furthermore, these results must be taken into account when instrument transducers of variable pressure are installed, since different connections (branch pipes) are frequently used for their mounting.

NOTATION

a, tube radius, mm; D, working-chamber diameter, mm; F_1, F_2, F_3, and F_4, frequencies of the 1st and 4th resonance peaks, Hz; F, frequency, Hz; m and n, integers (1, 2, 3, ...); L, tube length, m.

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