Highly non-linear resonance fluctuations of gas in a closed pipe

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Abstract. Highly non-linear oscillations of gas in a closed pipe were researched experimentally. Dependencies of the pressure oscillation amplitude were obtained for various frequencies and amplitudes of the gas excitation near the first eigenfrequencies when transiting to the shock-wave oscillation mode.

1. Introduction
The research of the effect of the medium oscillation to the plasma has a great applied significance. Mostly, peculiarities of processes occurring in cases of high-frequency and ultrasonic oscillations have been studied (see, for instance, digest [1]). Thus, the works [2-4] researched the effect of acoustic oscillations on features of a glow discharge and presented a self-consistent model of a positive glow considering the effect of the acoustic oscillations. High-frequency longitudinal oscillations of gas were created with an acoustic electrodynamic radiator. A necessity has occurred to research the effect of the medium oscillations at low frequencies, in particular, in systems of a resonator-pipe type, which a widely used in technics. When the medium is excited, highly non-linear pressure waves emerge in such systems near the resonance, which waves transform into periodic shock waves in resonance, with the pressure differential up to 0.8 atm [5]. Detailed digests of theoretic and experimental researches of non-linear resonance oscillations of homogeneous and inhomogeneous gas in closed and open pipes when excited with a flan piston in either end are presented in works [6-8]. One of the latest experimental works in this respect was focusing on movement of particles in case of non-linear oscillations of gas in an open pipe in the non-shock-wave mode [9, 10].

This work, being a part of the research cycle for features of plasma interacting with acoustic oscillations, presents the gas-dynamic part of the research of gas oscillations in a resonance mode when transiting to the shock waves.

2. Experimental setup
The research was performed in an installation based on a vibration generator 1 of TIRA vib S 5220/LS make with a power amplifier 20 of BAA 1000-ET model by TIRA firm (Figure 1). Into the table 3 of

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the vibration generator, a rod 5 was screwed, on which rod a flat piston 6 is attached with the diameter \( d = 100 \text{ mm} \); the total weight of the installation is 250 g.

The piston enters the cylinder 7 and oscillates according to the harmonic law with the set frequency \( \nu \) in Hz. In order to prevent the transition of the stand vibration to the floor, the installation was placed on pneumatic spring cushions 25. Four clamp bands 2 were fixed on metal angles 24 screwed to the base of the vibration installation. The clamp bands hold a support 13 with a special lower head 8 and cylinder 7. Ends of a glass pipe 10 with the length \( L = 916 \text{ mm} \), the inner diameter of \( d = 10.05 \text{ mm} \) and the wall thickness of \( 2 \text{ mm} \) were glued with epoxy resin in an opening of the upper head 8 and the lower head 12. The pipe was held vertical with clamp bands 9 fixed on the lower head 8 and the upper head 12. A cap 11 with the height of 22 mm and the inner diameter equal to that of the pipe was tightly screwed to the upper head. A cooling fan 26 was used to prevent overheating of the vibration coil and the field excitation coil.

![Figure 1](image)

**Figure 1.** 1 – vibration generator, 2 – lower clamp band, 3 – vibration table, 4 – piezoelectric IEPE accelerometer, 5 – rod, 6 – flat piston, 7 – cylinder, 8 – lower head, 9 – upper clamp band, 10 – glass pipe, 11 – cap, 12 – upper head, 13 – support, 14 – pressure sensor, 15 – ammeter, 16 – voltmeter, 17 – power supply unit, 18 – controller, 19 – positioning controller TMS-2, 20 – power amplifier, 21 – control computer, 22 – oscilloscope, 23 – three-channel bridge voltage amplifier, 24 – metal angles, 25 – pneumatic spring cushions, 26 – cooling fan.

The vibration table was controlled via a computer 21 by means of a piezoelectric IEPE accelerometer 4 of 4513 model by Brüel & Kjaer firm and a controller 18 of VR9500 type by Vibration Research Corporation firm using a specialized VibrationVIEW software. The positioning controller TMS-2 19 was used to adjust the table of the vibration generator. A pressure sensor 14 of 8530C-15 model by Brüel & Kjaer firm was screwed into an opening of the head 8, and the signal from the sensor was fed through a three-channel bridge voltage amplifier 23 of ENDEVCO model 136 by Brüel & Kjaer firm to a digital oscilloscope 22 of DSO 3062A model by Agilent Technologies firm, and then via an RS-232 interface to the computer, where the data for the gas pressure \( p \) in bar can be observed and saved using a specialized DSO3000 software.
Sine oscillation of the piston near the first proper frequency $\nu_1$ was set with the controller 18. Upon achieving the frequency and span of the piston oscillation $2l$ (where $l$ is the span amplitude) with a certain value, a record of the pressure oscillogram was performed on the computer monitor. The voltage value $\Delta U$ in mV with the accuracy of 0.3 mV was converted into the value of the pressure oscillation span in bar using the conversion ratio $\Delta P\ (\text{bar}) = 0.00025\ (\text{bar/mV}) \times \Delta U\ (\text{mV})$.

In the course of further experiments, flat ring electrodes will be placed inside a closed pipe, as well as in the wave field near an open end of the pipe, which electrodes are planned to be supplied with a high direct voltage from the power supply unit 17. To research the features of the plasma emerging between the electrodes, current-voltage characteristics will be read from the electrodes using an ammeter 15 and a voltmeter 16 connected serial and parallel at different frequencies and amplitudes of the gas excitation.

3. Experimental results

The Figure 2 represents oscillograms with records of the gas pressure oscillations in time at different dimensionless excitation frequencies $\tilde{\nu} = \nu / \nu_1$ and the piston span amplitude $l = 0.375\ mm$. The transition through the resonance near the observed first eigenfrequencies $\nu_1 = 182\ Hz$ was observed. It is obvious that away from the resonance ($\tilde{\nu} = 0.97$), the gas oscillates according to the harmonic law. Along with further increase of the frequency ($\tilde{\nu} = 0.98, 0.99$), a fracture is formed and the amplitude increases in the discharge area. An increase of the steepness of the rising edge of the pressure wave in observed. At the resonance ($\tilde{\nu} = 1$), the amplitude becomes maximum, and the front rising edge becomes close to the shock edge. After the resonance ($\tilde{\nu} = 1.01$), the amplitude decreases and a fracture is observed in the compression area. A further increase of the frequency $\tilde{\nu} = 1.02$) leads to a situation where the compression area in the pressure diagram is equal to the discharge area, but a fracture is observed in the crest of the wave. Away from the resonance ($\tilde{\nu} = 1.03$), the amplitude of the gas oscillation continues to decrease, and the gas oscillation once again assume a harmonic nature.

![Figure 2](image-url). Oscillograms of the gas pressure oscillation at the amplitude of the piston shift $l = 0.375\ mm$ at different dimensionless excitation frequencies $\tilde{\nu}$ near the first eigenfrequencies $\nu_1 = 182\ Hz$. 

$\tilde{\nu} = \nu / \nu_1 = 0.97$  
0.98  1.01  1.02  1.03  1
Quantitative results for the specified case are represented in Figure 3, where the amplitude-frequency curve is presented in the dimensionless form $\Delta \bar{p} = \frac{102 \cdot \Delta p}{p_0}$ ($p_0$ — atmospheric pressure, $\Delta p = p_2 - p_1$ and $p_1$ are maximum and minimum values for the period of the piston oscillation). Notably, the value of the gas pressure amplitude at the resonance frequency is 4 times as high as away from the resonance. The theoretical resonance frequency is calculated according to the following formula [11]

$$\nu_1^* = \frac{c_0}{2L(1+\beta')}, \quad \text{where} \quad \beta' = \frac{1}{2} \left(1 + \frac{\kappa - 1}{\sqrt{Pr}} \right) \frac{\delta}{R} \quad (1)$$

where $c_0$ is equilibrium sound velocity, and $\beta'$ is absorption factor, $\kappa$ is the adiabatic index, Pr is Prandtl number, $\delta$ is the acoustic interface thickness, $R$ is the pipe radius, $L$ is the pipe length.

There is a coincidence of values of the theoretic and the observed first and eigenfrequencies. The dotted line marks the ratio of the excitation frequency to the first eigenfrequencies calculated in consideration of the absorption according to the formula (1), the dashed line marks the ratio of the excitation frequency to that calculated without the consideration of the absorption. The observed resonance frequency has a lesser value than that calculated according to the linear acoustic theory ($\beta'$=0).

![Figure 3](image)

**Figure 3.** Dependency of the dimensionless span of the gas pressure oscillation on the dimensionless excitation frequency at the relative amplitude of the piston shift $\bar{l} = 3.99$. Dots mark the experimental results, and the solid line is Lorentz approximation.

Figure 4 shows oscillograms of the gas pressure oscillation at the first eigenfrequencies $\nu_1$ at different relative piston shift amplitudes. At $\bar{l} = 1.06$, the gas oscillates according to the sine law. Along with the increase of the amplitude ($\bar{l} = 2.66, 4.26, 5.86$), a deformation of the gas pressure wave form is observed: the steepness of the front rising edge becomes greater than the back, and a fracture is observed. In this case, the shape of the wave remains continuous, and at $\bar{l} = 7.46$, a form close to that of a shock wave is observed.
\[
\bar{l} = 1.06 \\
2.66 \\
4.26
\]

Figure 4. Oscillograms of gas pressure oscillation at the first eigenfrequencies at different relative amplitudes of the piston shift \(\bar{l}\).

Figure 5 shows the dependence of the dimensionless span of the gas pressure oscillation in the resonance on the relative amplitude \((\bar{l} = 10^{14} / L)\) of the piston oscillation, which characterizes the intensity of the oscillation. It is obvious that along with the increase of the piston oscillation amplitude, the span of the gas pressure oscillation increases. In these experiments, there is a power dependency \(\Delta \bar{p} = a \bar{l}^n\) (where \(a = 0.82, n = 0.75\)). Notably, in the experiments with the emergence of shock waves, the power index in the resonance has the value of \(n = 0.5\) [6].

Therefore, in these experiments, at small excitation amplitudes, where parietal losses are high compared to those for the gas compression in non-linear waves, there is a difference in the values of \(n\).

Figure 5. Dependency of the dimensionless span of the gas pressure oscillation on the relative amplitude of the piston shift at the first eigenfrequencies. Dots mark the experimental results, and the solid line is power approximation.
4. Conclusion

Peculiarities of non-linear gas pressure oscillation in a closed pipe in a wide range of frequencies and excitation amplitudes when transiting to the shock-wave oscillation mode in resonance were identified. Any increase of the excitation amplitude for all the frequencies in question leads to the increase of the span of the gas pressure oscillation, as well as to a deformation of the wave form: the steepness of the front rising edge becomes greater than that of the back one. The pressure oscillation has a continuous nature, but it becomes close to the interrupted one in the resonance. At the resonance frequency of the gas excitation, an increase of the piston stroke amplitude leads to the increase of the span of the gas pressure oscillation different from that observed in the mode of formation of shock waves. The experimental data obtained are necessary when researching the effect of acoustic waves with non-linear pressure forms on the plasma.

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