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LONGITUDINAL NONLINEAR OSCILLATIONS OF A GAS IN A CLOSED PIPE

R. G. Zaripov, R. I. Davydov, and N. V. Sonin

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Results of an experimental study of longitudinal nonlinear oscillations of a gas in a closed pipe are reported. Pressure waves in a broad range of excitation amplitudes and frequencies are studied. Strong nonlinear oscillations at a frequency thrice as low as the first natural frequency of the gas column are discovered.

In this work, some peculiarities of nonlinear pressure waves that arise in a steady regime in a broad range of excitation amplitudes and frequencies are studied. Most attention is given to the analysis of nonlinear oscillations of a gas discovered in the vicinity of an excitation frequency thrice as low as the first natural frequency (nonlinear resonance at $\omega_{13} = \Omega/3$). A review of some relevant experimental and theoretical studies is given in [1].

Longitudinal oscillations of the gas column in a closed glass pipe of length $L = 870.5$ mm were excited by a planar piston 39.3 mm in diameter. The harmonic motion of the piston was ensured by a VÉDS-400 electrodynamic test block.

The frequency and amplitude of piston vibrations were smoothly varied and measured by the test block's control system. The excitation frequency $\omega/(2\pi)$ was varied from 60 to 210 Hz and additionally controlled by a Ch3-24 frequency meter. The pressure was measured by a piezoelement, with the waveform of pressure fluctuations recorded by an S1-54 oscillograph. The gas-pressure measuring system was previously used in experiments [2–4]. The resonant frequencies were determined from the formula $\omega_{nm} = n\Omega/m$ ($n, m = 1, 2, 3, \ldots$), where $\omega_{11} = \Omega = \pi c_0/L$ is the fundamental frequency of the gas column, c_0 is the velocity of sound in an undisturbed gas, and L is the pipe length. For $m = 1$, we have the natural frequencies of the gas column, which correspond to the linear resonance. The values $m > 1$ and n that is not a multiple of m correspond to the frequencies at which nonlinear resonances are observed.

First, we consider results that refer to the linear resonance around the first natural frequency $\omega_{11}/(2\pi) = 195.9$ Hz. Figure 1 shows oscillograms of time-dependent pressure oscillations in a gas at the resonance frequency observed while increasing the excitation amplitude of piston displacement $\bar{l} = 10^4 l/L$. At a low excitation amplitude ($\bar{l} = 3.67$), the gas executes almost harmonic oscillations. The waveform of pressure fluctuations is symmetrical and continuous. With increasing excitation amplitude, the waveform is distorted, and inflections appear in the rarefaction and compression zones ($\bar{l} = 5.51$). The leading front of the wave between these zones becomes steeper ($\bar{l} = 13.32$), and the amplitude of gas oscillations increases. As the excitation intensity further increases ($\bar{l} = 22.28$), there develops a strongly nonlinear wave resembling the wave with a discontinuity. Some peculiarities of such pressure waves were discussed in [5, 6], where the work of a piston over one period of oscillations of the gas column under resonance conditions was calculated. At small amplitudes of piston motion, the work done by the piston is spent to cover the losses caused by the gas viscosity and thermal conductivity in the near-wall region and in the pipe volume. At higher excitation amplitudes, the work is spent mainly on compensating the losses for gas compression in nonlinear waves. Here,

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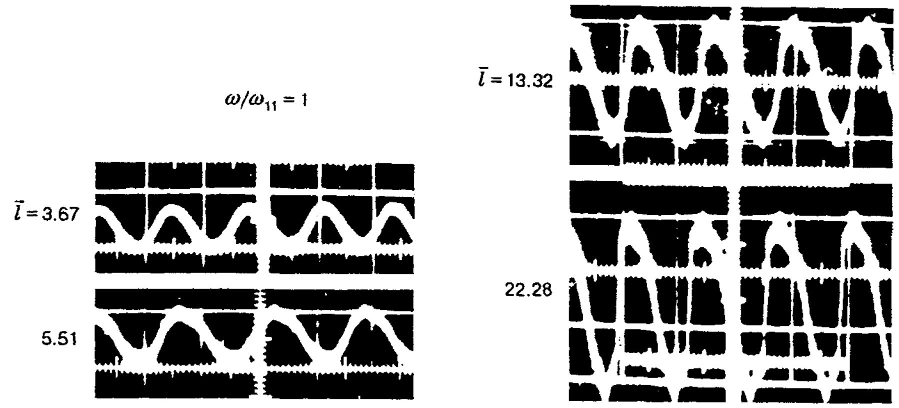

Fig. 1

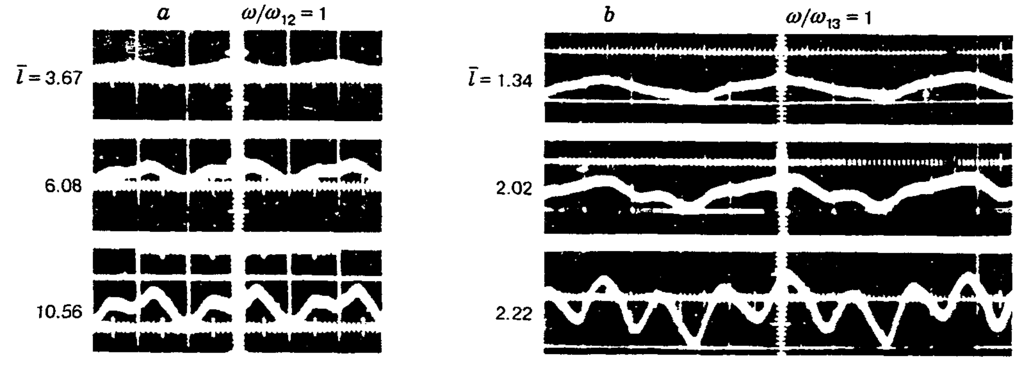

Fig. 2

the effects caused by viscosity and thermal conductivity only slightly reduce the amplitude of gas oscillations.

We turn now to analyzing gas oscillations in the frequency range where nonlinear resonances at $\omega \sim \omega_{12}$ and $\omega \sim \omega_{13}$ are observed. To the best of our knowledge, no experimental studies of oscillations at $\omega \sim \omega_{13}$ were reported.

Figure 2 shows oscillograms of the wave profiles observed at these resonance frequencies as the amplitude of piston motion increases. At small excitation intensities, the gas is seen to execute almost harmonic oscillations. As the excitation intensity increases, the nonlinearity of the gas-column response becomes more and more pronounced. During one period of piston motion, two nonlinear waves originate at $\omega = \omega_{12}$ (Fig. 2a), and three waves are observed at $\omega = \omega_{13}$ (Fig. 2b). In the first case, the wave gets twice reflected from the closed end of the pipe, and an intermediate wave (reflected from the piston) with only slightly reduced pressure is observed behind the primary wave. In the second case, the wave undergoes three reflections, and, in addition to the primary wave, two intermediate waves arise. The formation of waves at nonlinear resonances is less pronounced compared to the case of linear resonance. Under the conditions of linear resonance ($\omega = \omega_{11}$), the wave is reflected only once from the closed end of the pipe, and therefore, only the primary wave is observed (see Fig. 1). The maximum dimensionless amplitudes of pressure fluctuations $\Delta\bar{p} = 10^2\Delta p/p_0$ at the resonance frequencies $\omega_{12}/(2\pi) = 97.9$ Hz and $\omega_{13}/(2\pi) = 65.3$ Hz amount to 0.520 and 0.299, respectively.

Figure 3 shows oscillograms of pressure fluctuations recorded while passing over frequency ($\omega \sim \omega_{13}$) through the nonlinear resonance at $\bar{l} = 21.6$. At the subresonance frequency ($\omega/\omega_{13} = 0.95$), the oscillations have almost a harmonic waveform. On approaching the resonance ($\omega/\omega_{13} = 0.97$), inflections appear in the oscillograms and one intermediate wave forms. As the frequency further increases ($\omega/\omega_{13} = 0.98$), two intermediate waves arise. At the resonance ($\omega/\omega_{13} = 1.00$), the amplitudes of both the primary wave and

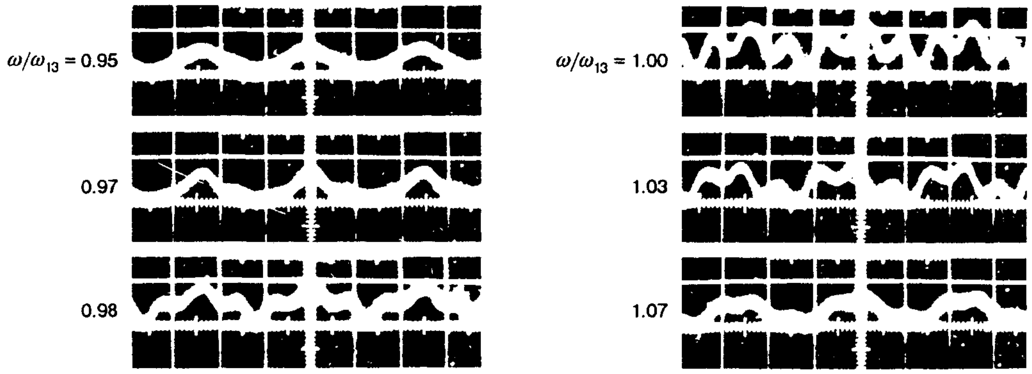

Fig. 3

two intermediate waves attain their highest values. Above the resonance ($\omega/\omega_{13} = 1.03$), the amplitudes of all three waves diminish, and the oscillations again acquire almost a harmonic waveform ($\omega/\omega_{13} = 1.07$).

The studies performed show that an increase in the excitation amplitude of oscillations generated in the frequency ranges around linear and nonlinear resonances leads to evolution of nonlinear phenomena with simultaneous variation of the waveform of gas oscillations in a closed pipe. The peculiarities of the formation of nonlinear pressure waves around a frequency thrice as low as the first natural frequency of the gas column are revealed and described.

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REFERENCES

1. M. A. Ilgamov, R. G. Zaripov, R. R. Galiullin, and V. B. Repin, "Non-linear oscillations of a gas in a tube," *Appl. Mech. Rev.*, **49**, No. 3, 137–154 (1996).
2. R. G. Zaripov and M. A. Ilgamov, "Non-linear gas oscillations in a pipe," *J. Sound Vibr.*, **46**, No. 2, 245–257 (1976).
3. R. G. Zaripov, "Nonlinear oscillations of a gas in an open pipe," *Akust. Zh.*, **23**, No. 3, 378–383 (1977).
4. R. G. Zaripov, M. A. Ilgamov, Yu. N. Novikov, and V. B. Repin, "Nonlinear oscillation of a gas in a pipe," in: *Nonlinear Phenomena Proc. All-Union Conf.* (Moscow, September 12–14, 1998) [in Russian], Nauka, Moscow (1991), pp. 47–53.
5. A. I. Gulyaev and V. M. Kuznetsov, "Large-amplitude gas oscillations in a closed pipe," *Inzh. Zh.*, **3**, No. 2, 236–244 (1963).
6. S. Temkin, "Non-linear gas oscillation in a resonant tube," *Phys. Fluids*, **11**, No. 5, 960–963 (1968).