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CONDITIONS FOR OSCILLATIONS IN A TUBE WITH AN INLET GAS FLOW

V. S. Demin and S. A. Gaponov

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An engineering structure in whose cavities one-dimensional longitudinal oscillations can arise may be considered as a long tube (length much greater than the diameter). In many cases, the energy source for these oscillations is the mechanical energy in an inhomogeneous flow incident at the inlet to the tube, and the oscillations occur because the flow in the tube becomes unstable under small perturbations. The inhomogeneity in the incident flow makes the flow at the inlet essentially other than one-dimensional. Numerical methods can be used [1] to obtain an exact solution for the stability of such a flow under small perturbations, but as the oscillations within a long tube are one-dimensional, one can assume that these oscillations are determined by the parameters of the incident flow averaged over the tube cross section. The treatment becomes one-dimensional, which simplifies the stability calculation and gives a clearer picture of the physical essence of how the inhomogeneous flow interacts with the oscillations in the tube.

That approach has been used in [2, 3], where parts having complicated flow short by comparison with the length of the tube are considered as discontinuities or boundaries in a waveguide. The solutions on the two sides of a discontinuity are linked up by equations describing the flow in the short part. In the case considered here, there are two such boundaries: the inlet and the outlet. The solution in [2, 3] on the stability were attained with certain boundary conditions. However, in general it remains uncertain which of the averaged parameters of the incident flow will govern the stability and for what values of these parameters the flow is unstable. These aspects are examined here.

In a one-dimensional approximation, the motion of small perturbations is described by an equation system for isentropic flow as given for example in [2]:

$$\frac{\partial v}{\partial \tau} + \frac{\partial p}{\partial \xi} + \mathrm{M}\frac{\partial v}{\partial \xi} = 0,\ \frac{\partial p}{\partial \tau} + \frac{\partial v}{\partial \xi} + \mathrm{M}\frac{\partial p}{\partial \xi} = 0. \tag{1}$$

Here $p = \delta p/\gamma p^*$; $v = \delta v/a$; $\xi = x/L$; $\tau = ta/L$; δp and δv are the perturbations in the pressure and velocity, p^* is the static pressure for the unperturbed flow in the tube, a the speed of sound in the tube, L the tube length, t is the time, M the Mach number for the flow in the tube, x the coordinate along the tube with its origin at the left-hand end of the tube where the gas enters, and $\gamma = C_p/C_V$ the adiabatic parameter.

If we assume that the entropy perturbations are small by comparison with the pressure and velocity ones, the boundary conditions are put in the form $p = Bv$ at $\xi = 0$ and $p = Cv$ at $\xi = 1$, where B and C are real numbers, i.e., p and v vary in time either in phase or in opposite phase. This is true if the flow outside the tube is greatly perturbed at a distance from the edges of the tube not more than the diameter. Then the flow at the ends of the tube can be taken as quasistationary [2, 3].

The solution to (1) is

$$\begin{aligned} v &= 0.5[A_v(\exp\varphi_1 + \exp\varphi_2) + A_p(\exp\varphi_1 - \exp\varphi_2)]\exp\beta\tau, \\ p &= 0.5[A_p(\exp\varphi_1 + \exp\varphi_2) + A_v(\exp\varphi_1 - \exp\varphi_2)]\exp\beta\tau, \end{aligned} \tag{2}$$

in which A_v and A_p are the values of v and p for $\xi = 0$ and $\tau = 0$; $\beta = \nu + i\omega$; $\omega = 2\pi fL/a$; f is the dimensional frequency

$$\varphi_1 = -\frac{\beta\xi}{\mathrm{M}+1};\ \varphi_2 = -\frac{\beta\xi}{\mathrm{M}-1};$$

$$\nu = \frac{1-\mathrm{M}^2}{2}\ln\left|\frac{1+H}{1-H}\right|;\ \omega = (1-\mathrm{M}^2)\pi k/2;\ H = \frac{B-C}{1-CB};$$

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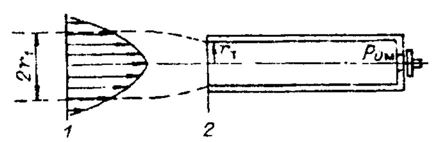

Fig. 1

k = 0, 2, 4,... for (1 + H)/(1 − H) > 0 or k = 1, 3, 5,... for (1 + H)/(1 − H) < 0.

It follows from the (2) solutions that the oscillations increase with time if $\nu > 0$, which occurs if one of the following two conditions is met:

$$BC > 1 \text{ for } B < C, \; BC < 1 \text{ for } B > C. \quad (3)$$

The signs of B and C are incorporated.

The physical meaning of these conditions is that when the acoustic waves are reflected from the ends of the tube, the attenuation at one end is more than balanced by the amplification on reflection from the other end. The coefficients B and C characterize the reflective of the tube ends [3].

In [2] there are examples of deriving B and C from the relationships for stationary isentropic flow at the ends of the tube.

If the ends of the tube are located in an unbounded space where there are no pressure pulsations, then p = 0 for ξ = 0 and 1, and B = 0 and C = 0. Here the absolute value of M is less than one.

For a closed tube end (ξ = 1), v = 0 and C = ∞.

For an outflow at the end of the tube (ξ = 1) through a construction (where M_1 = 1), C = 2/M(γ − 1).

For constant flow rate of the incoming gas through the critical section (where M_0 = 1), B = −1/M.

For constant total pressure in the inflowing gas [3], B = −M.

The condition for complete absorption of the wave at the end of the tube (e.g., cotton wool is placed at the end) is C = 1 for ξ = 1.

We derive B for an inhomogeneous incident flow at the inlet (ξ = 0). The one-dimensional oscillations interact with the flow averaged over the cross section. We assume that vortices within the tube caused by inhomogeneity in the incoming gas die away at a distance from the inlet approximately equal to the diameter. Then for a long tube one can assume that the flow is homogeneous in the inlet section and that the flow parameters are qual to the values averaged over the cross section.

Let the stagnation temperature in the incident flow be the same everywhere, which applies, for example, if the flow inhomogeneity is obtained by placing local resistances in a homogeneous flow or is due to local shock waves in supersonic flow. Then the incident flow has a distribution for the total head. For a stationary adiabatic flow with a given inhomogeneity in the unperturbed flow, one takes the total head for the incoming gas averaged over the inlet section p_{0t} as a function of only one parameter (e.g., incoming gas flow rate Q_t or the Mach number in the tube).

This can be seen if we express Q_t and p_{0t} in terms of the parameters of the unperturbed flow in that flow tube from which the gas enters the tube. Figure 1 shows dotted the flow tube from which the gas enters the tube during the oscillations in the entry phase. The flow in section 1 of the flow tube is not perturbed during the oscillations. Section 2 in the flow tube coincides with the inlet section of the tube. If we neglect the losses in total head on inlet, one can calculate Q_t and p_{0t} in terms of the flow parameters in the unperturbed section 1 from

$$Q_T = \int_0^{2\pi} \delta\alpha \int_0^{r_1} \rho u_x r \delta r, \; p_{0T} = \frac{1}{Q_T}\int_0^{2\pi} \delta\alpha \int_0^{r_1} p_0 \rho u_x r \delta r.$$

Here p_0, ρ, and u_x are the total head, the density, and the velocity, which are dependent on the radial coordinate r, with δr the increment in r, α azimuthal angle, and r_1 the radius of the current tube in the unperturbed section. The first expressions shows that if Q_t is increased, then r_1 increases, since the integrand expression is unaltered (the flow is not perturbed). This means that additional current lines arise as the flowrate increases, i.e., gas enters the tube from aflow tube in the unperturbed flow that has an increasing diameter. As r_1 is a function only of Q_t, and the second expression implies that p_{0t} is a function only of r_1 and Q_t, then p_{0t} is a function only of Q_t. When the inhomogeneous flow enters the tube and during the mixing, the stagnation temperature is preserved, since

$$T_0 = T\left(1 + \frac{\gamma - 1}{2} M^2\right), \tag{4}$$

in which T_0 is the stagnation temperature in the unperturbed flow in section 1, while T and M are the temperature and Mach number in the tube in section 2. Formulas for the averaged flow apply for section 2:

$$p_{0r} = p^* \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}, \; a^2 = \gamma p^*/\rho^* = \gamma RT. \tag{5}$$

Here a, p^*, and ρ^* are the speed of sound, the pressure, and the density in section 2, while R is the gas constant. Under these flow conditions, T_0 = const, while p_{0t} is variable. We use these formulas to show that p_{0t} is a single-valued function of M. The flow rate in the tube with cross section S can be represented by $Q_t = Ma\rho^*S = \gamma MSp^*/a$, and as shown above, Q_t is dependent only on p_{0t}, while p^* from (5) is dependent on p_{0t} and M. For T_0 = const, (4) and (5) give the speed of sound as dependent only on M, so p_{0t} is a single-valued function of M, and in general we can write $p_{0t} = F(M)$, so for small changes in the parameters we have $\delta p_{0t} = \partial p_{0t}/\partial M \; \delta M$, which is a boundary condition at the open end of the tube with the flow entering. For small changes in the paarameters, formula (5) gives $\delta a/a = \delta T/2T$. The formula for the stagnation temperature (4) with T_0 = const gives

$$\delta T/T = -(\gamma - 1)M\delta M \Big/ \left(1 + \frac{\gamma - 1}{2}M^2\right),$$

and (5) implies that

$$\delta p_{0r} = \delta p^* \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\gamma/(\gamma - 1)} + p^*\delta\left[\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\gamma/(\gamma - 1)}\right],$$
$$\delta M = \delta v/a - M\delta a/a.$$

Substitution for δp_{0t} and δM in the boundary condition and transformation given p/v = B, where

$$B = \frac{1}{\gamma p^*}\left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1/(\gamma-1)}\frac{\partial p_{0r}}{\partial M} - M. \tag{6}$$

We now derive the boundary condition at the inlet (ξ = 0) with stationary flow from the tube in the opposite direction. In that case, the dimensionless velocity M in the tube is negative, since the gas runs out in the opposite sense to the positive direction of the x axis. The static pressure p^* at the end of the tube is determined by the flow pattern at the end. This pattern is dependent on the structure of the incident unperturbed flow and the mode of flow from the tube. As the flow conditions in the tube are unambiguously defined by specifying three parameters (p_{0t}, M, T_0), we have $p^* = F_1(p_{0t}, T_0, M)$. With an unaltered structure for the unperturbed flow and T_0 = const in the tube, we have $p^* = F_2(p_{0t}, M)$. The p_{0t}, p^*, and M within the tube are related by (5). We therefore eliminate p_{0t} from the last equation and get in general form $p^* = F_3(M)$, so any change in the Mach number of the outflow from the tube may substantially affect the mode of flow at the inlet, and thus may alter p^*. For small changes in the parameters we have $\delta p^* = \partial p^*/\partial M \; \delta M$. This is the boundary condition for flow from the tube in the opposite sense to the incident flow. As $\delta M = [1 + (\gamma - 1)/2 \; M^2]v$, and $\delta p^*/\gamma p^* = p$, the boundary condition gives

$$B = \frac{1}{\gamma p^*}\left(1 + \frac{\gamma - 1}{2} M^2\right)\frac{\partial p_*}{\partial M}. \tag{7}$$

If there is no flow in the tube, i.e., M = 0 (e.g., the rear end is sealed), then during the oscillations there is a phase of inflow into the tube and outflow from it. We find the value of B for this case. Let the velocity at the inlet to the tube oscillate on a low satisfying system (1): $v = v_0/a \exp\nu^* t \sin\omega^* t$ (ν^* is a dimensional coefficient and ω^* the dimensional angular frequency). Negative values of v correspond to outflow and positive ones to inflow. The change in static pressure takes the form $p = B_i{}^v$ on the basis of the boundary condition p = Bv. The coefficient $B_i = B'$ in accordance with (6) for a positive value of $\sin\omega^* t$, while $B_i = B''$ in accordance with (7) for a negative value, i.e., on outflow from the tube. The time junction

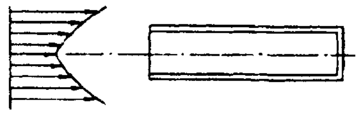

Fig. 2

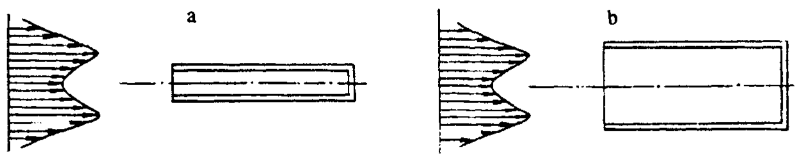

Fig. 3

$B_i \sin\omega^* t$ is a periodic curve unsymmetrical with respect to the time axis. The negative and positive half-periods have unequal maximal deviations B′ and B″. Such a function can be expanded as a Fourier series. In the expansion there is a term having the frequency ω^* of the velocity oscillation. Then that component in the expansion of the pressure pulsations in the inlet section may have certain phase relationships to the harmonic oscillations in the tube and either supply them with energy or damp them. That term has the form $B_0 \sin\omega^* t$, where $B_0 = 0.5(B' + B'')$. Then the required boundary condition is $p = B_0 v$, when a gas flow is incident on a tube without through flow (M = 0). Here from (6) and (7)

$$B = B_0 = \frac{0.5}{\gamma p^*}\left(\frac{\partial p_{0t}}{\partial M} + \frac{\partial p^*}{\partial M}\right). \tag{8}$$

We now consider how various boundary conditions affect the possibility of oscillations.

If a wave absorber is placed at the end of the tube, then from (3) with C = 1 we get B < 1 and B > 1, which is impossible for any value of B, so one-dimensional oscillations are impossible with any flow at the inlet. This is confirmed by experiment [5].

If $M_1 = 1$ in the hole at the end of the tube, then $C = 2/(\gamma - 1)M$. With an inhomogeneous flow incident at the inlet, B is derived from (6). When the total head of the incoming gas decreases as the inlet flow velocity increases, $\partial p_{0t}/\partial M < 0$, and if here $\gamma > 1$ and $M < 1$, then conditions (3) are not met and oscillations are impossible. When the total head increases with the incoming velocity, $\partial p_{0t}/M > 0$, and for $\gamma > 1$ and $M < 1$, one of the pair of conditions (3) is met if

$$\frac{1}{\gamma p^*}\frac{\partial p_{0t}}{\partial M} > M\left(1 + \frac{\gamma - 1}{2}M^2\right)^{1/(\gamma - 1)}. \tag{9}$$

We see from (9) that there is a threshold value of the positive quantity $\partial p_{0t}/\partial M$, above which oscillations arise. The higher M in the tube, the larger $\partial p_{0t}/\partial M$ should be for oscillations to arise.

It is well known that oscillations (pumping in the air inlets of aviation engines) occur in the zone where the total head increases in the flow characteristic of the air intake ($\partial p_{0t}/\partial Q_t > 0$) [4].

If the rear end of the tube is sealed ($M = 0$, $C = \infty$), the conditions (3) become $BC > 1$, $B < \infty$, i.e., $B > 0$. We use (8) to obtain the excitation condition for such a semi-closed tube:

$$\frac{\partial p_{0t}}{\partial M} + \frac{\partial p^*}{\partial M} > 0. \tag{10}$$

Then (10) implies that if oscillations are to arise here it is necessary for the total head averaged over the inlet section to increase with the inlet velocity. And when there is gas outflow, the static pressure in the inlet section should decrease as the outlet flow velocity increases for this purpose (the Mach number of the outflow is negative). We see from (10) that if the signs of the derivatives differ, oscillations arise when the absolute value of the positive derivative is larger.

We use (10) for simple cases to estimate without calculation the effects on the flow stability in the tube from the incident flow velocity profile. Here significance attaches to the velocity distribution in the inlet section of distances from the center of that section of the order of and less than the internal radius of the tube r_t. The velocity profile may be produced by

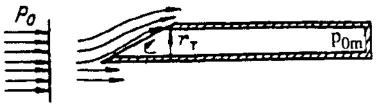

Fig. 4

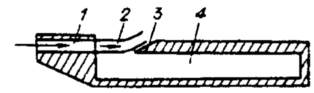

Fig. 5

devices close to the inlet section. The wall construction at the tube inlet affects the flow conditions and thus the static pressure at the tube end.

Consider a long tube with closed end having a thin wall and straight end section, on which is incident a subsonic flow having axisymmetric velocity distribution near the inlet section (Fig. 1). The total head in the tube p_{0m} (pressure in the bottom part) according to our experiments is close to the total head on the current line that has the maximum total head in the area are the end of the tube. This occurs because the flow line with the maximum total head fills the volume of the tube, so a flow line with less head cannot enter the tube. Instead, such flow lines are sent back by the reverse flow from the tube. The three-dimensional flow within the tube at the inlet can be neglected if the tube is long. The intake phase is taken as occurring at moments when the flow of incoming gas in the inlet section exceeds the flow of outgoing gas. This difference is the flow rate for the incoming gas and determines the Mach number within the tube.

Physical considerations imply that the sign of $\partial p_{0t}/\partial M$ coincides with that of $[p_0(r_t) - p_{0m}]$, where $p_0(r_t)$ is the total head of the current line incident on the thin wall of the tube when there are no pulsations in the tube. In fact, if the gas begins to flow into the tube, i.e., the inflow velocity increases from zero, then the peripheral current line with coordinate r_t is displaced towards the tube axis and enters the tube. Here if $p_0(r_t) > p_{0m}$, p_{0t} is increased ($\partial p_{0t}/\partial M > 0$), while if ($p_0(r_t) < p_{0m}$, p_{ot} is reduced, i.e., $\partial p_{0t}/\partial M < 0$.

We thus have a peripheral-maximum condition for the axisymmetric case: oscillations arise in this tube if the velocity of the incident flow near the inner wall of the tube is higher than in the inlet section and increases in the radial direction.

Oscillations do not arise for the velocity shown in Fig. 1 because $\partial p_{0t}/\partial M < 0$ in (8) in accordance with the peripheral-maximum condition. Also, $\partial p^*/\partial M < 0$, the latter following from the fact that the static pressure at the tube inlet is equal to the total head $p_0(r_t)$, i.e., the stagnation pressure at the end of the tube wall. When outflow starts, the current line for the incident jet is displaced radially, and higher-pressure stream lines begin to be retarded at the end, which lie closer to the tube axis. Then as the outflow velocity increases, the static pressure at the inlet begins to rise ($\delta p^* > 0$), and $\delta M < 0$, since the outflow velocity is negative.

Such arguments suggest that oscillations occur when a flow is incident on the tube with the velocity profile shown in Fig. 2. The peripheral-maximum condition here gives $\partial p_{0t}/\partial M > 0$, $\partial p^*/\partial M > 0$. so (10) is met. Such oscillations have been demonstrated by numerical calculations [1] and by experiment [5, 6].

Oscillations arise in the case shown in Fig. 3a because the velocity distribution in the inlet section does not differ from that in Fig. 2. Here the peripheral-maximum condition is met. The velocity profile is the same in Fig. 3b, but the tube diameter is larger than in Fig. 3a, and oscillations do not occur, since the peripheral maximum conditions is not met.

That condition is applicable to a tube without through flow ($M = 0$), e.g., in the situation shown in Fig. 3b, one may make a hole in the bottom part of the tube, in which case a through flow is formed ($M > 0$). Then the averaged total head in the tube p_{0t}' will not always be equal to the maximum on the velocity profile p_{0m}. If the constant gas flow rate through the tube exceeds the total flow rate for the streamers having total head p_{0m}, then lower-pressure streamlines enter the tube. Therefore, we have $p_{0t}' < p_{0m}$. When the velocity pulsations cause the inflow velocity to exceed the constant value in the tube, one gets peripheral streamlines having total head $p_0(r_t) < p_{0m}$, but they may have a total head higher than p_{0t}'. Then $[p_0(r_t) - p_{0t}'] > 0$, and therefore $\partial p_{0t}/\partial M > 0$. According to (9), oscillations become possible for a certain value $\partial p_{0t}/\partial M > 0$. Then if the velocity profile has the form shown in Fig. 3b, oscillations in principle can arise if there is through flow in the tube.

With an arbitrary inlet of velocity profile for a tube without through flow, the sign of $\partial p_{0t}/\partial M$ is determined by that of $[\bar{p}_0(r_t) - p_{0m}]$ ($\bar{p}_0(r_t)$ is the total head averaged over the length of the generator for the internal tube wall). When there is flow into the tube, streamlines with coordinate r_t arise, which in general have differing total heads. Then the averaged quantity $\bar{p}_0(r_t)$ determines the sign of $\partial p_{0t}/\partial M$ and oscillations are possible.

The examples given below show that positive $\partial p_{0t}/\partial M$ at the inlet (and thus oscillations) can be obtained with special constructions at the inlet. Figure 4 shows a tube whose end is cut obliquely, and on which there is incident homogeneous flow. This can also be a tube cut straight across but set at an angle to the incident flow. We know [7] that oscillations arise in a tube for a certain range of angles. We can show that here the condition $\frac{\partial p_{0\tau}}{\partial M} = \frac{\bar{p}_{0\tau} - p_{0\tau}^*}{\Delta M} > 0$ may be obeyed, where p_{0t}^* is the total head in the tube in the absence of oscillations, with $\bar{p}_{0t}$ the averaged total head of the gas at the inlet in inflow phase at the start of oscillation, while ΔM is the increment in the Mach number.

In fact, the pressure p_{0t}^* in a half-closed tube with oblique end is dependent on the inclination angle and is lower than the total head p_0 in the incident flow. This dependence is usually employed in measurements to determine the flow direction [8]. Figure 4 shows that there is a detached flow at the inlet of the tube. The current lines in the incident flow envelop the tube and may be retarded at the end of the wall. At the start of the inlet phase, the retarded current lines with coordinate r_t enter the tube. These lines have a total head $p_0 > p_{0t}^*$, so the averaged total head for the incoming gas $\bar{p}_{0t}$ will be greater than p_{0t}^*, and hence $\partial p_{0t}/\partial M > 0$. When the tube is cut almost straight across, p_{0t}^* is close to p_0 and $\bar{p}_{0t} \approx p_0$. Then as $\frac{\partial p_{0\tau}}{\partial M} = \frac{\bar{p}_{0\tau} - p_{0\tau}^*}{\Delta M} \approx 0$, oscillations are absent. If the cutting angle for the tube is too small, the current lines remotely envelop the detachment region and do not fall on the end of the tube wall. Therefore, for a small inflow velocity they do not enter the tube. Consequently, the total head on inlet varies only slightly ($\bar{p}_{0t} = p_{0t}^* \approx$ const, $\partial p_{0t}/\partial M \approx 0$), and there are no oscillations.

Figure 5 shown a scheme for a whistle. A gas jet 2 enters through the slot 1, and falls on the wedge 3. If the distance between the edge of the slot and the sharp edge of the wedge is comparable with the length of the tube 4, then wave (bending) processes in the jet are important in the oscillations.

The mechanism has been described in [9]. If the length of the resonant tube is greater than its height and the distance between the edge of the slot and the sharp edge of the wedge is much less than the length of the tube, the flow oscillates as a pendulum (with a single phase), and then the above method is permissible for evaluating the excitation conditions. For example, if the sharp edge is in the middle of the jet, the total pressure in the tube will be equal to that in the jet, i.e., $p_{0t}^* = p_0$, so if there is additional flow inward due to the pulsations, additional flow lines enter with the same total head, and $\delta p_{0t}/\delta M = 0$, and so oscillations are impossible with that position for the wedge.

If the sharp edge lies somewhat lower than the boundary of the jet, so that the jet with total head p_0 does not enter the tube, the pressure in the tube will be equal to that near the sharp edge of the wedge $p_{0t}^* = \lambda p_0$, where $\lambda < 1$ is the recovery coefficient of the total head for the jet at the wedge.

If the extreme streamlines in the jet are near the sharp edge, they are deflected downwards for small pulsations in the inflow phase and enter the tube. Then the total head for the inflowing gas $\bar{p}_{0t}$ is p_0, so $\frac{\partial p_{0\tau}}{\partial M} = \frac{\bar{p}_{0\tau} - p_{0\tau}^*}{\Delta M} = \frac{p_0(1 - \lambda)}{\Delta M} > 0$, and oscillations occur. If the sharp edge is below the jet and far from its edge, the jet does not enter the tube for small oscillations, and the pressure in the tube does not alter ($\partial p_{0t}/\partial M = 0$), and no oscillations occur.

This shows that researching a physical model for oscillations in a long tube when a flow strikes the inlet amounts to studying the features of the stationary flow at the inlet, which increases the total head in the tube as the inflow rate increases. For a tube without through flow or with reverse flow, the research amounts to examining the reasons for the fall in static pressure at the end of the tube when the outflow speed from the tube in opposition to the inflow increases. The processes responsible for the increase in oscillation amplitude within a long tube are physically of the same type, and a description of them can be found in [2, 3, 5].

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