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EXCITATION OF NARROW-BAND PULSATIONS IN A SHORT PORTION OF TRANSITION FROM THE SMALLER DIAMETER OF A PIPE TO A LARGER DIAMETER AND POSSIBILITIES OF PREVENTING THEM

V. G. Zasetskii, R. K. Karavosov, A. G. Prozorov, and L. I. Sokolinskii

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By using models of the portions of the circuit of main gas-compressor stations, data on the frequencies of narrow-band pressure pulsations have been obtained; these data demonstrate the jet character of flow in divergent channels with angles of opening on one side of $12^{o}47'$ *and* $23^{o}50'$*. It has been shown that narrow-band acoustic disturbances are generated in the internal flow with large-scale hydrodynamic structures. Intense narrow-band pulsations are prevented by a grid of internal divergent channels in the transition portion with small angles of opening in canals and in excitation of certain disturbances upstream of a short divergent channel.*

Until recently, numerous investigations of short divergent channels with large angles of opening $\alpha > 5^{o}$ have essentially sought only to decrease the total-pressure loss caused by the separation of flow occurring in them and by the formation of vortex structures in the flow. The idea of the character of flow in these divergent channels was created based on visual observations of its laboratory analogs for small Reynolds numbers, which, apparently, were not always adequate to nature.

As full-scale investigations on the main gas-compressor stations and on models of pipelines with short divergent channels have shown, the structures mentioned initiate narrow-band pulsations of pressure and vibrations of constructions which are a certain hazard to the latter. Therefore, a more detailed evaluation than before of the structure of flow in short separating divergent channels and the efficiency of the methods of correction of the flow in them was required. Consideration was given to different variants of correction which were aimed at obtaining a nearly continuous spectrum of pressure pulsations in the range of frequencies f = 20–20,000 Hz in the flow without narrow-band components. The results of separation of the flow in a short transition portion by a grid of internal divergent channels turned out to be the most encouraging.

The angles of opening on one side calculated from the hydraulic radii of divergent annular channels were $4^{o} < \alpha < 5^{o}$ according to the recommendations of [1]. However the effect produced in this case was lower than the expected one.

Taking into account the foregoing, in the present investigation we posed the problem of gaining a more authentic fundamental idea of flow in a separating divergent channel and the disturbances inherent in it and of the possibility for these disturbances to interact with other disturbances in the flow. The work also sought to determine the optimum angles of opening in the channels of the grid of internal divergent channels which make it possible to get rid of the narrow-band components of the spectra of pressure pulsations.

Investigation Procedure. The experiments were conducted on a portion of a pipeline (Fig. 1) with collector 1 installed at its inlet; the portion was located inside the plenum chamber 2 of a special test stand

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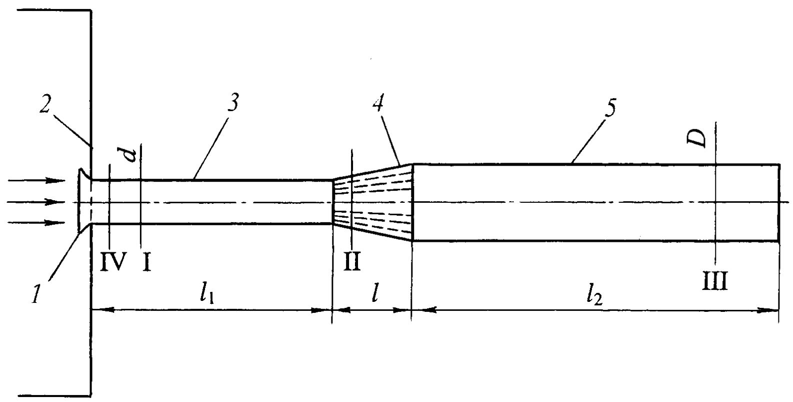

Fig. 1. Scheme of the experimental setup.

with a blower. The air from the chamber successively arrived first at pipeline 3 of diameter d = 156 mm and length l_1 = 1000 m, then reached the short divergent channel 4, and from it pipeline 5 of diameter D = 300 mm and length l_2 = 1500 mm.

The mean-flow-rate velocity of the flow V at the inlet to the divergent channel was 35.5–81 m/sec in the tests; the Reynolds numbers $\mathrm{Re} = Vd/\nu$ varied within $(3.7–8.6)\cdot 10^5$.

Two models of short divergent channels (one of length l = 318 mm with the angle of opening $\alpha = 12^o 47'$ and the other of length 163 mm with the angle of opening $\alpha = 23^o 50'$) were the initial ones in the investigations. In both cases, the degree of divergence n equal to the ratio of the outlet and inlet areas was equal to 3.7. In two models alternative to the indicated ones, we installed 3 and 7 internal divergent channels, respectively, which formed a grid of coaxial conic surfaces with truncated vertices. In the scheme (see Fig. 1) where $\alpha = 12^o 47'$, the internal divergent channels are shown dashed.

The air flow rate was determined from the results of pneumometric measurements (with a Pitot tube and a micromanometer) of the velocity profiles at the outlet from the pipe 300 mm in diameter.

To measure the pressure pulsations p and their frequency spectra $L(f)$ we used a 00026 precision noise meter, MK102/MV102 capacitor microphones, a 02013 RFT self-recorder, a Robotron 01025 narrow-band analyzer, and an S1-107 oscilloscope multimeter. The pressure pulsations were analyzed in the range of frequencies f = 2–2000 Hz and 20–20,000 Hz, which could account for a significant part of the pulsation processes.

We measured the pressure pulsations with the microphones on the interior surface of the pipe 800 mm upstream of the inlet to the divergent channel (cross section I in Fig. 1), beyond the flow at a distance of 3 mm from the divergent-channel wall and 75 mm downstream of the inlet to it (cross section II), and at a distance of 9 mm from the divergent-channel wall and 1250 mm downstream of the outlet from the divergent channel (cross section III).

The measurement results made it possible to determine the frequencies f_d of the narrow-band components of the spectra of pressure pulsations $L(f)$, their standard level $\sqrt{\langle p^2 \rangle}$, the intensity $\varepsilon_p = \sqrt{\langle p^2 \rangle}/q$, the dynamic pressure $q = \rho V^2/2$, the Strouhal number $\mathrm{Sh} = f_\mathrm{d} d/V$, and the dimensionless frequency $\overline{f}_\mathrm{d} = f_\mathrm{d} \nu / V^2$ of intense disturbances.

As the generator of coupled hydrodynamic and acoustic vibrations which simulate natural disturbances in the framework of the compressor station and act on the flow in the divergent channel, we used a blind branch piece. Manufactured from a pipe with inside diameter d_bl = 73 mm, it was installed at a right angle to the pipe of diameter d = 156 mm 927 mm upstream of the inlet to the transition portion (cross section IV in Fig. 1). In the experiments, the depth of the blind branch piece and accordingly the frequency of the disturbances were varied by displacement of a special insert in it.

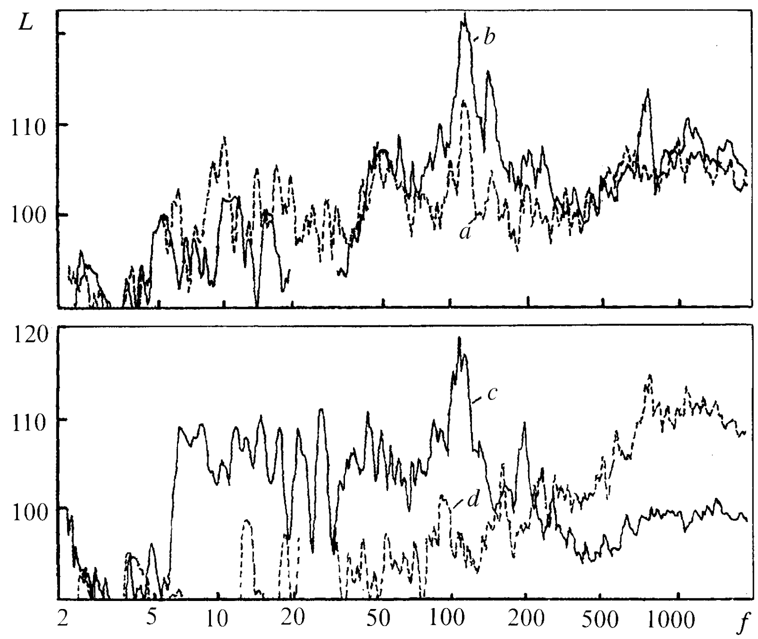

Fig. 2. Spectra of pressure pulsations (Re = (6.6–6.8)$\cdot 10^5$): a) $\alpha = 12^{o}47'$, Sh = 0.28, $\bar{f}_{\rm d} = 0.41\cdot 10^{-6}$, and ε_p = 0.35%; b) $\alpha = 23^{o}50'$, Sh = 0.28, $\bar{f}_{\rm d} = 0.42\cdot 10^{-6}$, and ε_p = 1.05%; c) without a pipe of D = 300 mm behind the divergent channel, $\alpha = 12^{o}47'$, Sh = 0.26, $\bar{f}_{\rm d} = 0.39\cdot 10^{-6}$, and ε_p = 0.71%; d) without a divergent channel and a pipe of D = 300 mm behind it.

In conducting the investigation, we did not bear in mind accurate reproduction of dimensionless parameters in the experiments, for example, of a Reynolds number characteristic of communications. It was clear beforehand that the manifestations of the separating flow in a short divergent channel are basically of the same type in a wide range of Reynolds numbers, and it is precisely to it that the methods of fighting separation must be oriented.

Results of the Experiments. The spectra of pressure pulsations obtained in different cross sections demonstrate that for both angles of opening in the range of Reynolds numbers investigated narrow-band pressure pulsations are excited in the same region of frequencies f = 114–129 Hz (Fig. 2a and b for cross section I). The corresponding Strouhal numbers and dimensionless frequencies are Sh = 0.22–0.57 and $\bar{f}_{\rm d}\cdot 10^6$ = 0.27–1.57.

The narrow-band components in the indicated spectrum region were also observed in the experiments in the case where the pipe of diameter 300 mm was absent behind the divergent channel (Fig. 2c). At the same time, the narrow-band pressure pulsations did not occur (Fig. 2d) if one pipe of diameter 156 mm was left on the working portion while the divergent channel and the pipe of diameter 300 mm which followed it were removed from the test stand.

Comparison of the above results to the data of investigations of self-oscillations in a wind tunnel with an open working portion and an outlet diameter of the nozzle of 150 mm [2] revealed the proximity of the Strouhal numbers and the dimensionless disturbance frequencies characterizing the narrow-band pulsations in the cases compared. Also noteworthy was the fact that in both cases the dimensional frequency of the narrow-band pressure pulsations does not substantially vary in certain intervals of change of the flow velocity.

In connection with the above-noted, we conducted the experiments in which: (1) a 334-mm-wide gap was left between the pipe of diameter 156 mm and the divergent channel with an angle of opening of $12^{o}47'$ adjacent to the pipe; (2) the gap between the pipes of diameter 156 and 300 mm was 320 mm and the divergent channel was absent. In both cases we observed virtually the same low-frequency narrow-band noise as on the initial working portion made of pipes of the indicated diameter which were adjacent to the divergent channel.

All the presented experimental data make it possible to assume that, first, a jet or nearly jet flow with large-scale coherent structures of the type of annular vortices at the periphery is formed in the short conic divergent channel with a large angle of opening. Second, it is precisely the internal flow with coherent structures in it that generates the narrow-band pressure pulsations whose acoustic mode propagates upstream and downstream and beyond the flow in the room where the model of the portion of the circuit is located.

It must, however, be borne in mind that the pulsation processes in question in the divergent channel are not self-oscillating. This is demonstrated, in particular, by the character of the spectra which differ from those obtained in the case of self-oscillations in wind tunnels [3].

It should be noted that with all the distinctions between the spectra of pressure pulsations in the three measurement cross sections, all demonstrated the generation of the above narrow-band disturbances by the flow.

Thus, in this part of the present work, we have essentially answered the question (posed by the investigation [4]) of localization of the source of narrow-band noise in excitation of self-oscillations in closed wind tunnels with an open working portion.

At the same time, the conclusions of the theoretical investigation [5] on generation of narrow-band noise by a hypothetic flow with large-scale coherent structures in a channel of constant cross section have been confirmed.

Finally, the minimum values of $\overline{f}_{\mathrm{d.mod}}$ obtained in the experiments make it possible to calculate the natural frequencies of the narrow-band component which is caused by the structure of the flow in a short divergent channel with a large angle of opening.

In evaluations of such kind, use is usually made of the Strouhal number $\mathrm{Sh} = f_{\mathrm{d}}d/V$. This is far from being always correct since even when the boundaries confining the flow in the cases compared are geometrically similar the pulsation processes in them can be determined, for example, not by the pipe diameter but by other linear quantities. At the same time, it is clear that the topology and evolution of the large-scale structures and the stability of vibrations caused by them in the flow depend on the viscosity of the medium. Therefore, in the present work, just as in [6], the dimensionless frequency $\overline{f} = f\nu/V^2$ is preferred in characterizing narrow-band pulsations and in recalculating.

When the Reynolds numbers of the natural and model flows differ by two orders of magnitude, judging from the data of [6], the dimensionless frequencies of the disturbances differ by a factor of 1.5, i.e., $\overline{f}_{\mathrm{d.nat}} \approx \overline{f}_{\mathrm{d.mod}}/1.5$. Taking into account that the kinematic coefficient of viscosity of the natural medium is $\nu_{\mathrm{nat}} \approx 0.3 \cdot 10^{-6}$, we can calculate the order of magnitude of the natural values of the dimensional frequency of the narrow-band pulsations, i.e., $f_{\mathrm{d.nat}} \approx 730$ Hz.

This suggests that the very intense narrow-band pulsations at frequencies of the order of 700 and 1400 Hz and multiples of them which have been observed in the investigations on the main gas-compressor stations are caused first of all by the large-scale coherent structures in the flow inside the short divergent channels. In the case where the vane frequency of the disturbances from the blower of the main gas-compressor station turns out to be equal to or a multiple of the frequency of the considered narrow-band pulsations in the divergent channel, the latter, judging, for example, from the results of [7], turns out to be an unusual kind of hydrodynamic amplifier of vibrations.

In the present work, we have considered the possibility of radically altering the character of flow in a short transition portion from the smaller diameter of the pipeline to a larger one by subdividing the initial channel into canals with small hydraulic angles of opening $\alpha \le 3^{\circ}20'$. We installed grids consisting of three and seven internal divergent channels into the initial divergent channels with angles of opening of $12^{\circ}47'$ and $23^{\circ}50'$ respectively.

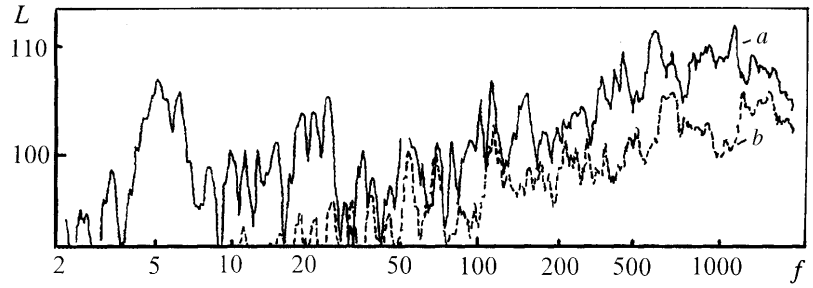

Fig. 3. Spectra of pressure pulsations (a grid of internal divergent channels is installed in the transition portion with an initial angle of opening α_{in}): a) $\alpha_{in} = 12^o47'$ and Re = $6.90 \cdot 10^5$; b) $\alpha_{in} = 23^o50'$ and Re = $6.62 \cdot 10^5$.

The results of determination of the spectra of pressure pulsations in the investigated range of Reynolds numbers presented in Fig. 3 for cross section I demonstrate that the two-frequency oscillations in the region 100–130 Hz virtually are prevented by such an alteration of the flow structure. Quite apparently, this is caused by the fact that the separating flow is not realized in the initial divergent channel subdivided into the canals.

Since the flow in the framework of the compressor station is subjected to hydrodynamic and acoustic disturbances, for example, from the blower, this problem has also been considered in the experiments.

As has already been noted, in a number of investigations [8] it has been established that when the frequency of the disturbing actions and the frequency of the large-scale vibrations which are caused by the initial structure of the flow coincide the intensity of these vibrations increases. It has also been shown that the amplification of the initial pressure pulsations can also be observed in the case of the multiplicity of the frequencies forcing large-scale pulsations and of the large-scale pulsations inherent in the flow. Therefore, in the present work, we have investigated the manner in which the hydrodynamic and acoustic disturbances with a frequency differing from that observed in the flow influence the vibrations existing in it.

The generator of hydrodynamic and acoustic vibrations that disturb the flow made it possible to change their frequency in the experiments in rather wide limits — from 200 to 1000 Hz or more.

Certain regularities of pulsation processes are noteworthy in comparing and analyzing results of numerous measurements of the spectra of pressure pulsations. Thus, in a number of cases the frequency and level of narrow-band disturbances initiated by the hydrodynamic generator in the measurement cross section are the same, in practice, on installation of both the initial divergent channel and the divergent channel with a grid.

In other cases, the narrow-band pressure pulsations differ significantly in frequency and level. As the narrow-band component caused by the structure of the flow in the initial divergent channel becomes attenuated or totally disappears, the level of the narrow-band component initiated by the generator, i.e., the blind branch piece, increases.

Quite unique results are given in Fig. 4a and b ($\alpha = 12^o47'$) and Fig. 4c and d ($\alpha = 23^o50'$). All four spectra are obtained in cross section I for the same depth of the generator, i.e., the blind branch piece. As is seen, in the initial flow where there are no grids in the divergent channels with the angles of opening in question, no narrow-band components (either the components caused by the structure of the flow in the divergent channel or those initiated by the generator) stand out against the general background of the spectrum (Fig. 4a and c). When the nonseparating flow is realized in the divergent channel with a grid the narrow-band pulsations, conversely, substantially exceed the pulsations of the wide-band spectrum.

Such a pronounced phenomenon is, apparently, caused by the occurrence of a common acoustic field of a combination of two hydrodynamic disturbance sources which is not a result of the simple interaction of the acoustic fields of each source. Similar phenomena, but not so pronounced, have been observed on natural

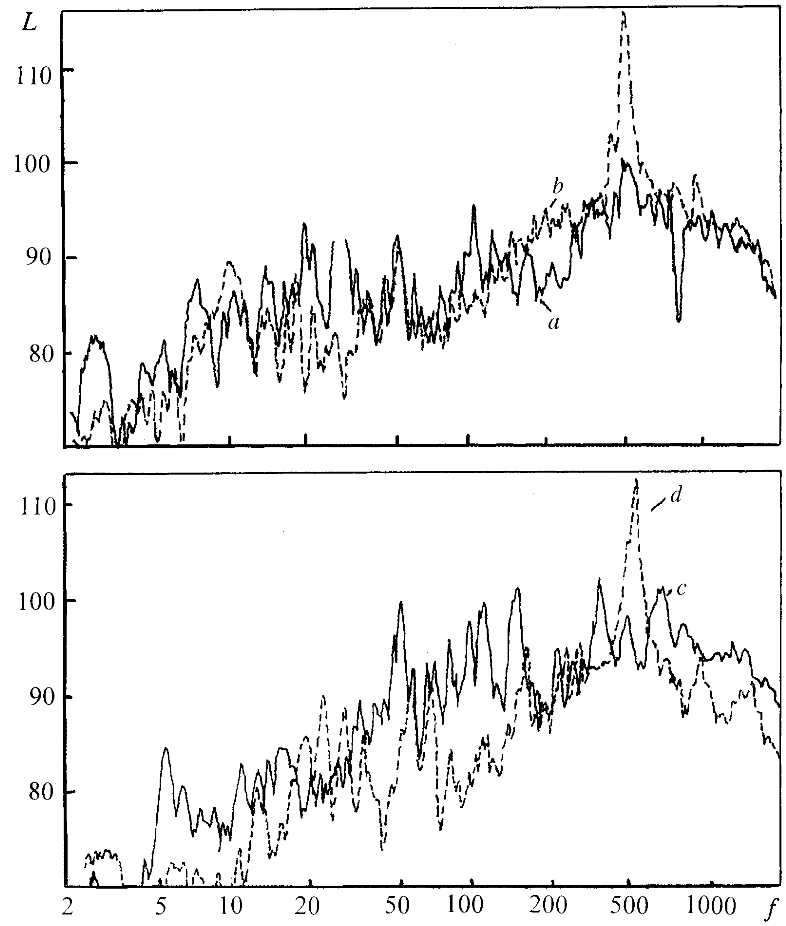

Fig. 4. Spectra of pressure pulsations (a generator of disturbances is installed on the working portion), Re = (3.6–3.8)·10^5: a) initial divergent channel, α = $12^o47'$; b) transition portion with a grid of internal divergent channels, α_{in} = $12^o47'$; c) initial divergent channel, α = $23^o50'$; d) transition portion with a grid of internal divergent channels, α_{in} = $23^o50'$.

main gas-compressor stations and in model investigations in the case of flow in a collector with two blind branch pieces.

In the remaining cases, the interaction of the vibrations induced by the generator with the initial narrow-band spectral component in the zone of frequencies of 115–130 Hz was not so fundamental.

The investigations on the model of a portion of a pipeline with short divergent channels enable us to draw the following conclusions. In short divergent channels with large angles of opening (of the order of 13 and 24^o), a jet flow with annular hydrodynamic structures is formed. Narrow-band pressure pulsations whose acoustic mode propagates upstream and downstream over a significant distance are generated in the internal flow with large-scale coherent structures. Apparently, the frequency of the narrow-band pressure pulsations which are excited inside the short divergent channel on natural gas-compressor stations is close to the vane frequency of the blower or is a multiple of it. In such a situation, the flow in the divergent channel is the amplifier of disturbances coming from the compressor.

The pressure-pulsation field caused by the flow in a divergent channel with a large angle of opening can interact with the fields of pulsations of the disturbance sources in a variety of manners. The fundamental possibility exists of preventing the narrow-band acoustic radiation from a hydrodynamic source of disturbances by formation of a combination which incorporates another source of hydrodynamic disturbances differing from the first source in structure. The narrow-band pressure pulsations generated inside a short transition portion can be prevented by a grid of internal divergent channels with hydraulic angles of opening close to 3^o, and the divergent channel will not be the amplifier of disturbances with a vane frequency from the blower.

NOTATION

f, frequency of pressure pulsations; *d* and *D*, diameters of the pipeline; *V*, mean-flow-rate velocity at the inlet to the divergent channel; ρ, density of the gas; ν, kinematic coefficient of viscosity of the gas; Re, Reynolds number; α, angle of opening of the divergent channel on one side; *p*, pulsation component of the instantaneous value of the pressure; *L*, level of pressure pulsations; ε, intensity of pulsations; *q*, dynamic pressure; Sh, Strouhal number; $\bar{f}$, dimensionless frequency. Subscripts: d, disturbance; *p*, pressure; nat, nature; mod, model; in, initial; bl, "blind" branch piece.

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