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HYDROGASDYNAMICS IN TECHNOLOGICAL PROCESSES

STUDY OF INTERACTION OF DISTURBANCES IN AN INTERNAL FLOW

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Data on narrow-band acoustic disturbances that arise in manifold pipes with one or two blind branches and in wind tunnels with an open working section are analyzed. The ranges of acoustic instability that correspond to excitation of self-oscillations in a flow in the cases mentioned are determined. The dependence of the intensity of acoustic radiation in two blind branches and in the manifold between them on the multiplicity of the length of the resonance section to the length of halfwaves of resonance frequency is considered. The possibility of attenuation of self-oscillations by organizing hydrodynamic structures that interact with formations generating acoustic oscillations is determined.

Excitation of intense narrow-band oscillations of pressure in pipelines with heterogeneities of main gas-compressor stations was widely studied on full-scale and model setups [1–4]. The main sources of these oscillations are large-scale hydrodynamic structures that originate due to shear flow instability in the zones of junction between manifold pipes and blind branches in short divergent segments of the framework with large angles of opening where a close-to-jet flow is realized.

In the first of the cases mentioned, the acoustic mode of oscillations, which is generated by coherent structures, is amplified by a resonator — a blind cavity — and realizes feedback in the forming self-oscillating system, thus increasing the amplitude of hydrodynamic disturbances upstream from the junction and on its leading edge. Correspondingly, oscillations of the same frequency that propagate from a coherent hydrodynamic structure in the pipeline heterogeneity increase.

In the second case, in the flow with large-scale structures inside the divergent channel narrow-band noise is generated, which can amplify greatly under the effect of acoustic radiation, e.g., from a supercharger or a blind branch, and also in the presence of a resonator in the pipeline.

Thus, the studies are aimed at determination of effective and technological means of prevention and attenuation of self-oscillations that are capable of causing fatigue breakdown of structures. It appeared possible to obtain actually realizable solutions of the posed problem on the basis of the above-formulated general notions on generation of narrow-band oscillations in pipes. Namely, in some cases, the topology of flow and scales of the structures in pipeline heterogeneities [1, 3, 4] and in other cases, resonance characteristics of mains [5] were changed purposefully.

The experimental data were used to determine the characteristics of hydrodynamic instability that causes excitation of self-oscillations in manifold pipes with blind branches. Acoustic instability of the observed oscillating processes was not analyzed, and one of the problems of the present paper was to fill this gap.

As has already been mentioned, excitation of self-oscillations in a single inhomogeneity of the pipeline can be prevented in principle. However, in the operating main gas-compressor stations the sources of disturbances in the pipeline are not of an individual nature; the problem of their interaction arises and the necessity of determining which of them is primary and which becomes a generator — amplifier of oscillations. It was observed on one of the real pipe-

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lines that intense narrow-band noise appeared in the blind branch of the manifold pipe only in the case where noise appeared in another blind branch substantially downstream. At the same time, interaction of heterogeneous sources of disturbances is possible [3]. Therefore, it is necessary to elucidate how interactions between disturbances become possible on the internal flow.

1. Experimental studies [1, 3, 4] serve as data sources for analysis of these problems. These studies were conducted both on full-scale gas-compressor stations and in three wind tunnels and on special model benches of TsAGI. It should be noted that in all experiments we considered the case where the manifold and branch pipes were joined at a right angle. In the models, the junction edge was rounded.

The mean rates of flow in the full-scale manifold pipe were $V \approx 8$–19 m/sec with Reynolds numbers $\mathrm{Re} = Vd_{\mathrm{mf}}/\nu = (2.7–6.6)\cdot 10^7$ corresponding to them. In similar processes in wind tunnels the flow velocity reached 52 m/sec and the Reynolds number was 10^7. On the model bench, the maximum values of the mean flow rate of the flow in the pipe and the Reynolds number were 81 m/sec and $8.6\cdot 10^5$, respectively.

We should note that in studies [1, 3, 4] the problem of reproducing natural Reynolds numbers on the models was not posed, since it was clear *a priori* that the principal mechanism of the considered processes is mainly the same for a wide range of Re numbers.

To measure pressure oscillations on full-scale gas-compression stations in blind branches and near short divergent sections of the pipeline framework we used sensors of pressure oscillations of a 101A06 type (RSV, USA). In the blind branches, the sensors were mounted at the closed end. In each experiment, measurements were made in a simultaneous multichannel mode of signal recording at all points using a measuring SONY PC216 tape-recorder. A multichannel analyzing system 3550 (Bruel & Kjaer, Danemark) and a CMVA-30 collector-analyzer (SKF, Sweden) with the PRISM2 data base were used in laboratory analysis of the recorded signals.

In the wind tunnels and on special model benches of TsAGI, microphones and a precision noise-meter with a spectrum analyzer, self-recorder, and oscillograph were used for similar measurements on the inner wall of the manifold model pipes. A more thorough description of the experiments is given in [1, 3, 4]. In the studies on the models of the manifold with one and two blind branches, the microphone was installed outside the flow at the outlet from the pipe.

Measurement results allowed determination of frequencies f_{d} in the narrow-band components of spectra of pressure oscillations $L(f)$, their root-mean-square quantity $\sqrt{\langle p^2 \rangle}$, intensity $\varepsilon_p = \sqrt{\langle p^2 \rangle}/q$, dynamic pressure $q = \rho V^2/2$, and the Strouhal number $\mathrm{Sh} = f_{\mathrm{d}} d_{\mathrm{b}}/V$.

2. As has been mentioned above, in the earlier-conducted studies of self-oscillations in pipes with blind branches only one aspect (hydrodynamic) of the problem was analyzed. Experimental results were systematized in the plane of the parameters Sh–Re or Sh–$\bar{\tau}$, where $\bar{\tau} = 2\tau/\rho V_{\mathrm{m}}^2$. It is along this pathway that the idea of the regions of hydrodynamic instability, which is the origin of excitation of self-oscillations, was gained.

In the present paper, we consider another aspect of the problem — acoustic — and the results of the tests are systematized in the plane of the parameters Sh–$\bar{t}$. Here $\bar{t} = tf_{\mathrm{d}}/a$, t is the distance between the hydrodynamic source of disturbances and the blind-branch bottom or the manifold wall or the distance between these two reflecting surfaces. In this case, in particular, it is assumed that the equality of the Strouhal numbers to the parameter $\bar{t}$ of self-oscillations in geometrically similar structures means the identity of the fields of narrow-band components of hydrodynamic and acoustic oscillations in them.

The main results of the experimental studies of self-oscillations in pipes with a blind branch at different ratios of their diameters and variations within wide ranges of the Reynolds number are given in Fig. 1. It should be mentioned that, due to the high density, it was impossible to plot all experimental points in the figure, e.g., those related to the tests [4] of full-scale dimensions of the manhole on the wall of wind tunnels. It is vividly seen that two regions of realization of acoustic instability exist in the plane of the parameters Sh–$\bar{t}$. As is shown in [1], to each region there corresponds its own character of variation of, for example, dependences Sh (t/d_{b}), which virtually undergo discontinuity at t/d_{b} values of an order of 2.6.

It should be noted that this potential instability is not obligatory and can be realized in different ways. The development of the process depends on a number of factors just as in the case with transition from laminar to turbulent mode of liquid flow [6]. Among these factors are, in particular, outer acoustic disturbances. In the above-mentioned case, when in the blind branch on the real manifold of the compressor station acoustic disturbances were

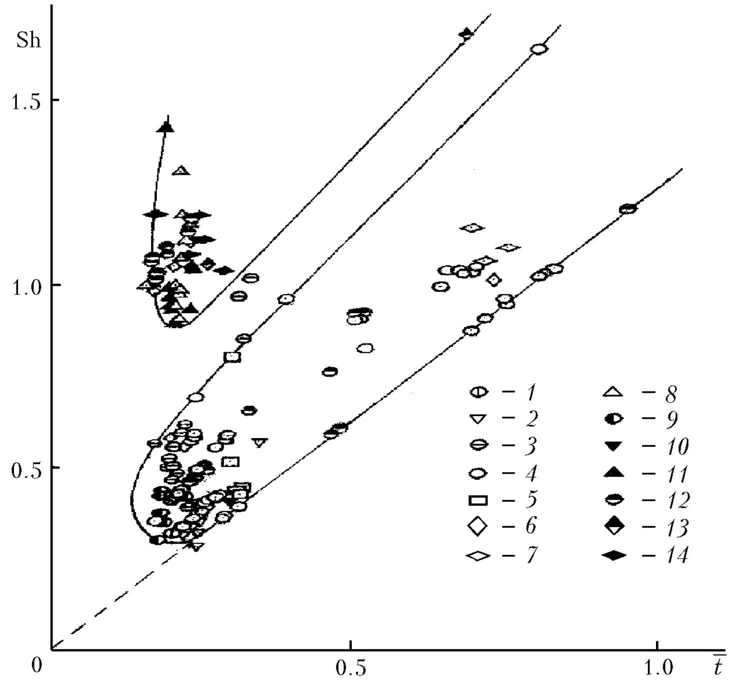

Fig. 1. Dependence of the Strouhal number Sh of self-oscillations in pipes with one blind branch on the relative length of the resonance section $\bar{t}$: $\mathrm{Re}\cdot 10^5 \geq 1.5$, $t/d_b \geq 2.6$ [1) d_b/d_{mf} = 0.179; 2) 0.276; 3) 0.353; 4) 0.468; 5) 0.7, full-scale; 6) 0.733; 7) 0.853]; $\mathrm{Re}\cdot 10^5 < 1.5$, $t/d_b > 2.6$ [8) d_b/d_{mf} = 0.353]; $\mathrm{Re}\cdot 10^5 > 1.5$, $t/d_b \leq 2.6$ [9) d_b/d_{mf} = 0.179; 10) 0.276; 11) 0.353; 12) 0.468; 13) 0.733; 14) 0.853].

observed only upon their appearance in the other blind branch of the framework, the first branch could become not only a resonator but also a generator of oscillations.

A very important practical conclusion follows from Fig. 1. That is, since Sh = $1.27\bar{t}$ corresponds to the lower boundary of the region of instability realization, self-oscillations in the manifold with a blind branch must probably not originate when $d_b/t < 1.27V/a$.

3. Having obtained such pronounced regions of acoustic instability in the plane of parameters Sh–$\bar{t}$ for pipes with a blind branch, we could not but note the study [7] of self-oscillations in closed-type wind tunnels with an open working section. In these wind tunnels, as is known, the closed section of the pipe with a length t from the inlet to the divergent channel to the outlet from the nozzle is a resonator, and the source of generation of hydrodynamic disturbances is a free jet with its large-scale annular structures on the periphery in the open working section. In [7], an approach to systematization of experimental data similar to that formulated above was designated; however, it has not been realized.

The results of processing the experimental data [7] obtained on six wind tunnels in the form in which they existed in the years of investigation are given in Fig. 2.

We should immediately note that only two pipes — T-20 and T-102 — were geometrically similar. Therefore, if in the plane of parameters Sh–$\bar{t}$ we relate the data of all pipes only to two regions of acoustic instability, the latter appear stretched compared to similar regions shown in Fig. 1. Nevertheless, the similarity of the regions of acoustic instability of the two considered unlike systems does not cast doubt.

It turned out to be possible to estimate the authenticity of the curves in Fig. 2 by using the results [8] of calculation by the model [7] of self-oscillation modes in a small wind tunnel and the data of the experimental studies in it [8, 9]. Of seven modes, in which, according to the calculations [8], self-oscillations would be realized, these were observed in only four cases; in the rest they did not appear, which is in full agreement with the data in Fig. 2.

4. In contrast to the case considered in item 2, more than one blind branch is more often present on real manifolds and it turned out to be necessary to estimate interaction of narrow-band acoustic disturbances initiated by

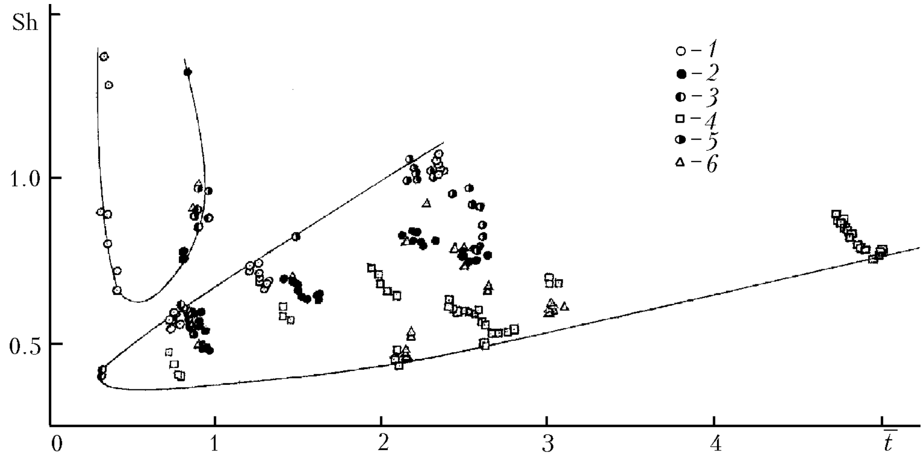

Fig. 2. Dependence of the Strouhal number Sh of self-oscillation in wind tunnels with an open working section on the relative length of their closed section $\bar{t}$: 1) wind tunnel T-4, d_n = 0.6 m, t = 13.6 m; 2) T-5, d_n = 2.25 m, t = 52 m; 3) T-20, d_h = 0.877 m, t = 17.7 m; 4) T-23, d_n = 0.5 m, t = 17.8 m; 5) T-102, d_h = 2.89 m, t = 58.4 m; 6) T-103, d_h = 2.91 m, t = 73.7 m.

TABLE 1. Results of the Full-Scale and Model Studies of Self-Oscillations in the Pipeline

Line No.	t_1:t_2:t_{mf}, m	V_1	V_2	$Re_1 \cdot 10^{-5}$, $Re_2 \cdot 10^{-5}$	f, Hz	Sh_1, Sh_2	$t_i f_d/a$	$d_{mf} f_d/a$	$(\Sigma t) f_d/a$	ε_p, %
		m/sec								
				Full-scale study, d_b/d_{mf} = 0.7, d_{mf} = 1 m						
1	10.89:10.89:36	19.1	10.8	$6.37 \cdot 10^2$, $3.6 \cdot 10^2$	11.8	0.432, 0.765	0.310	—	1.644	274
2	10.89:10.89:36	18.9	10.8	$6.3 \cdot 10^2$, $3.6 \cdot 10^2$	11.6	0.430, 0.752	0.300	—	1.594	231
3	10.89:10.89:36	18.6	10.5	$6.2 \cdot 10^2$, $3.5 \cdot 10^2$	11.6	0.437, 0.773	0.300	—	1.589	515
4	10.89:10.89:36	19.3	11	$6.43 \cdot 10^2$, $3.67 \cdot 10^2$	11.8	0.428, 0.751	0.312	—	1.655	339
5	10.89:10.89:36	18.7	10.6	$6.23 \cdot 10^2$, $3.53 \cdot 10^2$	11.8	0.442, 0.779	0.305	—	1.618	713
6	10.89:10.89:54	19.0	3.3	$6.33 \cdot 10^2$, $1.10 \cdot 10^2$	11.6	0.427, 2.460	0.301	—	2.096	167
				Model study, d_b/d_{mf} = 0.438, d_{mf} = 0.105 m						
7	0.53:0:0	105	105	6.57	1148	0.503	1.721	0.341	—	2.59
8	0.53:0.53:1.062	104.4	104.4	6.53	1140	0.502	1.71	0.339	6.845	1.04
9	0.34:0:0	91.3	—	5.90	767	0.386	0.74	0.229	—	2.82
10	0.34:0.25:1.06	91.4	91.4	5.82	770	0.387	0.744 0.547	0.23	3.61	1.39

Note. $\Sigma t = t_1 + t_2 + t_{mf}$.

the blind branches. These narrow-band acoustic disturbances, as has already been mentioned, are dangerous for the structures.

Vast information on these interactions in the presence of two blind branches on the manifold was obtained in measurements on a real main gas-compressor station. Some experimental results (lines 1–6 of Table 1) indicate that at a length of the resonance section between the closed cocks of the blind branches close to the length of three half-waves of low-frequency oscillations with a frequency of 11.6–11.8 Hz, their amplitudes reach very high values. So, in the mode (line 5 in Table 1) where pressure in the manifold is higher than 50 kg/cm^2, the spread of pressure oscilla-

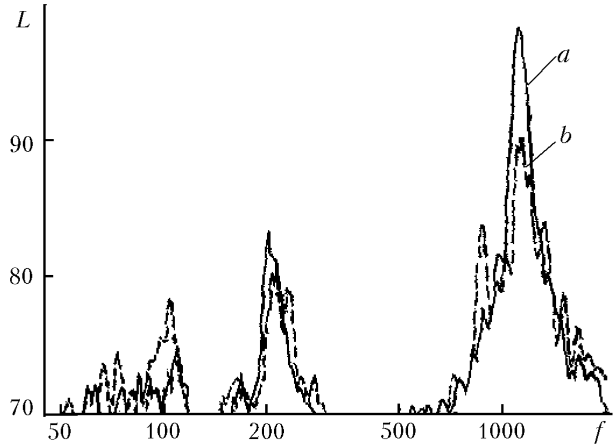

Fig. 3. Spectra of pressure oscillations $L(f)$ that correspond to line 7 (a) and line 8 (b) (see Table 1).

TABLE 2. Results of the Studies of Attenuation of Self-Oscillations on Models at $d_b/d_{mf} = 1$, $d_{mf} = 0.105$ m, $t = 0.585$ m

Line No.	V, m/sec	$Re \cdot 10^{-5}$	f_d, Hz	Sh	tf_d/a	$d_{mf}f_d/a$	ε_p, %
Original pipeline							
1	74.2	4.96	731	1.034	1.232	0.221	2.39
2	90.1	6.03	739	0.861	1.245	0.223	1.72
3	103	6.89	900	0.917	1.516	0.272	3.37
Fin in front of the junction							
4	73	5.13	650	0.935	1.108	0.199	0.78
5	89	6.26	695	0.820	1.184	0.213	0.66
6	102.5	6.95	956	0.979	1.612	0.289	0.68

tions on the resonance frequency is 1.57 kg/cm^2. This is almost fourfold larger than in the mode described on line 6 of Table 1, where narrow-band acoustic disturbances are likely to be generated by only one blind branch.

At the same time, in one of the experiments where the flow velocity in two T-junctions with blind branches is 18.4 m/sec and the distance between the closed cocks is not a multiple of a half-width of the sound wave on the resonance frequency, the narrow-band component is barely pronounced against the background of the continuous spectrum of pressure oscillations — acoustic instability is not realized.

The bench tests conducted on models smaller than full scale and, correspondingly, at higher resonance frequencies repeated the principal mechanism of the considered self-oscillation processes and at the same time supplemented the range of parameters studied. Some results given on lines 7–10 of Table 1 indicate that as the number of half-waves increases, the amplitude of narrow-band pressure oscillations decreases noticeably compared with that observed in generation of sound by one of the two blind branches (Fig. 3). This tendency is also observed in comparison of separate results of full-scale studies for low-frequency oscillations and $t_{tot}/\lambda_a \approx 1.5$ and 2.5. This is probably due to the boundedness of the energy of acoustic radiation arriving at the self-oscillating system from large-scale hydrodynamic structures in the zones of junction of the manifold pipes and branches.

5. In [1], the possibility of preventing intense acoustic radiation in the considered pipelines by changing the flow structure directly in the zone of junction of the blind branch and the manifold-grid of fins oriented along the flow was established. In the present study, we considered a simpler solution of this problem — by positioning a low fin-plate in front of the junction of pipes on the manifold wall in its symmetry plane. It was assumed that longitudinal vortices that are formed in the corners between the fin and the manifold wall will interact with a vortex flow in the zone of the junction mentioned.

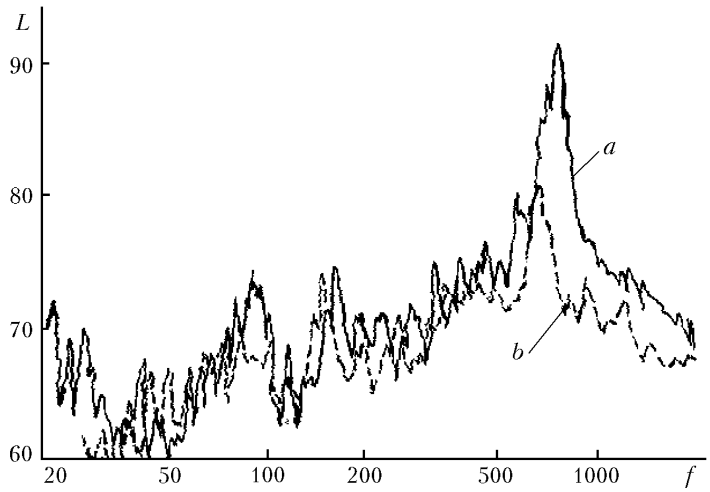

Fig. 4. Spectra of pressure oscillations $L(f)$ that correspond to line 1 (a) and line 4 (b) (see Table 2).

Comparison of the results of the bench experiments conducted on the original pipeline and with a fin mounted in it, which are presented in Table 2, confirmed the fundamental possibility of decreasing the level of narrow-band acoustic radiation by organizing interaction of two large-scale hydrodynamic structures (compare lines 1 and 4, 2 and 5, and 3 and 6 in Table 2; see Fig. 4).

CONCLUSIONS

1. The regions of realization of acoustic instability correspond to excitation of combined narrow-band hydrodynamic and acoustic disturbances in pipes with blind branches and wind tunnels with an open working section in the plane of parameters Sh–$\bar{t}$.

2. The level of narrow-band acoustic pressure oscillations initiated in two blind branches and the manifold between them depends on the multiplicity of the length of the resonance section to the length of half-waves of the resonance frequency.

3. The intensity of acoustic disturbances in pipelines can be reduced by organization of the interaction between inhomogeneities generating them in the flow and hydrodynamic structures that differ from them. The results obtained can be useful for solving the corresponding practical and research problems.

NOTATION

a, velocity of sound propagation in gas, m/sec; d_h, hydraulic diameter of an elliptic nozzle of the wind tunnel, m; d_n, outlet diameter of a nozzle of the wind tunnel, m; d_{mf} and d_b, inner diameters of the manifold pipes and the blind branch, m; f, frequency of pressure oscillations, Hz; L, level of pressure oscillations, dB; t_{mf}, manifold length between two blind branches, m; p, oscillating component of the instant value of pressure, N/m^2; q, dynamic pressure in the flow, N/m^2; Re, Reynolds number; Sh, Strouhal number; t, length of the resonance section of the pipeline, m; t_i, length of the blind branch between the place of its junction with the manifold and the closed cock, m, i = 1, 2; t_{tot}, total length of the resonance section, which includes the length of two blind branches and the manifold between them, m; V, mean-flow-rate velocity of the flow in the manifold in front of the junction of pipes, m/sec; V_m, velocity on the pipe axis or on the outer boundary of shear flow, m/sec; ε_p, intensity of pressure oscillations, %; λ_a, length of the acoustic wave on resonance frequency, m; ν, coefficient of kinematic viscosity of gas, m^2/sec; ρ, gas density, kg/m^2; τ, friction on the wall in front of the junction of the manifold pipes and the blind branch, N/m^2. Indices: h, hydraulic; d, disturbance; mf, manifold; tot, total; n, nozzle; b, blind branch; m, maximum value; p, pressure; 1, 2, first and second (along the flow) blind branches.

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