UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
OFFICE OF CHIEF ENGINEER

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INFLUENCE OF A METHOD OF AIR ADMISSION ON PRESSURE SURGES IN DRAFT TUBE MODELS OF AXIAL HYDRO-TURBINES

(Vliianie sposoba vpuska vozdukha na pulsatziiu davleniia b otsasivaiushchei trube modeli osevoi gidroturbiny)

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Iu. M. Isaev

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Translated from the Russian: Gidromashinostroenie Trudy LPI, No. 215, Moscow and Leningrad, pp 58-68, 1961

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ABSTRACT

This paper describes hydraulic model tests of the effects of air admission on pressure surges in axial hydraulic turbines. The reduction or growth in surge amplitude and the change in unit efficiency were investigated for several locations of air admission and varying quantities of air. The particular study described was for a Kaplan turbine. It was concluded that the most effective method was introduction of air through the flow deflecting part of the cone. Surge amplitudes were reduced by up to 45 percent and efficiency of the unit increased 0.5 to 1.0 percent.

DESCRIPTORS--/ foreign design practices/ hydraulics/ model studies/ hydraulic models/ axial flow turbines/ draft tubes/ hydraulic turbines/ hydraulic transients/ *Kaplan turbines/ turbines/ surges/ unsteady flow/ vortices/ water pressures/ instrumentation/ piezometers/ statistical analysis/ vibrations/ *aeration/ efficiencies/ pressure sensors/ recording systems

IDENTIFIERS--/ USSR/ Leningrad Metalworks, USSR/ Leningrad Poly Inst, USSR/ *machine design/ foreign research/ hydraulic design

INFLUENCE OF A METHOD OF AIR ADMISSION ON PRESSURE SURGES IN DRAFT TUBE MODELS OF AXIAL HYDRO-TURBINES

by Iu. M. Isaev

In many cases, in the operation of hydraulic machinery, strong vibrations take place, resulting from hydrodynamic causes such as: collapse of vortices in flow around the blades, nonuniformity in the fixed fields of velocity and pressure in the region of the runner, and also cavitation disturbances in the continuity of flow.

In connection with significant difficulties of direct vibration investigation on hydraulic turbine models, laboratory experiments are proceeding by way of the investigation of pressure pulsation in the running parts and its change under the action of these or other factors; having this in mind: that the pulsating pressures are namely those disturbing forces which cause vibration of the hydraulic machinery as a whole (Reference 1).

However, only comparative results can be obtained for a case when there are one or several known prototype operating conditions reproduced in the model.

At the present time, on the basis only of laboratory investigations of pressure surges, it is not possible to make conclusions about vibration of field units since, on the one hand, they depend on those factors usually not modeled in hydrodynamic tests, such as mass and rigidity of the separate elements of the hydrounits. On the other hand, not every pressure surge in the flow passage of the hydroturbine should, without exception, cause vibration of the unit.

In order to reduce the vibrations, sometimes hydraulic machinery engineers resort to the admission of air into the region of the runner. Through this they suggest that the presence of air in the flow has a damping effect on the perturbing forces and increases the dissipation of energy in the unstationary perturbations. In the presence of cavitation cavities, the admission of air leads to the breaking of the vacuum, which also must be a means of decreasing the vibration of the unit.

The investigation, carried out on models of the Francis turbines at LMZ[1/], showed that admission of even very small quantities of air--a total of only 0.2 percent--in the center of the spiral vortex led to disappearance of the pressure surges.

In operating practice, axial-hydraulic-turbine vibrations take place very often; however, laboratory investigations of methods for preventing them have not been carried out.

1/Translator's note: Leningrad Metalworks.

In the Hydraulic Machine Laboratory of LPI[2/], special work was carried out for explaining the effect of air on pressure surges and for establishing the most rational method of its admission. Below are given the results of these investigations.

1. Test stand and method of measuring

Experimental investigations of the effect of admission of air on pressure surges were carried out in the closed cavitation stand in the Hydraulic Machine Laboratory with heads similar to the prototype.

The Kaplan turbine model had a working runner Type PL-548 with a diameter of 250 mm and draft tube with elbow No. 20 with a height of 1.54 D_1[3/].

Admission of air was accomplished by forcing from a compressor:

1. Through each of four rows of openings in the wall of the throat ring, 40 2-mm-diameter openings to a row--Figure 1,a

2. Through six openings with a diameter of 4 mm in the torus of the draft tube--Figure 1,b

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2/Translator's note: Leningrad Polytechnic Institute.
3/Translator's note: See Appendix I.

3. Through 16 openings with a diameter of 3 mm in the flow deflecting part of the inner head cover--Figure 1,c

4. Through 8 openings with a diameter of 3 mm in the runner hub--Figure 1,d

In the latter case, a hollow-shaft model was used and a special fitting was installed in the stuffing box. The amount of air was varied from 0.2 to 4 percent of the amount of water passing through the model, considering the volume of air in relation to the pressure under the runner.

The air was withdrawn from the tailwater of the stand by a vacuum pump; pressure in the vacuum tank during this was maintained constant. The pressure surge was measured at the inlet section and in the torus of the draft tube, as shown in Figure 1.

Specially built strain-gage transducers were used for measuring. One of these is shown in Figure 2.

The membrane of the instrument with a diameter of 30 mm and a thickness of 0.2 mm was turned as one unit from a piece of

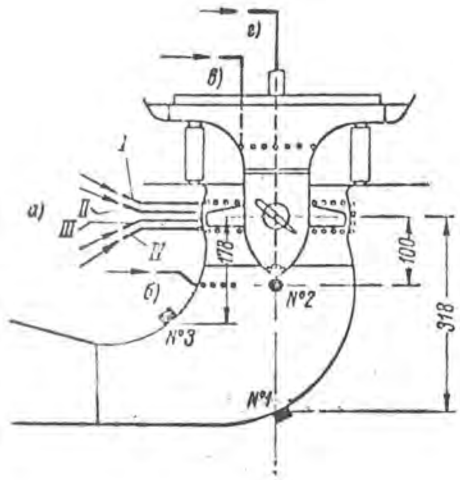

Figure 1. Means of admitting air and points of surge measurement.

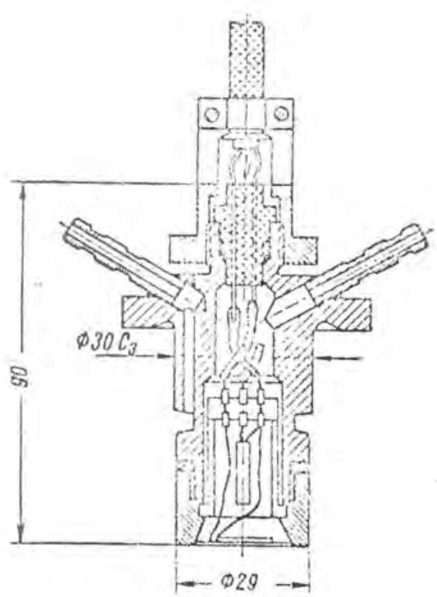

Figure 2. Strain-gage transducer

steel mark 2Khl3[4]. To the membrane was glued, with Glue BF-2, an operating pressure sensitive element from constantan[5] wire with a diameter of 0.03 mm and a base of 6 mm. A compensated pressure sensitive element was glued to the wall of the bronze case, which is pressed to the housing of the cap.

The calculated natural frequency of the membrane was equal to 4 khz[6]. The recording instrument was installed flush with the inside surface of the draft tube.

Oscillograms of pressure were recorded with the aid of a nine-channel electromagnetic oscillograph of type "Siemens" on 120-mm photosensitive paper with a sensitivity of 600° H and D[7].

The strain-gage transducers worked with a sensor station Type ETS-23-57 and an oscillator IV class. The maximum deflection of the stylus in the recording process was ± 50 mm. In this case, the sensitivity of the transducers reached 0.5 m of water for 10 mm of stylus deflection on the photosensitive paper.

4/Translator's note: This is a chromium stainless steel.
5/Translator's note: An alloy of nickel and copper.
6/Translator's note: Kilohertz, thousands of cycles per second.
7/Translator's note: Initials refer to Hurter and Driffield, who developed an early photo processing method.

The static calibration of the transducers was made before each series of tests, practically two per day. The maximum relative error of recording the pressure surges reached ± 15 percent.

To increase the operating range of the oscillogram, the constant-pressure components were compensated by the method of M. M. Fetisov (Reference 4). Pickup of the static pressure was made through a ring-shaped 0.5 mm hole between the casing of the instrument and the wall of the draft tube.

2. Method of Analyzing the Oscillograms

The pressure surges in the draft tube were not of a strictly periodic character. The values of the amplitudes and periods of the individual surges proved to be fluctuating in a certain interval. From examination of one of the typical oscillograms, shown on Figure 4, it can be seen that the element of chance plays an important role in formation of the surge impulses. All of this makes it very difficult to compare objectively by investigations which must take into account the basic features of the phenomena.

Therefore, the most valuable analysis of the oscillograms of the same processes can be made basically by statistical methods (References 5 and 6).

In the case given, the surge amplitudes measured on oscillograms as the deflection from the average value were examined as random values at a certain frequency of the phenomenon. Later on, a statistical series was established and a starting frequency of the amplitudes was computed, not exceeding the given value, according to the formula:

$$P = \sum_{\Delta A_1}^{\Delta A_i} \frac{m_i}{n} \cdot 100\%, \tag{1}$$

where m_i is the number of amplitudes, occurring in a given interval;

n is the number of all the amplitudes in the given oscillogram period.

The resulting values of the frequency plotted on the graph of the statistical function of the distribution of amplitudes sometimes are called S-curves[8/] (Reference 6). Some of these S-curves of pressure surges for a varying quantity of air admitted through the lower row of openings in the wall of the throat ring are presented on Figure 3, where values of amplitudes are given as percentages of the head.

8/Translator's note: Literal translation is "ogives."

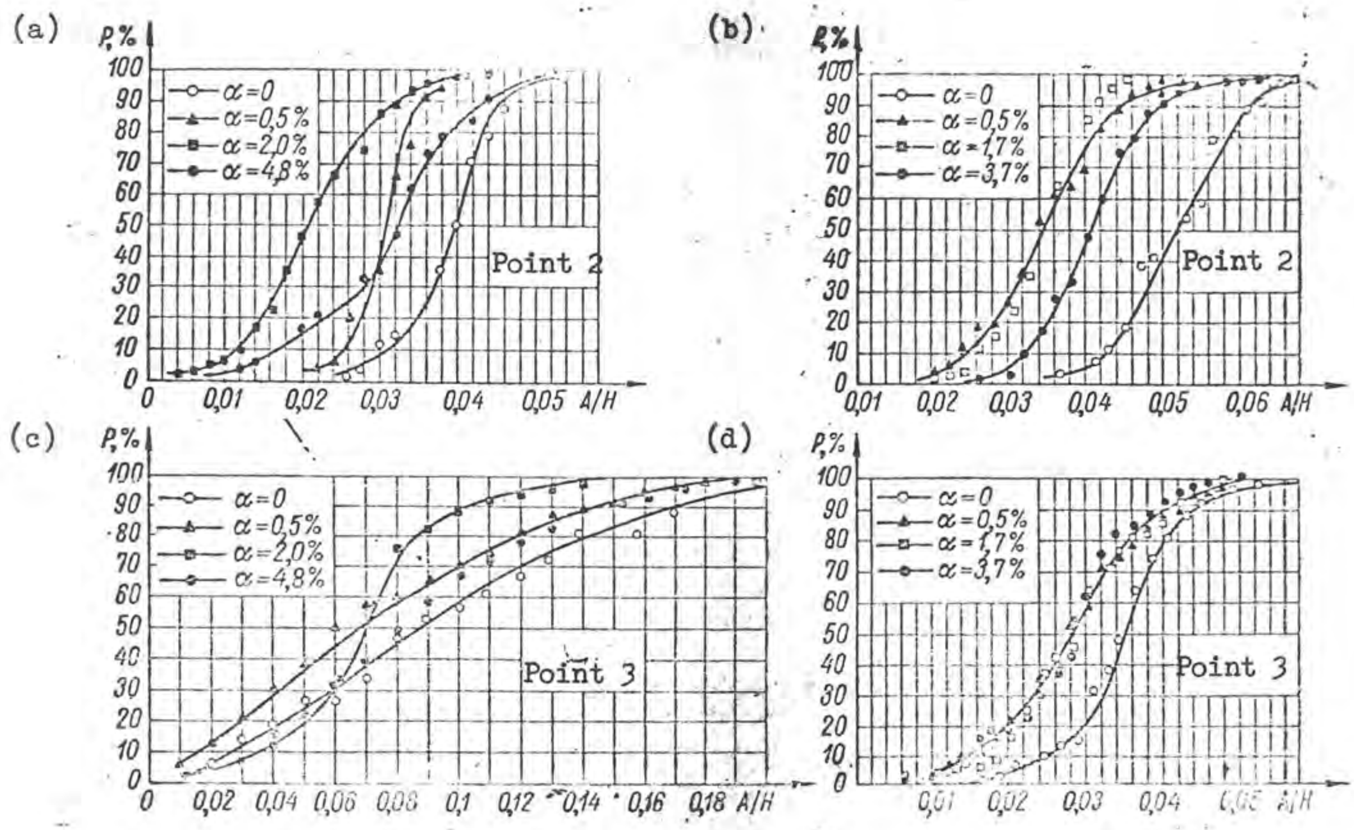

Figure 3. Statistical function of the distribution for the amplitude of the pressure surges for various quantities of air, admitted through the lower row of openings in the wall of the throat ring, $\varphi = +10°$, $n_I' = 135$ rpm: a--idling condition, $Q_I' = 1380$ 1/sec; b--combiner operation, $Q_I' = 1500$ 1/sec[9].

[9]Translator's note: See Appendix II for definitions of terms.

3. The character of the pressure surges

The investigations, carried out on a significant part of the field of universal characteristics with angles of placement of the blades $\varphi = 0°$, $+10°$ and $+20°$ and unit speeds of $n_I' = 115$, 135 and 165 rpm under a head of 11 m, made it possible to establish that the pressure surges in the draft tube are connected with the operating conditions of the turbine model and the character of the flow below the runner.

In the laboratory tests, two types of surges occurred: high-frequency and low-frequency. Both of them depended on the special features of operation in the water passage.

The first type of pressure surge took place during combiner operation[10] and at propeller motoring speeds when Q_I' was greater than at the combiner point. The flow below the runner can have either an axial direction or a small reverse twist in the central part.

10/Translator's note: Soviet terminology uses the word "combiner" to indicate the Kaplan gage control mechanism, consisting of cams, levers, links, etc. "Combiner operating conditions" indicates combined control operation where the blades and wicket gates move simultaneously according to a set ratio.

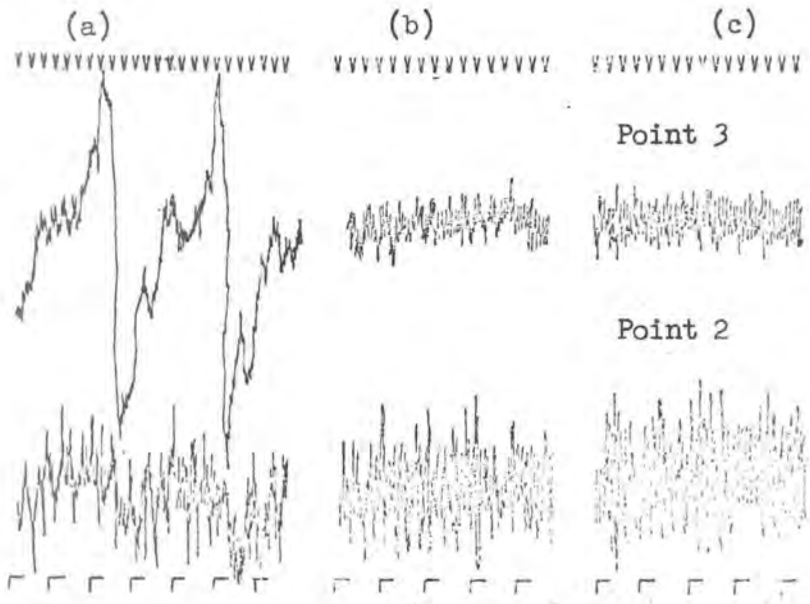

Figure 4. Oscillogram of pressure surges. $\phi = 10°$, $n_I' = 135$ rpm: a - $Q_I' = 1200$ liters/sec, b - $Q_I' = 1500$ liters/sec (combiner operation); c - $Q_I' = 1680$ liters/sec.

The frequency of such surges in the model is in the range of 300-400 hz with a value of about ± 0.05 H for the average amplitude. One of the oscillograms of such a process is shown on Figure 4,b and c. Increase of the distributor opening at the combiner operating condition leads to some increase of the amplitude of the pressure surges up to an average value on the order of ± 0.1 H.

Similar high-frequency surges evidently create spiral-shaped vortices in the flow around the blades and the onset of vortices due to local irregularities in the draft tube itself. Increasing the unit discharge with n_I' = constant at combiner operation leads to an increase in pressure surges in the case of a draft tube with Elbow No. 20. This increase may be characterized by the graph on Figure 5, curve "a".

Prototype experiments carried out on the Kakhovsk Hydrocomplex[11/] by Lengidep (Engineers Timye, Svichensky, and others) in 1958 show that the vibration of the hydrounit increases with an increase in power and, after being converted in relation to the unit discharge, takes the form of curve b. These data qualitatively coincided with the laboratory experiments.

11/ Translator's note: This term is used in the USSR to indicr all the structures of a hydraulic installation located at one site, not any particular combination of structures.

The second type of surge arises at small distributor openings to the left of the combiner point. It is characterized by a quite low frequency--4-6 hz on the model and large values of the amplitude: its average value has a range of ± 0.1-0.2 H and a specific maximum up to ± 0.35 H. The period of such surges has a duration of 2.5-5 revolutions of the runner (Figure 4,a).

The appearance of these low-frequency surges always coincided with the arising of a spiral vortex through the positive twist of the flow. Visual observation determined that the frequency of the surges is determined by the rotational speed of the vortex.

Since the vortical collapse from the ends of the blades and other causes generating the high-frequency surges are not eliminated; the high-frequency components are also recorded on the oscillogram with the low-frequency surges.

The processes observed in these tests are found to be in agreement with a fact well known in operating practice that disturbance in the combiner setting is the cause of the increase in the vibration of the unit. This vibration whould be more intensive if the opening of the guide apparatus is less than the combiner.

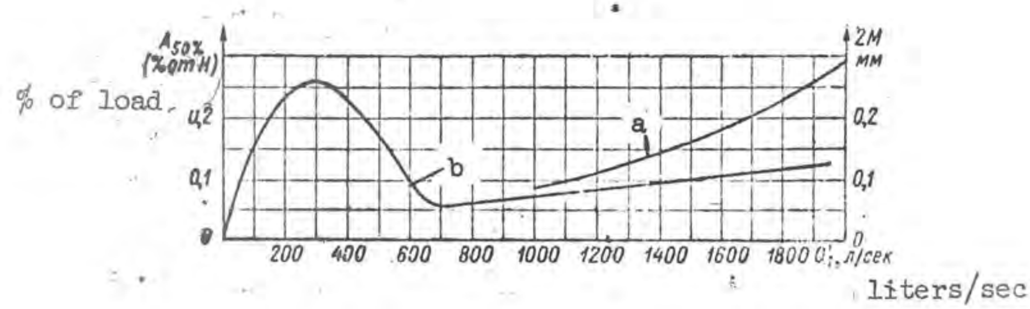

Figure 5. Pressure surges in draft Tube No. 20: a--average amplitude of surges; b--vertical vibration of the turbine cover of the unit at Kakhovsk Hydroelectric Plant.

4. The effect of admission of air on the pressure surges

The model hydraulic operating conditions were chosen for investigating the effect of air admission considering the fact that there occurs two types of surges: low frequency in the presence of an axial vortex and high frequency in other cases.

For an angle of blade placement $\varphi = +10°$ and a unit speed $n_I' = 135$ rpm, two conditions were assumed: combiner operation with a unit discharge $Q_I' = 1500$ liters/sec and motoring with $Q_I' = 1380$ liters/sec.

The effect of admission of air on the pressure surges depended on the method of air intake and on the quantity of air.

The admission of air through openings in the wall of the throat ring was carried out alternately in each row.

Visual observations through viewing windows in the draft tube showed that air admitted during the combiner condition was distributed quite uniformly along the entire flow regardless of the row used; but during motoring it was largely concentrated within the vortical braid. Analysis of the oscillogram and structure of the S-curve made it possible to establish that the very best results are given by admission of air through openings located below the trailing edges of the blades at an angle of placement $\varphi = +10°$, at a spacing of 4 mm (Row IV, Figure 1). From this proceeds a weakening of the pressure surge during combiner operation as well as during motoring operating conditions, on an average 35 percent at the inlet section elbow and significantly less in the torus part. The quantity of air necessary for maximum reduction of the pressure surges depends on the working conditions of the model hydraulic turbine. Thus, at combiner operation the largest decrease in the surges was observed at 0.5 percent air. Further increase in the quantity of air by 3 or 4 times had practically no effect on the degree of reduction of the surges. With very large (about 3-4 percent) quantities of air some increase of surges was observed in the inlet section of the elbow.

With motoring conditions the presence of stronger surges requires a larger quantity of air for their reduction. The greatest reduction of the surges (even 35 percent) occurred with 2-percent air. Increase in the quantity of air above 2 percent leads to larger surges.

Change in the pressure surges in relation to the quantity of air are shown on the graph of Figure 6, where curves of the change of amplitude for 90 percent and 50 percent probability at combiner operation are shown. The values of these amplitudes were plotted in relation to the graphs of statistical distribution similar to the graphs of Figure 4.

From Figure 6, it is seen that with the admission of air through the fourth row of openings, the increase in amplitudes of all values proceeds sufficiently uniformly.

Admission of air through the upper row of holes shows less weakening action on the pressure surges. Admission of air through the second and third rows of holes leads to magnification of the surges during combining and motoring conditions, in comparison with operation without air admission, of approximately 20-40 percent in the region of largest amplitudes. This demonstrates to us that admission of air through rows of holes, past which passes the edge of the blade, impairs the flow around the blade, stripping off the vacuum on its lower side and showing the reason for additional disturbances.

Admission of air through openings in the surface of the torus was made with the aim of reducing the surge activity in that part of the draft tube to which the spiral vortex comes the closest during the motoring condition. It turned out with combiner operation during admission of air, a reduction of pressure surges was observed not only on the surface of the torus but also in the inlet section of the elbow.

This fact indicates that the unsteadiness observed in the flow is determined not only by the processes occurring in the runner area, but also by the disturbances occurring in the draft tube itself below the point of measurement of the surges. Evidently, the admission of air improves the conditions of flow through the draft tube elbow due to which the surge level is also reduced in the entrance section of the elbow.

Nevertheless, the reduction of pressure surges is not large. As seen in Figure 6, it reaches about 20-22 percent when the amount of air is 1 percent.

During motoring, admission of air through openings in the torus weakens the low-frequency surge by 40 percent, with 1 percent air. Further reduction in the amount of air leads to an increase in the maximum amplitude of the surges.

On the surface of the torus the damping action of the air by the given method of admission is 1.5-2 times more effective than

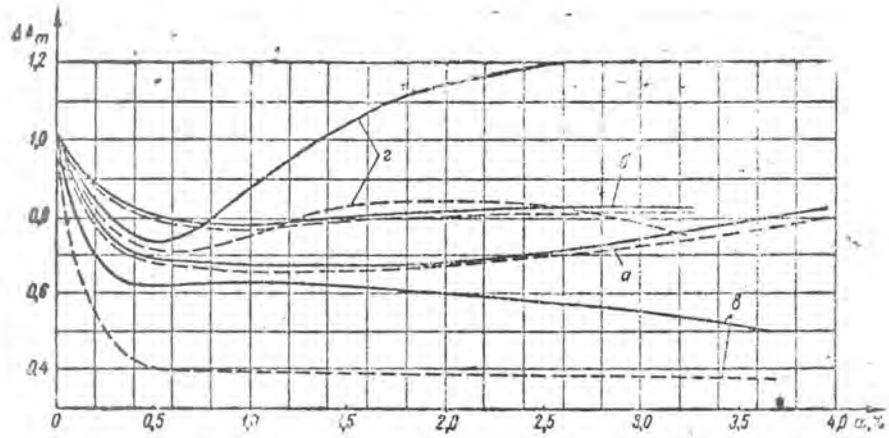

Figure 6. Effect of air on pressure surges as related to the method of admission (combiner operation): a--IV row of holes in the wall of the throat ring; b--holes in the torus; c--the cone; d--the inner head cover

--- P = 50 percent

—— P = 90 percent

admission at the inlet section of the elbow, since the air covers the "crown" of the draft tube with an unbroken film and causes significant absorption of the pressure surges.

Admission of air through the deflecting surface of the inner head cover turned out to be somewhat less effective than the admission of air through openings in the wall of the throat ring. The maximum weakening of the surges (by 28 percent) occurred with 0.5 percent air. Increase of the admission of air led to growth of the high-amplitude portion of the spectrum of the surges and their value increased.

During motoring, there occurs a comparatively monotonic reduction of the surges from 35-40 percent in proportion to an increase in admission of air from 0.5 to 3 percent.

Admission of air through the runner cone is characterized during visual observations by the fact that all the air is directed to the flow axis in the form of a foamy trail beyond the hub as much during combiner conditions as during motoring. In the latter case, the spiral vortex increased in diameter by 2-3 times and intensely disintegrated in the diverging part of the draft tube.

During combiner operation, the amplitudes below the average ones were reduced even more effectively--by 60 percent for admission of 0.4 percent air. Maximum amplitudes in this case were reduced by 40 percent.

Admission of air by this method during motoring led to a decrease in pressure surges by 40 percent.

5. Effect of admission of air on efficiency

The presence of undissolved air in the water passages of hydraulic turbines increases the energy losses and as a rule leads to a reduction of efficiency which is greater when there is a larger amount of air in the flow. Moreover, the influence of air on the efficiency depends both on the operating condition of the turbine and on the method of air admission. The least reduction in efficiency for the investigations carried out takes place at smaller values of the openings of the distributor for admission through the lower row of holes in the wall of the throat ring. Figure 7 shows the value for the decrease in efficiency where the relative change in efficiency is represented by the difference in efficiencies with and without admission of air.

Admission of air through the deflecting surface of the inner head cover led to reduced efficiency. A greater reduction in efficiency occurred during admission through the middle rows of the openings in the wall of the throat ring.

Admission of air through the runner cone is an exception since it leads to some increase in the efficiency. This improvement has a tendency to increase with an increase in the quantity of air admitted. Due to the fact that this increase in efficiency is commensurate with the accuracy of measurement, a clear relationship to the size of the distributor opening cannot be demonstrated sufficiently. Therefore, for a given case the curve on the graph in Figure 7 is given which was reduced according to the averaged results of measurements with the size of the distributor opening a_o = 12, 13, 14, 16, and 18 mm.

Such an increase of efficiency can be explained by the more intensive disintegration of the vortex in comparison with the foregoing methods of air admission and by the fact that the air is thus concentrated in a smaller portion of the flow axis beyond the draft tube elbows.

6. Analysis of results

Investigation of the various methods of air admission has shown that for determined conditions it is possible to assure a reduction in the surge level by 30-40 percent. The latter factor must be regarded as the limit, since not one of the described methods of air admission into the region of the runner and the draft tube leads to a larger decrease in the pressure surges. Although the connection between the pressure surges and vibration of the prototype unit is confirmed by the experiment, this confirmation is obtained by indirect means. Only some specially organized laboratory experiments or some prototype experiments may give the answer of whether such a weakening of the surges leads to a reduction or elimination of vibration of the prototype unit.

The most important effect from the point of view of reducing the nonstationary process in the draft tube is admission through the runner cone during combiner operation, as well as motoring operation; thus is discovered some improvement in the efficiency of the turbine. The use of a dynamic vacuum under the hub of the runner would assure admission of air due to self-injection. Directed calculation shows that for the Kakhovsk turbines it was necessary to admit 750 liters/sec of air by volume, reduced to atmospheric pressure when the discharge was 480 m^3/sec (strong vibration of the units).

For a dynamic vacuum of 4-5 meters of water inside the shaft and at the hub, it is necessary to have a flow passage for the air with a cross-sectional area of approximately 350 cm^2. It is completely evident that on the already manufactured turbine this technically is not possible. Therefore, a structural development permitting the admission of air through the hub of the runner would be desirable.

Of secondary importance is the admission of air through the wall of the throat ring, by means of a circular row of holes below the trailing edges of the blades at the limiting angle of blade rotation. Thus, for motoring, insignificant weakening of the pressure surge is obtained but this case practically is excluded if the combiner is in adjustment. During combiner operation, a somewhat larger quantity of air is required than when air is admitted through the cone, but the surge is reduced by 7-10 percent less. For its use, it is necessary to install a ring manifild with a diameter of about 300 mm in the concrete of the supporting cone and to bring out the penstock higher up through the supporting stay vanes of the speed ring. During the construction period, this would not require great expense. Use of this method of reducing surges in an operating plant should be determined by the specific conditions.

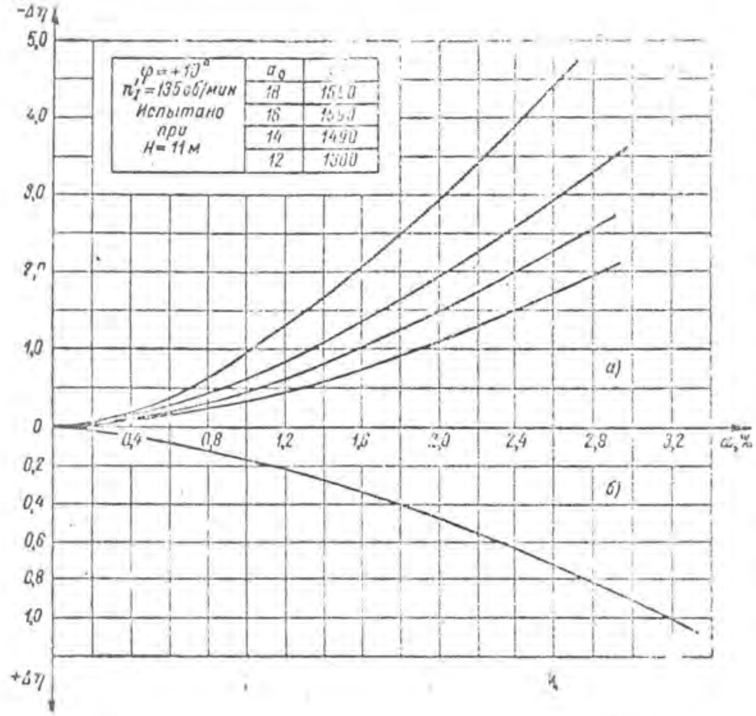

Figure 7. Change in efficiency with admission of air: a--through the lower row of holes; b--through the runner cone.

Legend in upper left corner: ϕ =+10°, n_1' = 135 rpm, test at H = 11 m.

Thus, one must keep in mind that elimination of vibration along with an improvement in operating conditions of the plant will lead to a reduction in the efficiency and it will be necessary to consider the determined losses in the output of electrical energy.

Technically it is somewhat easier to arrange for the admission of air through the turbine head cover; however, not a great deal easier, on the order of 25 percent; reduction of the pressure surge or its growth when there is an increase of air points to the fact that this method requires especially careful field verification.

Admission of air into the draft tube through openings in the torus would be sufficiently simple to arrange for by using pumps and other installations usually located above the draft tube. However, it leads to an essential reduction in pressure surges only during motoring and only then with the admission of very large quantities of air; for this reason, it is not recommended.

CONCLUSIONS

1. The most effective method of reducing the pressure surges by means of admission of air is very complicated technically; however, its use leads to a reduction of unsteadiness by 45 percent.

2. The most effective is admission through holes in the flow deflecting part of the cone during combiner and motoring operation. Due to the better flow arrangement, an increase in efficiency of 0.5 to 1.0 percent was observed (Figure 6, Curve c).

3. Admitting air through a circular ring of openings in the throat ring wall located below the trailing edges of the blades at the limiting angle of blade rotation is 7 to 10 percent less effective than the method indicated in the preceding conclusion. In certain cases, it is required to specify a manifold in the concrete of the support cone during the period of construction and in already built powerplants to go to a certain determined expense for removal of the operating unit for repair.

4. Admission of air through the turbine head cover reduces the pressure surges by 25 percent with a 0.5 percent quantity of air. A further increase of air leads to an increase in the pressure surges. Using this method sometimes is not too successful and requires having a special compressor.

5. Admission of air to the draft tube through holes in the torus cannot be recommended due to large discharge of air and the low level of reduction of pulsations during combiner operation.

Also, the admission of air through holes in the wall of the throat ring should be considered infeasible, if the jet of exiting air is broken as it passes next to the blade, since for this condition there occurs a growth in pressure surges.

6. To clarify the problem of the necessary degree of decrease of the pressure surges with the aim of eliminating the vibrations, special field and laboratory investigations should be arranged. Thus, attention should be given to the study of the interconnection between the unsteady processes in the water passage of a turbine and vibration in its specific components.

7. The method used here by a brief statistical analysis of oscillograms was very useful for investigating the unsteady processes.

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ТРУДЫ ЛЕНИНГРАДСКОГО ПОЛИТЕХНИЧЕСКОГО ИНСТИТУТА
имени М. И. КАЛИНИНА

№ 215 *1961*

Ю. М. Исаев

ВЛИЯНИЕ СПОСОБА ВПУСКА ВОЗДУХА НА ПУЛЬСАЦИЮ ДАВЛЕНИЯ В ОТСАСЫВАЮЩЕЙ ТРУБЕ МОДЕЛИ ОСЕВОЙ ГИДРОТУРБИНЫ

При эксплуатации гидроагрегатов в ряде случаев имеет место сильная вибрация, обусловленная гидродинамическими причинами: срывом вихрей при обтекании лопастей, неравномерностью стационарных полей скоростей и давлений в области рабочего колеса, а также кавитационными разрывами сплошности потока.

В связи со значительными трудностями непосредственного исследования вибрации на моделях гидротурбин в практике лабораторного экспериментирования идут по пути исследования пульсации давления в проточной части и ее изменения под действием тех или иных факторов, имея при этом в виду, что пульсация давления является именно той возмущающей силой, которая вызывает вибрацию гидроагрегата в целом [1]. Однако таким путем могут быть получены только сравнительные результаты для случая, когда уже имеется один или несколько известных натурных режимов, воспроизведенных на модели.

На современном этапе на основании только лабораторных исследований пульсации давления нельзя дать заключение о вибрации натурного агрегата, так как, с одной стороны, она зависит от таких обычно не моделируемых при гидродинамических испытаниях факторов, как масса и жесткость различных элементов гидроагрегата, а с другой стороны, не всякая пульсация давления в рабочем канале гидротурбины должна непременно вызывать вибрацию агрегата.

В целях уменьшения вибрации иногда прибегают к впуску воздуха в область рабочего колеса. При этом предполагают, что наличие воздуха в потоке оказывает демпфирующее действие на возмущающие силы и увеличивает поглощение энергии нестационарных возмущений. При наличии кавитационных разрывов впуск воздуха приводит к срыву вакуума, что также должно способствовать уменьшению вибрации агрегата.

Исследования, проведенные на моделях радиальноосевых гидротурбин на ЛМЗ, показали, что впуск даже очень небольшого количества воздуха — всего около 0,2% — в центр вихревого шнура приводил к исчезновению пульсации давления.

В практике эксплуатации осевых гидротурбин вибрации также достаточно часто имеют место, однако лабораторные исследования способов борьбы с нею не проводились.

В лаборатории гидромашин ЛПИ была проведена специальная работа по выяснению влияния воздуха на пульсацию давления и по установлению наиболее рационального способа его впуска. Ниже излагаются результаты этого исследования.

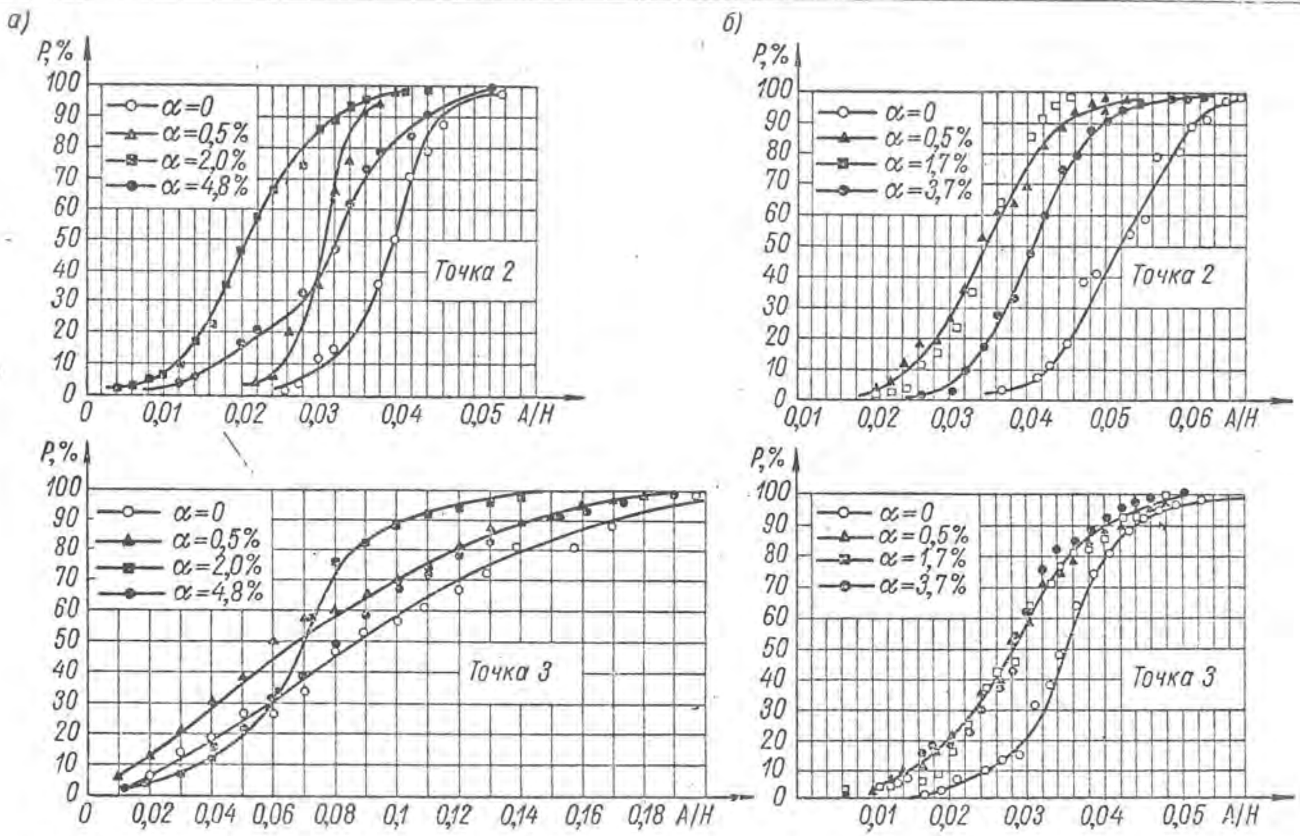

Рис. 3. Статистическая функция распределения для амплитуд пульсации давления при различных количествах воздуха, впускаемого через нижний ряд отверстий в стенке рабочей камеры, $\varphi = +10°$, $n_1' = 135$ об/мин.: *а* — пропеллерный режим, $Q_1' = 1380$ *л/сек*; *б* — комбинаторный режим, $Q_1' = 1500$ *л/сек*.

3. ХАРАКТЕР ПУЛЬСАЦИИ ДАВЛЕНИЯ

Исследования, проведенные по значительной части поля универсальной характеристики при углах установки лопастей $\varphi = 0°, +10°$ и $+20°$ и приведенных оборотах $n_1' = 115$, 135 и 165 об/мин. на напорах в 11 *м*, позволили установить, что пульсация давления в отсасывающей трубе связана с режимом работы модели турбины и характером потока позади рабочего колеса.

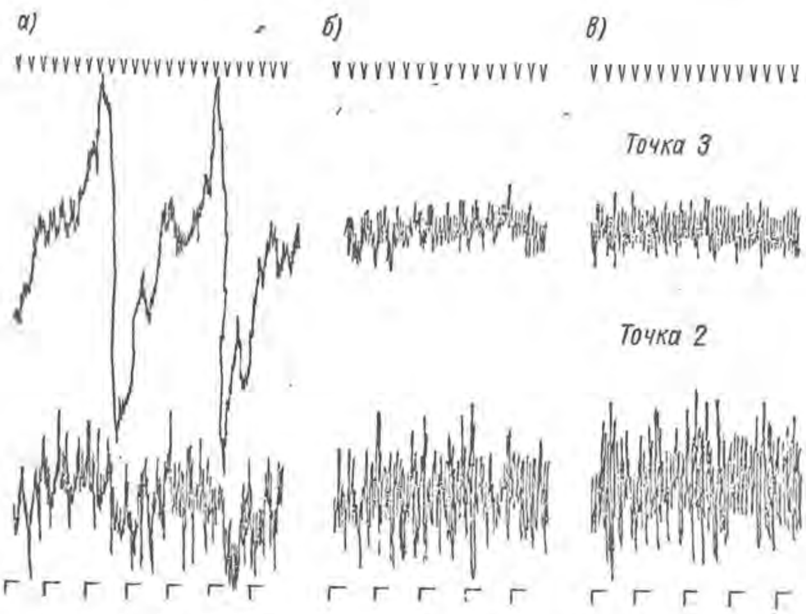

Рис. 4. Осциллограммы пульсации давления.
$\varphi = +10°$, $n_1' = 135$ об/мин.: *а* — $Q_1' = 1200$ *л/сек*; *б* — $Q_1' = 1500$ *л/сек* (комбинаторная точка); *в* — $Q_1' = 1680$ *л/сек*.

При проведении лабораторных опытов выявилось два вида пульсации: высокочастотная и низкочастотная. Оба они обусловлены особенностями рабочего процесса в проточной части.

Первый вид пульсации давления имеет место на комбинаторных режимах и на пропеллерных при Q_1' больших, чем в комбинаторной точке. Поток за колесом при этом либо имеет осевое направление, либо небольшую отрицательную закрутку в центральной части.

Частота такой пульсации на модели имеет порядок 300—400 *гц* и величину средних амплитуд около $\pm 0{,}05H$. Одна из осциллограмм такого процесса приведена на рис. 4, *б* и *в*. Увеличение открытия направляющего аппарата от комбинаторного режима приводит к некоторому возрастанию амплитуд пульсации давления до средних значений порядка $\pm 0{,}1H$.

Подобная высокочастотная пульсация, по-видимому, вызывается вихреобразованием при обтекании лопастей и зарождением вихрей из местных неоднородностей в самой отсасывающей трубе. Увеличение приведенного расхода при $n_1' = \text{const}$ на комбинаторных режимах приводит к росту пульсации давления в случае отсасывающей трубы с коленом № 20. Этот рост может быть охарактеризован графиком рис. 5, кривая *а*.

Натурные испытания, проведенные на Каховской ГЭС Ленгидэпом (инж. Тиме, Свиченский и др.) в 1958 г., показывают, что вибрация гидроагрегата растет с увеличением мощности и, будучи пересчитанной в зависимости от приведенного расхода, имеет вид кривой *б*. Эти данные качественно совпадают с лабораторным экспериментом.

Второй вид пульсации возникает при малых открытиях направляющего аппарата влево от комбинаторной точки. Он характеризуется довольно низкой частотой — 4—6 *гц* на модели и большой величиной амплитуды: ее средние значения имеют порядок $\pm 0{,}1—0{,}2H$, а отдельные максимумы до $\pm 0{,}35H$. Период такой пульсации имеет продолжительность 2,5—5 оборотов рабочего колеса (рис. 4, *а*).

Возникновение такой низкочастотной пульсации всегда совпадает с появлением вихревого шнура при положительной закрутке потока. Визуальными наблюдениями установлено, что частота пульсации определяется при этом скоростью вращения вихревого шнура.

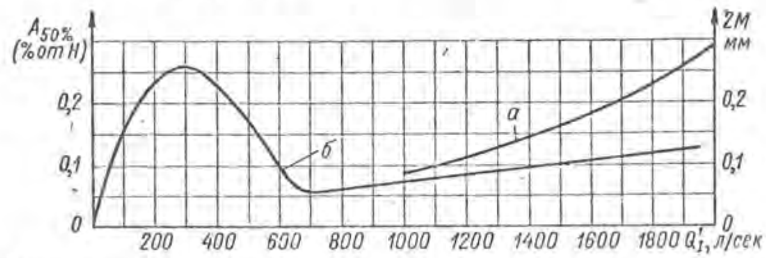

Рис. 5. Пульсация давления в отсасывающей трубе № 20: *а* — средние амплитуды пульсации; *б* — вертикальная вибрация крышки турбины агрегата Каховской ГЭС.

Так как вихревые срывы с концов лопастей и другие причины, порождающие высокочастотную пульсацию, при этом не устраняются, то на осциллограмме низкочастотной пульсации фиксируются также и высокочастотные составляющие.

Наблюдаемые в этих опытах процессы находятся в соответствии с хорошо известным из практики эксплуатации фактом, что нарушение комбинаторной связи является причиной усиления вибрации агрегата. Эта вибрация должна быть более интенсивной, если открытие направляющего аппарата меньше комбинаторного.

4. ВЛИЯНИЕ ВПУСКА ВОЗДУХА НА ПУЛЬСАЦИЮ ДАВЛЕНИЯ

Выбор режимов работы модели гидротурбины для исследования влияния впуска воздуха был произведен с учетом того, что имеют место два вида пульсации: низкочастотная при наличии осевого вихря и высокочастотная в остальных случаях.

При угле установки лопастей $\varphi = +10°$ и приведенном числе оборотов $n'_I = 135$ об/мин. было принято два режима: комбинаторный с приведенным расходом $Q'_I = 1500$ *л/сек* и пропеллерный $Q'_I = 1380$ *л/сек*.

Влияние впуска воздуха на пульсацию давления зависело от способа впуска и количества воздуха.

Впуск воздуха через отверстия в стенке рабочей камеры производился поочередно через каждый ряд.

Визуальные наблюдения через прозрачные окна в отсасывающей трубе показали, что независимо от ряда отверстий впускаемый воздух на комбинаторном режиме распределялся достаточно равномерно по всему потоку, а на пропеллерном — преимущественно сосредоточивался в пределах вихревого жгута. Обработка осциллограмм и построение огив позволили установить, что наилучший результат дает впуск через ряд отверстий, расположенных ниже выходных кромок лопастей на угле установки $\varphi = +10°$ на 4 *мм* (ряд IV, рис. 1). При этом происходит ослабление пульсации давления как на комбинаторном, так и на пропеллерном режимах в среднем на 35% во входном сечении колена и значительно меньше на торовой части. Количество воздуха, необходимое для максимального ослабления пульсации давления, зависит от режима работы модели гидротурбины. Так, на комбинаторном режиме наибольшее уменьшение пульсации наблюдалось при 0,5-процентном количестве воздуха. Его дальнейшее увеличение

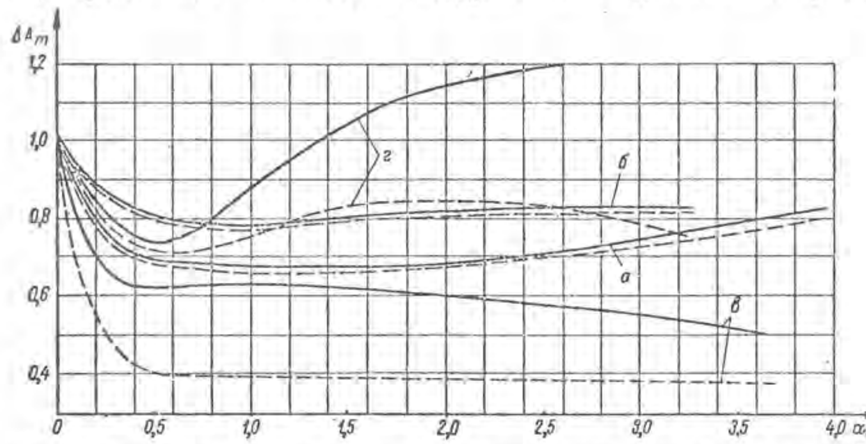

Рис. 6. Влияние воздуха на пульсацию давления при различных способах впуска (комбинаторный режим): *а* — IV ряд отверстий в стенке рабочей камеры; *б* — отверстия в торе; *в* — конус; *г* — обтекатель.
— — — $P = 50\%$; ——— $P = 90\%$.

в 3—4 раза практически не влияло на степень ослабления пульсации. При очень большом (порядка 3—4%) количестве воздуха наблюдалось некоторое увеличение пульсации во входном сечении колена.

На пропеллерном режиме наличие более мощных пульсаций требует большего количества воздуха для их ослабления. Наибольшее ослабление пульсации (также на 35%) происходило при 2-процентном количестве воздуха. Увеличение количества воздуха свыше 2% приводит к увеличению пульсаций.

Изменение пульсации давления в зависимости от количества воздуха показано на графике рис. 6, где приведены кривые изменения амплитуд 90-процентной и 50-процентной вероятности для комбинаторного режима. Значения этих амплитуд брались с соответствующих графиков статистического распределения, аналогичных графикам рис. 4.

Из рис. 6 видно, что при впуске воздуха через IV ряд отверстий происходит достаточно равномерное уменьшение амплитуд всех величин.

Впуск воздуха через верхний ряд отверстий оказывает меньшее ослабляющее действие на пульсацию давления. Впуск воздуха через второй и третий ряды отверстий приводит к увеличению пульсации в комбинаторном и пропеллерном режимах по сравнению с работой без впуска воздуха примерно на 20—40% в области больших амплитуд. Это объясняется тем, что впуск воздуха через ряды отверстий, мимо которых проходит кромка лопасти, ухудшает обтекание лопасти потоком, срывает вакуум на ее нижней стороне и является причиной дополнительных возмущений.

Впуск воздуха через отверстия в поверхности тора производился с целью уменьшить пульсационное воздействие на ту часть отсасывающей трубы, к которой ближе всего подходит вихревой шнур на пропеллерных режимах. При этом оказалось, что на комбинаторном режиме при впуске воздуха наблюдается уменьшение пульсации давления не только на поверхности тора, но и во входном сечении колена.

Этот факт говорит о том, что наблюдающаяся в потоке нестационарность определяется не только процессами в области рабочего колеса, а также и возмущениями, возникающими в самой отсасывающей трубе ниже точки замера пульсации. Очевидно, впуск воздуха улучшает условия протекания потока в колене отсасывающей трубы, вследствие чего и снижается уровень пульсаций во входном сечении колена.

Однако уменьшение пульсации давления при этом невелико. Как видно из рис. 6, оно составляет около 20—22% при количестве воздуха в 1%.

На пропеллерном режиме впуск воздуха через отверстия в торе ослабляет низкочастотную пульсацию на 40% при 1-процентном количестве воздуха. Дальнейшее его увеличение приводит к росту максимальных амплитуд.

На поверхности тора демпфирующее действие воздуха при данном способе впуска в 1,5—2 раза более эффективно, чем во входном сечении колена, так как воздух покрывает сплошной пеленой «потолок» отсасывающей трубы и способствует значительному поглощению пульсации давления.

Впуск воздуха через обтекатель направляющего аппарата оказался несколько менее эффективным, чем впуск через отверстия в стенке рабочей камеры. Максимальное ослабление пульсации (на 28%) происходит при 0,5% воздуха. Увеличение впуска воздуха приводит к росту доли больших амплитуд в общем спектре пульсаций, и их величина возрастает.

На пропеллерном режиме происходит сравнительно монотонное уменьшение пульсации с 35 до 40% по мере увеличения впуска воздуха с 0,5 до 3%.

Впуск воздуха через конус рабочего колеса характеризовался при визуальных наблюдениях тем, что весь воздух сосредоточивался на оси потока в виде пенистого следа за втулкой как на комбинаторном, так и пропеллерном режимах. В последнем случае, вихревой шнур увеличивался в диаметре в 2—3 раза и интенсивно размывался в диффузорной части отсасывающей трубы.

На комбинаторном режиме амплитуды меньше средних уменьшались более интенсивно — на 60% при впуске 0,4% воздуха. Максимальные амплитуды в этом случае уменьшались на 40%.

Впуск воздуха этим способом на пропеллерном режиме приводил к уменьшению пульсации давления на 40%.

5. ВЛИЯНИЕ ВПУСКА ВОЗДУХА НА КОЭФФИЦИЕНТ ПОЛЕЗНОГО ДЕЙСТВИЯ

Наличие воздуха в рабочем потоке гидротурбины в нерастворенном состоянии увеличивает потери энергии и, как правило, приводит к ухудшению к. п. д. тем большему, чем больше воздуха находится в потоке. Кроме того, влияние воздуха на к. п. д. зависит также и от режима работы гидротурбины и способа впуска воздуха. Наименьшее ухудшение к. п. д. при проведении данного исследования имело место на меньших значениях открытия направляющего аппарата при впуске через нижний ряд отверстий в стенке рабочей камеры. О величине такого ухудшения к. п. д. дает представление график рис. 7, где относительное изменение к. п. д. представляет собой разность коэффициентов полезного действия без впуска воздуха и при впуске.

Впуск воздуха через обтекатель направляющего аппарата приводил к примерно такому же ухудшению к. п. д. Более значительное снижение

МИНИСТЕРСТВО ВЫСШЕГО И СРЕДНЕГО СПЕЦИАЛЬНОГО ОБРАЗОВАНИЯ РСФСР

ЛЕНИНГРАДСКИЙ ПОЛИТЕХНИЧЕСКИЙ ИНСТИТУТ
имени М. И. КАЛИНИНА

ГИДРОМАШИНОСТРОЕНИЕ

ТРУДЫ ЛПИ

№ 215

МАШГИЗ

ГОСУДАРСТВЕННОЕ НАУЧНО-ТЕХНИЧЕСКОЕ ИЗДАТЕЛЬСТВО
МАШИНОСТРОИТЕЛЬНОЙ ЛИТЕРАТУРЫ

МОСКВА 1961 ЛЕНИНГРАД