HYDROTECHNICAL CONSTRUCTION

SAYANO-SHUSHENSKAYA CATASTROPHE — SYNCHRONOUS HYDROACOUSTIC RESONANCE?

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Two models are considered for propagation of acoustic waves in the water conduits of Francis turbines at hydroelectric power plants (HPP). Transfer functions are cited for a dynamic “pressure-conduit/turbine/draft-tube” system during a pressure disturbance beyond the turbine. Fulfillment of the Nyquist criterion for the above-mentioned system indicates its stability at any openings of the final-control element. Analysis of analytical relationships between frequency characteristics and parameters characterizing the wave properties of sections of the water conduit makes it possible to isolate frequency regions in which manifestation of resonance is possible, and also evaluate its amplitude. The frequency response of the water conduit at the Sayano-Shushenskaya HPP, for which three resonances are isolated in the ultra-low acoustic region is given in the conclusion. A mathematical model of the process is developed and investigated. Oscillograms of pressure pulsation during pressure disturbances in the final third of the draft tube are presented. Results of the investigation are compared with published data derived from full-scale tests.

Keywords: hydraulic turbine, pressure conduit, draft tube, pressure pulsations, resonance, frequency response, mathematical model.

The failure of the No. 2 generating set at the Sayano-Shushenskaya HPP (SShHPP) has not been related to one hypothesis concerning the physical nature of the phenomena resulting in fatigue failure of the studs securing the turbine cover, and ascent of the rotor of the generating set. The majority of specialists consider pressure pulsations in the turbine setting, which are caused by the non-steady nature of the flow, and, as a consequence, the high vibration level of the subassemblies in the generating set, which result in fatigue failures, to be the cause of the catastrophe [1, 2]. A version citing malfunction of the vane-guide drives should be mentioned as a plausible cause [3]. Analysis of oscillograms of the dynamic processes at the moment of failure indicates, however, that there were no malfunctions in the operation of the automated control system for the turbine. The assumption concerning the development of a divergent oscillatory process in a pressure conduit of the HPP is the most paradoxical of the explanations offered for the cause of the failure of the No. 2 generating set [4].

In calling the attention of the readers to the paper, the problem of the stability and resonance properties of the pipelines of Francis generating sets is discussed. It should be stipulated in advance that instability of the pipeline as a dynamic link cannot be addressed here, because instability of the pipeline would have automatically led to instability of all regulating circuits of the hydraulic turbine, and, consequently, to uncontrollable displacements of the final-control elements. The discussion below will address resonance phenomena in the conduits, which were revealed during investigations of the dynamics of energy exchange between wave processes in the pressure pipeline and draft tube of the Francis turbine. These phenomena could exert a significant influence on exhaustion of the strength of the parts securing the turbine cover under cyclical loads.

It is known that the flow of water in hydroelectric units is an accumulator of kinetic energy. In transitional processes, this kinetic energy goes over into potential pressure energy. The elasticity of the walls of the pipeline and the compressibility of the water will lead to appearance of shock waves along the pipeline. This process is described by a wave equation, the history of investigation of which as applies to the flow of liquid through tubes ascends toward N. E. Zhukovskii [5]. The water-hammer phenomenon not only influences selection of the structure of the system controlling the generating sets, but also, by virtue of the wave pattern, contributes to propagation of the pressure pulses that develop at the outlet from the turbine over the entire water run of the generating set.
A large number of studies, for example, [6, 7], are devoted to investigation of pressure pulses in the conduits of Francis and Kaplan turbines. Pressure pulses in the draft tubes of the turbines are examined in these studies without analysis of their propagation along the conduits of the HPP.

Experimental data [17] derived from full-scale investigations of the generating sets at the Sayano-Shushenskaya HPP in the mid-1990s, and seismographic recordings of vibrations within the body of the dam during failure of the No. 2 generating set in August 2009 suggest that pressure pulsations in the draft tube of the turbine may have resulted in development of hydroacoustic resonance within the conduits of the HPP. One of the first investigations in this field was conducted by the Siberian Division of the Russian Academy of Sciences [4]. Results of similar studies on the stability of pipelines in pumping plants, and notions regarding a conduit as a half-wave resonator were based on this study. The emergency at the SShHPP has imparted new impetus to rejuvenation of interest in the investigation of hydroacoustic resonance in conduits at HPP. A study group for analysis of processes occurring at the SShHPP and development of a system for its monitoring was created on 4 September 2009 at the Siberian Division of the Russian Academy of Sciences.

Results of investigations of the formation and propagation of pulsations in the water run of a turbine are generalized in one of the latest studies [8]. Let us cite the basic conclusion of this publication: “Hydroacoustic resonance in the run of a generating set results from formation of a large-scale coherent eddy structure that emits narrow-band infrasound, and from the presence of a quarter-wave resonator — the pressure channel and scroll.” Experimental and theoretical investigation of eddy flows [9, 10] in which it is demonstrated that pressure pulsations are nonuniform with respect to azimuth in the draft tube, are of major theoretical and practical interest for investigation of the phenomenon of pressure-wave propagation in the water run of a turbine.

Thus, modern notions concerning hydroacoustic resonance are based on the following model:

— the delivery pressure pipeline is a quarter-wave resonator;
— the eddy flow in the draft tube is a generator of narrow-band acoustic noise;
— the blade cascades of the impeller and vane guide of the turbine, which partially lapse into an acoustic-noise resonator that may generate into a vortical chord, and partially reflect it backward, are situated between the pressure pipeline and draft tube; and,
— the waves of acoustic noise that develop in the resonator are intensified.

These notions reflect the physical pattern of development of hydroacoustic resonance in the power conduits with a certain approximation. It is known that a quarter-wave resonator is formed from a pipeline, one end of which is open, and the second end plugged. If the “draft-tube/turbine/pressure-conduit” system is analyzed from this standpoint, the roles in this system may be assigned to one of the following two means:

— the draft tube is, as previously mentioned, an acoustic-noise generator, the turbine an element for removal of energy from the dynamic system under consideration to the power grid, and the pressure conduit a regulator for removal of acoustic-noise energy into the electric grid; and,
— the draft tube and pressure pipeline are regulators for the removal of the energy of periodic acoustic excitations to the electric grid, while the turbine, as in the previous case, is an element through which it is carried out.

During synchronous pressure fluctuations prior to an after the turbine (the pressure differential in the turbine is maintained), neither the flow rate through it, nor the power delivered to the consumers will vary. A situation characterized by the absence of transfer of vibrational energy to the electric grid and the absence of variations in flow rate in the sections where the pressure pipeline and draft tube adjoin the turbine is therefore created. The absence of variation in flow rate is equivalent to the placement of a plug precisely for the periodic component of the pressure variation and transformation of the pressure pipeline alone, or in combination with the draft tube, into quarter-wave resonators. Both types of synchronous resonance appeared during experimental investigation and operation of the generating sets at the SShHPP.

The existence of oscillatory linkages with similar resonant frequencies in the dynamic structures of the conduit at the SShHPP should be inevitably adduced to synchronous resonances in conformity with general principles of synchronization, a review of which is given in [11].

**Static input-output characteristic of Francis turbine.**

The flow rate of water through a Francis turbine and the power delivered to the consumers will depend on the pressure differential in the turbine (active head) and the rotational speed of the rotor. There are no analytical expressions for the static input-output characteristic of the turbines. The recorded form of the input-output characteristics that can be used for investigation of control systems is the result of transformation of the designated coordinates in which the universal characteristic is plotted to coordinates corresponding to it, but which are in relative units of the basic regime parameters. This procedure is described, for example, in [12, 13].

Let the following values corresponding to the basic design regime be assigned as conditional units for variable states of the controlled activity of the hydraulic turbine:

\[ Q_0 \text{ nom} \] — flow rate through the turbine; \( H_0 \text{ nom} \) — head; \( Y_{\text{max}} \) — maximum constructive operation of main servomotor; \( \theta_{0, \text{max}} \) — clear opening corresponding to \( Y_{\text{max}} \); and, \( n_{\text{nom}} \) — number of turns corresponding to synchronous rotational speed. On the universal characteristic, the points with the coordinates

\[ \left( \frac{n_{i, \text{nom}}}{n_{\text{nom}}}, \frac{Q_{i, \text{nom}}}{Q_0 \text{ nom}} \right) \]

correspond to the design regime. Let us construct the universal characteristic, introducing new coordinate axes: abscissa \( \frac{n_{i}}{n_{\text{nom}}} \), and ordinate \( \frac{Q_{i}}{Q_0 \text{ nom}} \).