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Seismic Vibration Pressures and their Impact on the Stability Regime of Hydraulic Structures in the Rezaksai Reservoir

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Abstract: The occurrence of cavitation currents within swirling flows of multiphase media in a cylindrical pipe with circular cross sections is analyzed. These phenomena arise due to the introduction of access-rotational movements.

Keywords: Rezaksai Reservoir, cavitation, vibration, hydraulic units, multiphase mixtures, caverns, solid boundary, pipeline, hypothesis.

Introduction.

Vortex Cavitation and Fluid Flow Dynamics

Vortex cavitation occurs at the centre of vortices, particularly in areas with significant shear stresses. There is no substantial difference between cavitation in a liquid stream and cavitation around a body moving in a stationary liquid; in both scenarios, relative velocities and pressures are critical parameters. The primary distinction is the lower turbulence level in a stationary liquid. Cavitation in a fluid flow often manifests in relatively long channels where turbulence fully develops to the cavitation zone【1,3,6】.

Vibration Monitoring in Hydroelectric Power Plants

The primary objective of vibration monitoring at hydroelectric power plants is to identify operational defects through the analysis of vibration signals from sensors installed on these units. Accelerometers measuring the absolute vibration of a turbine bearing are located in the supports of servomotors that control the rotation of the guide device blades【1】. The pipeline often acts as the causative agent of self-oscillations with positive feedback, with its vibrations influenced by the conduit system's vibrations【1】.

Comparative Analysis of Hydroelectric Power Plants

A comparative analysis of the characteristic operational zones of the Sayano-Shushenskaya and Krasnoyarsk hydroelectric power plants reveals significant similarities in the alternation of working zone parts: zone (I) allows operation; zone (II) does not recommend operation; zone (III) recommends operation; and zone (IV) prohibits operation. The recommended operation area for the hydraulic unit constitutes approximately a quarter of the total working area. The boundaries of zones (I) - (IV) are determined by the position of the guide vanes. The origin of zone (II), which is not recommended for operation, remains unclear. Hypotheses suggest that non-stationary processes in hydraulic unit operation may arise from hydrodynamic instability in the turbine's flow part or from hydroelastic vibrations occurring when hydraulic turbine blades are enveloped in a closed flow【1】.

Methodology.

Impact of Liquid Movement on Hydraulic Structures

The stability regime of hydraulic structures is influenced by the movement of liquid in pipelines, which can vary based on the properties of the components. The observed cases include:

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1. All media behave as elastic gases.
2. A mixture of elastic and perfectly plastic media.
3. A combination of elastic and elastoplastic media with re-sealing effects.
4. Elastic gases and ideally plastic media exhibiting re-laying effects.
5. Elastoplastic solid media.

These different media properties significantly impact the behavior and stability of hydraulic systems.

It is important to note that gases can be considered both ideal and viscous. Depending on which of the aforementioned combinations we are examining, the equation of motion will take the appropriate form. The potential number of equations is virtually unlimited. In this context, the pressure at a given point can be assumed to be common to all components of the medium. It is also logical to consider cases where the pressure is common to certain groups of media involved in the movement.

As is well known, all fluid flows occur in a multiphase medium, and the moving fluids themselves are multiphase. During the movement of these media, interpenetration and interaction between the phases occur【1】. The interpenetrating motion of two or more media can be considered as their movement in a porous medium. For any of these liquids (media), the rest will act as a porous medium through which they move. Therefore, the properties of a porous medium are crucial for our analysis.

Figure 1: Analysis of Cavitation Flow Photographs

Photographs of cavitation flows, conducted in the laboratory of the Institute of Mechanics and Seismic Resistance of Structures, AN Uz, provide valuable insights into the interpenetrating and interacting movements of several media, which can induce cavitation and cavitation flows. The multiphase nature of the liquid plays a pivotal role in the emergence of cavitation. During interpenetration and interaction, the velocity vectors of different phases are directed in different directions, leading to collisions that primarily cause bubbles in the liquid.

The intensity of the agitation effect from the emerging bubbles varies with the stage of cavitation development, which can be categorized into the small bubble stage and the supercavitation stage. The small bubble stage is characterized by an accumulation of cavitation bubbles, which are spherical or irregular in shape, freely floating in the liquid flow and forming a cavitation torch or cavity. As the pressure decreases, the concentration of bubbles increases, resulting in the complete removal of water from the cavitation area. This leads to the formation of a stationary cavity filled with steam in the wake of the streamlined body, with a clear vapor-liquid phase boundary, characterizing the supercavitation stage.

Design Considerations for Spillways

When designing a spillway to prevent cavitation, the engineering calculation involves determining the onset of cavitation by comparing alternative designs of its elements. The prediction of cavitation onset can be based on absolute pressure, limiting combinations of characteristic pressure and velocity, or critical parameters. Methods for predicting cavitation onset can be classified into calculated methods, which use theoretical (hydromechanical) or empirical dependencies, and experimental methods, which use laboratory research data specific to a model.

Photographic Analysis of Cavitation Flows

Analysis of the photographs (Fig. 1) of cavitation flows allows the identification of three characteristic sections of the cavity configuration. The initial section, directly adjacent to the cavitator, has a small length commensurate with the size of the cavitator. The main section extends approximately three-quarters of the theoretically determined length of the cavity. The final section has a blurred boundary not determined by calculation. Each section is characterized by unique physical processes that define the cavity configuration. This segmentation allows for separate analysis of flow at each section, with the combined solutions forming the composite cavity scheme.

Results and Discussion.

Existing models of cavitation occurrence often fail to account for numerous real factors that can significantly distort the flow pattern. Experimental values of the initial cavitation number vary significantly across different laboratories due to unaccounted factors, often attributed to a large-scale effect. The level of cavitation nuclei in the water stream, defined by gas saturation, plays a crucial role but is difficult to adjust, leading to deviations from the ideal scheme. Real water viscosity also impacts the flow, particularly in forming a boundary layer on the surface of the body, which can be laminar, transient, or turbulent.

Effect of Viscosity and Surface Roughness

Viscosity significantly alters the flow in the forward part of the body of rotation. For instance, on a cylindrical body with spherical bluntness, a local laminar flow separation, known as a "nasal bubble," is observed at the articulation of the sphere with the cylinder, establishing film cavitation at the pressure coefficient transition point. Bubble cavitation occurs slightly earlier. To reduce initial cavitation numbers, special profiling of nasal outlines, such as using the Shibe body or the Taylor laboratory flow basin body (USA), is employed. The cavitation number is critical in this context, and surface roughness significantly influences cavitation occurrence. Empirical dependence for the initial cavitation number of single roughness has been established through numerous experiments.

$$\sigma_{ш} = C\left(\frac{h_{ш}}{\delta}\right)^{a}\left(\frac{u_{\delta}\delta}{\nu}\right)^{b} \quad (1)$$

Here - height of roughness; - thickness of boundary layer; " - velocity at the boundary of boundary layer. Constants are defined for roughness of different kinds, for example, for half-spheres C=0,0106, a=0,439, b=0,298, for cones C=0,0338, a= 0,632, b=0,451.

If the single roughness is located on the curvilinear surface of the body of rotation, the corresponding initial cavitation number is defined as:

$$\sigma_1 = -C_{p.ш} + \frac{\left(1 - C_{p.ш}\right)}{\sigma_{ш}} \quad (2)$$

where is the pressure coefficient at the location of roughness, calculated by the potential theory for a smooth surface.

In the presence of distributed roughness, the initial cavitation number is closely related to the local friction coefficient C_{xf} ;

$$\sigma_2 = 16C_{xf} \quad (3)$$

The flow in the bottom region behind poorly streamlined bodies is characterized by intensive vortex formations. Bubble cavitation can occur in the vortex nuclei. The initial cavitation numbers in this case are expressed by formulas of the form:

$$\sigma_{вихр} = a + b\,\mathrm{Re}^n$$

whose coefficients are found semi-empirically. In particular, for a disk with sharp edges it is found:

$$\sigma_{вихр} = 0{,}44 + 0{,}00036\sqrt{\mathrm{Re}}\,. \quad (4)$$

Methods of predicting the onset of cavitation are subdivided into: calculated, based on the use of theoretical (hydromechanical) methods.Aerated flow is known to consist of a mixture of water and air. Air penetration into the flow occurs mainly through the free surface, in the areas of cavern formation, air cavities can be formed at the loss of wave stability on the surface. [3],[4], [5], [6].

Reynolds, Froude, and Weber Numbers

In cylindrical pipes, air is drawn into the pipe during non-pressurized, turbulent, and partially pressurized currents. This air penetration into the flow occurs due to the tangential stresses at the water-air interface. We consider the swirling flows of a non-compressible water-air mixture in a cylindrical pipe with circular cross-sections, performing translational and rotational movements (Fig. 1). It is assumed that the flow of the mixture is stationary, axisymmetric, and circulating. However, unsteady, axisymmetric, and circulating flow can also be considered with additional conditions.

Flow Assumptions and Vortex Formation

Both phases of the mixture (water and air) are assumed to be incompressible. The radial velocities of the phases are significantly less than their tangential and axial velocities. The appearance of vortices during the flow has various origins, including the presence of a swirl in the inlet part of the pipe. The site of active transformation of the flow of a water-air mixture is considered critical in the analysis.

Multiphase Flow Model

For modelling the mixture, we will use the interpenetrating multiphase media model proposed by H.A. Rakhmatulin【3】. This model provides a framework for understanding the complex interactions between the water and air phases in the flow. It accounts for each phase's distinct yet interdependent behaviors, enabling a detailed analysis of the flow dynamics within the cylindrical pipe.

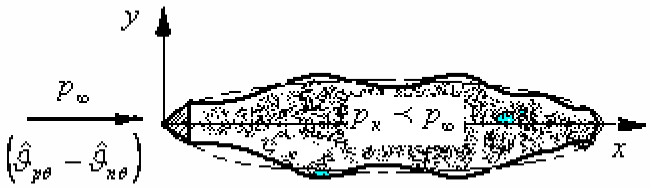

Рис.2.

Conclusion

The study of swirling flows of a non-compressible water-air mixture in cylindrical pipes involves understanding the complex interactions at the water-air interface, influenced by tangential stresses. By considering both stationary and unsteady flow conditions, and applying the interpenetrating multiphase media model, we can better predict and analyze the behaviour of such flows, including the formation and dynamics of vortices.

$$\rho_n \frac{\partial \vec{\vartheta}_n}{\partial t} + \rho_n \left[rot\vec{\vartheta}_n \vec{\vartheta}_n \right] = -\rho_n grad \frac{\vartheta_n^2}{2} - f_n gradp - \rho_n gradu_n + \mu_n \Delta^2 \left(f_n \vec{\vartheta}_n \right)$$

Where,

is the cavitation number.

$\rho_n = f_n \rho_{ni}$, $\vec{\vartheta}_n = \vartheta_{n\theta}\vec{e}_\theta + \vartheta_{nr}\vec{e}_r + \vartheta_{nz}\vec{e}_z$

- volume concentrations and true phase densities.
- velocity vector -phases of the mixture.
- components of the velocity vector -phases of the mixture in cylindrical coordinates.
- dynamic coefficient -phases of the mixture.

By introducing dimensionless parameters and taking into account the smallness of the radial velocity, we obtain a system of equations.

$$\frac{\hat{\vartheta}_{n\theta}^2}{r} = f_i \frac{\partial \hat{\rho}}{\gamma_i} + \frac{1}{Fr} \frac{\partial \hat{\Pi}}{\gamma_i}$$

$$\frac{\partial \hat{\vartheta}_{n\theta}}{\partial \hat{z}} = \frac{1}{\mathrm{Re}_i} \frac{\nu_n}{\nu_i} + \frac{\partial^2 \hat{\vartheta}_{n\theta}}{\hat{\gamma}_i^2} + \frac{1}{\hat{r}} \frac{\partial \hat{\vartheta}_{n\theta}}{\gamma_i} - \frac{\hat{\vartheta}_{n\theta}}{\hat{r}^2} + K\left(\hat{\vartheta}_{p\theta} - \hat{\vartheta}_{n\theta} \right) \quad (6)$$

The formula (6) of A. Epstein does not reflect the influence of the Euler number. [6] At small Euler numbers, taking into account the systems of equations of phase interaction, the cavitation number is defined as:

$$\sigma = \frac{p_\infty}{\frac{\hat{\rho}\left(\hat{\vartheta}_{p\theta} - \hat{\vartheta}_{n\theta} \right)^2}{2}} \quad (7)$$

Recommendations

1. Velocity of Interpenetrating and Interacting Phases:

Solutions to the systems of equations (5) and (6) enable us to determine the velocity of interpenetrating and interacting phases. The mutual penetration and interaction of these phases may induce cavitation and cavitation currents.

2. Role of Multiphase Fluid:

The primary factor in the occurrence of cavitation is the multiphase nature of the fluid. During interpenetration and interaction, the velocity vectors of different phases are directed in varying directions, resulting in collisions.

3. Cavitation-Induced Bubble Formation:

These collisions are chiefly responsible for the formation of bubbles in the liquid. This process generates seismic vibration pressures that impact the stability regime of hydraulic structures in the Rezaksai reservoir (Fig. 2).

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