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The effect of inertia and angular momentum of a fluid annulus on lateral transversal rotor vibrations

Ida Jansson[a,*], Hans O. Åkerstedt[a], Jan-Olov Aidanpää[b], T. Staffan Lundström[a]

[a] Division of Fluid Mechanics, Luleå University of Technology, 971 87 Luleå, Sweden
[b] Division of Solid Mechanics, Luleå University of Technology, 971 87 Luleå, Sweden

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ABSTRACT

An extensive amount of work exists on experimental and theoretical analysis of unsteady flow phenomena in hydraulic turbines. Still, resonance phenomena and self-excited vibrations of the rotor of hydropower machines are not considered as a major problem during normal operation conditions. Nevertheless, in development and research it is not sufficient to rely on earlier experience. An accurate predictive rotor model is crucial in risk assessment of rotor vibrations of hydraulic generator units. This paper discusses the effects of inertia and the rotational energy of the fluid in the turbine on lateral transversal shaft vibrations of hydraulic generator units. There is a lack of agreement among engineers upon how fluid inertia of the turbine should be included in rotor models. The rotational energy of the fluid has a potential risk of feeding self-excited vibrations. A fluid-rotor model is presented that captures the effect of inertia and angular momentum of a fluid annulus on vibrations of an inner rigid cylinder. The purpose of the model is to gain physical understanding of the phenomena at work and it is not applicable to specific turbines. The linearized equation of motion of the cylinder surrounded by a fluid annulus is solved for by one single complex equation. The constrained cylinder has two degrees of freedom in the plane perpendicular to its axis. By the assumption of irrotational cyclic flow, the fluid motion is described by a complex potential function. The motion of the cylinder is described by three parameters. Two surfaces are defined that splits the parameter space into regions with different qualitative behaviour. One surface defines the limit of stability whereas the other defines a limit when the eigenvalues have opposite signs or are both positive. The response to an external periodic rotating force is visualized by the magnitude of the inverse of the complex dynamic stiffness.

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1. Introduction

In design of hydraulic turbines, the trend has gone towards smaller units and lighter material that transfer the same amount of torque. Operational schemes of hydraulic turbines reflect not only technical aspects but also fluctuations of prices at the power market. More starts and stops and operation at off-design points increase wear and put the health of the machine at stake. During the last decade, hydraulic turbine manufacturers and operating companies have put attention on dynamic loads of hydraulic origin (Sick et al., 2009). An extensive amount of work exists on experimental and

* Corresponding author. Tel.: +46 920491154; fax: +46 736498147.
E-mail address: Ida.Jansson@ltu.se (I. Jansson).

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theoretical analysis of unsteady flow phenomena in hydraulic turbines. Numerical simulations are today easily accomplished to resolve unsteady features formed in the fluid, such as vortex shedding and the well-documented counterrotating vortex rope in the draft tube, and time-dependent phenomena due to interaction between static and rotating parts. The dynamic response of an unsteady hydraulic load on the hydraulic system and the turbine was investigated by several scientists and engineers, e.g. Sick et al. (2009) and Blommaert (2000). Rodriguez et al. (2007) conducted experiments on the effect of the surrounding fluid on the natural frequencies and mode shapes of a Francis runner that was compared with numerical simulations (Liang et al., 2007). Münch et al. (2010) estimated the linearized fluid-induced force on a 2D-hydrofoil in pitching motion surrounded by turbulent flow based on unsteady computational simulations and validated by experiments.

The dynamic behaviour of rotors of hydraulic turbine generator (HTG) units has not received the same amount of attention. Much of the framework of rotordynamic analysis are built on criteria of horizontal supercritical turbomachinery such as compressors and steam turbines. The dynamics of such units differ at several points from HTG units. HTG units do not have flexible couplings which implies that the dynamics of the rotor must be modelled as one single unit including the generator, the bearings and the turbine. HTG units operate in subcritical regimes and therefore self-excited vibrations and resonance phenomena are not considered as a major problem (Round, 2004; Rodriguez et al., 2007). In spite of that the fluid flow in the turbine is more susceptible to vibration problems than the rotating shaft, a proper dynamic analysis of the rotor is still necessary in new designs and also in diagnosis of faulty behaviour of hydraulic turbines. Documented evidence of vibratory problems of HTG units could be found in a number of publications. Cases of self-excited vibrations of Francis turbines are reported by Den Hartog (1984) in 1956 and in Toshiba Review in 1965 according to Song et al. (2010). The self-excited whirling motion was explained by a destabilizing fluid force in the seal opposite to the direction of the damping force. Another documented case is reported by Nässelqvist et al. (2008). In 2005 after recommissioning, violent vibrations of a 42 MW Kaplan vertical hydropower unit emanated at a frequency of 2.4 times the rotational speed. The frequency was identified as a natural frequency with low damping of the unit by rotordynamic calculations. The vibrations could not be traced to any present excitation frequency in the system. Hofstad (2004) reports on some of the peculiarities of rotordynamic analysis of HTG units. He claims that shroud forces in Francis turbines could excite self-sustained nonsynchronous vibrations at a frequency of 1.8–2.5 times the rotational speed. Vibratory problems have been reported in a number of recent publications on signal analysis of experimental data of HTG units operated at transient conditions. Roberts and Brandon (2003) studied the motion of the shaft at a location beneath the generator during transient conditions of a large Francis-type pump-turbine. The frequency spectra were visualized as a function of the rotation speed at start-up. The motion of the shaft and the static pressure variations at the turbine bottom cover pressure were acquired simultaneously during load rejection. During start-up, acoustic noise from the turbine could be detected as perturbations of the motion of the shaft. Feng and Chu (2007) stress the importance of signal analysis during transient conditions of hydropower units. They apply Adaptive Chirplet Decomposition to identify the characteristic frequency components during start-up, shutdown and load rejection. Feng et al. (2003) estimate the life damage by signal analysis and Li et al. (2009) determine a parameter defined as frequency reliability of hydraulic generator units which aims at avoiding resonance. Bettig and Han (1998) developed a rotordynamic model of a HTG unit including the turbine and the generator that could be used for predictive maintenance. The model of the turbine included Alford forces.

The Rotordynamics of turbomachinery depends largely on physical phenomena taking place in surrounding fluids. In various kinds of turbomachinery, fluids are present in fluid-filled bearings, seals and in the turbine/impeller. In fact, those fluids are part of the rotating system. Common for the surrounding fluids is the rotating character of the flow field imposed by the rotation of the shaft or the external flow field. The motion of the fluids depends on the motion of the shaft and vice versa. In fluidlubricated bearings, in seals and shrouded leakage paths, the fluids are contained in annular gaps. The fluid flow varies in those gaps ranging from laminar shear flow in hydrodynamic bearings to fully developed turbulent flow in seals and clearances. The effect on turbulent annular flow on rotor vibrations was treated by Fritz (1970). Childs (1983) studied the influence of annular seals on rotor vibrations by using the bulk-flow model developed by Hirs (1973). Antunes et al. (1996) extended Fritz' analytical model to account for the eccentricity of the rotor as well as the influence of rotor spinning velocity. The results were compared and validated by experiments (Grunenwald et al., 1996).

Perhaps the most discussed problem associated with the fluids is excitation of self-sustained vibrations (Ehrich and Childs, 1984). The rotational energy in the tangential velocity component induces a destabilizing fluid force on the shaft. Muszynska (1986) explained fluid-induced self-excited vibrations in her fluid model as the effect of fluid damping rotating at an average velocity $\lambda\Omega$, where Ω is the rotational speed of the shaft and λ denotes the fluid circumferential average velocity ratio. She claims that her model correctly predicts self-excitation induced by fluid-filled clearances in bearings, seals and leakage paths in the impeller/turbine. Apart from an asymmetric pressure field in narrow annular gaps, self-excited vibrations could arise in turbines/impellers due to

- Uneven distribution of torque.
- Impeller/turbine–volute/guide vanes interaction.

An eccentric turbine results in an uneven torque distribution. This effect is commonly referred to as Alford forces. The mechanism was identified by Alford (1965) in compressors. The German scientist explained the same phenomenon applied to steam turbines in his paper *Instabile Eigenschwingung von Turbinlaufen, Angefacht durch die Spaltstromnungen in*

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