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Experimental study of a Francis turbine under variable-speed and discharge conditions

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ABSTRACT

This work investigates the unsteady pressure fluctuations in a hydraulic turbine that are observed during steep ramping. Although hydraulic turbines are expected to operate seamlessly during steep ramping, the resulting pressure amplitudes are so significant that they take a toll on a machine's operating life. Objective of the present study is to investigate time-dependent pressure amplitudes in the vaneless space, runner and draft tube during power ramping-up and -down under variable-speed configuration. Novelty is to vary both discharge and rotational speed of a runner. The measurements are performed on a high-head model Francis turbine. The investigations revealed that amplitudes of characteristics frequencies, especially rotor-stator interaction, are small during steep ramping however, at the end of transient cycle, the amplitudes quickly increased 30-fold. During steep ramping, blade passing frequency was appeared in the runner, which is uncommon phenomenon in high-head Francis turbines. Strong reflection of pressure waves towards runner from vaneless space (guide vane walls) may be one of the causes for the appearance of blade passing frequency in the runner.

1. Introduction

Electricity is produced using both continual and intermittent types of energy sources. Competitive electricity prices and the inclination towards wind and solar energy have forced industries to utilize intermittent energy sources. This has resulted in power imbalance and frequent grid disruptions [1]. For the stable and uninterrupted operation of a power grid, demand factor (i.e. electricity demand/generation) must be maintained within the allowable limit [2]. Hydropower is considered as a vital alternative to accommodate the real-time demand after the gas turbine. The gas turbines have generally low efficiency and the cost per kWh is more than the hydropower. The large-scale power plants such as thermal, nuclear and geothermal are operated at their maximum efficiency point, and the response time is very low.

Hydraulic turbines have capability to change power output by 1–25 MW per second, depending upon turbine type and the power generation capacity [3,4]. Output power is regulated using one of three approaches: (1) low flexibility- Synchronous speed and constant discharge, (2) medium flexibility- synchronous speed and variable discharge and (3) high flexibility- variable speed and discharge. The first approach is used for run of river power plant where guide vanes are fixed permanently (or no guide vanes) to reduce the operating/maintenance cost. Turbines are operated for the fixed load depending on available head/discharge and are not applicable to meet the real-time demand. The second approach is widely used due to high efficiency and low cost. Turbines are operated at the best efficiency point (BEP) except load picking hours. Such turbines experience dynamic instability when they are operated at the off-design load, i.e. away from BEP [5–7]. Third approach provides moderate to high flexibility to meet real-time demand and stabilize the power grid when wind/solar power fluctuates rapidly [8,9]. Advantage of this approach is the flexibility of two variables, i.e. angular speed and discharge, which enables the wide range of power output and two different combinations for the same load. Thus, dynamic stability can be maintained unlike the second approach.

Currently, research is inclined towards design and development of a variable-speed turbine [2], that will accommodate increased numbers of transients cycles, i.e. start-stop/load-variation. Traditionally, turbines are designed for certain numbers of transient cycles during their operating life [10] and majority of them exceed the limit within half of their life [11,12]. Each transient cycle costs runner life equivalent to certain numbers of operating hours [13–19]. Moreover, turbine operating cost increases with the

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number of transient cycles and it becomes unprofitable to operate a turbine due to low electricity prices when wind/solar power is high. Further, when the demand is low, turbines are operated at off-design load, which causes more fatigue to the turbine (thus high operating cost) as compare to the profit margin [20–22]. The developed fatigue loading is directly associated with the unsteady pressure pulsations in the turbine [23–25].

During the transient cycle, pressure loading is not coherent as observed for steady operating conditions. The pressure amplitudes vary rapidly during load change [26,27]. Experimental studies (using second approach) on a Francis turbine showed that the pressure amplitudes during the transient cycles can vary up to three times that of the steady BEP load in short time span [28–33] depending upon the rate of guide vane movement and the runner angular speed. In a high head turbine, vaneless space (a space between runner and guide vanes) is very small [34] and the amplitudes of rotor-stator-interaction (RSI) frequencies are high. This results in time dependent stresses in the blades [35]. In addition, development of swirl in the blade passages due to guide vane movement causes flow separation and asymmetric blade loading [36]. The rate of guide vane movement is defined by considering the exterior parameters such as water hammer, surging, runner inertia and the runner torque [37]. For more reliable design of a runner, unsteady pressure loading on the blades with respect to guide vane aperture is equally important [38].

Very few numerical studies have been performed to investigate the transient operating conditions of hydraulic turbines [39]. One the key challenges is requirement of computational power to perform simulations with guide vane opening/closing, i.e., mesh deformation. To save simulation time and resources, blade and guide vane passages are modelled and good agreement between the experimental and numerical pressure loading was obtained [40–42]. The numerical results enabled to estimate the fatigue loading on the blades. However, this approach requires two-way coupling and the simulation time is extremely long due to involved complexities of structural deformation [43–45]. A new approach of turbine simulation is considered in recent years that allows coupling between 1D and 3D simulations [46]. Simulation of conduit system including penstock is performed using 1D approach whereas simulation of the turbine is performed using 3D approach. Thus, simulation time can be saved to a certain extent.

In order to cope with the variable electricity demand from end users and variable power generation from the wind/solar energy, research on variable-speed technology of hydraulic turbines is vital. Currently, it is a good alternative as it allows stable performance at off-design conditions and wide range of combinations. When both runner angular speed and discharge vary, complex pressure and velocity field is developed in the runner. Flow angle, tangential velocity and swirl component of velocity vary in time. Therefore, it is important to study how a pressure field changes for variable-speed configuration and how pressure amplitudes vary [47]. Current study focuses on: (1) how a pressure field varied with the discharge and runner angular speed, (2) what are the pressure amplitudes at different locations inside the turbine, (3) how torque/power changes, (4) what is the flow condition in the runner and draft tube when a turbine operates at the part-/minimum-load and (5) how flow condition changes when the load changes from a stable to the unstable condition, i.e. off-design.

2. Measurements

2.1. Test facility

The test rig available at the Waterpower laboratory of the Norwegian University of Science and Technology is used for the

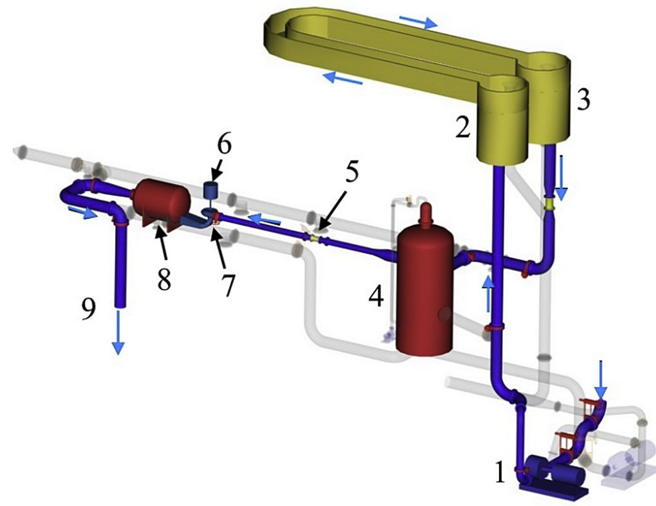

Fig. 1. Open loop hydraulic system at the Waterpower laboratory, NTNU. (1) feed pump (2) overhead tank-primary, (3) overhead tank-secondary, (4) pressure tank, (5) magnetic flowmeter, (6) induction generator, (7) Francis turbine, (8) suction tank and (9) basement.

experimental studies. This test rig is capable of operating under two configurations (closed and open loop) according to measurements. The closed loop is preferred for steady-state measurement while the open loop is preferred for transient measurements because the open loop provides hydraulic system to the prototype. Fig. 1 shows open loop hydraulic system. Water from a large reservoir (9) was continuously pumped to an overhead tank (2) then flowed down to the turbine (7). Discharge to the turbine was regulated by guide vanes. Feed pump (1) was operated at the selected speed to maintain constant head. Two pumps are driven by a 315 kW variable speed motor, and the pumps can be operated in series or parallel depending on discharge/head discharge/head requirements for the measurements. Draft tube outlet was connected to a suction tank (8) wherein a constant water level was maintained at atmospheric pressure, and water above the runner centerline was discharged to the basement (9). The open loop can produce head up to 16 m whereas the closed loop can produce a head up to 100 m (discharge up to 0.5 $m^3 s^{-1}$). For our measurements, an open loop was used to enable variable-speed configurations similar to a prototype. The investigated Francis turbine was a reduced scale (1:5.1) model of a prototype operating at Tokke power plant in Norway. The turbine included 14 stay vanes integrated within spiral casing, 28 guide vanes, a runner with 15 blades and 15 splitters, and a draft tube. The runner inlet and outlet diameters are 0.63 m and 0.347 m, respectively. Estimated Reynolds numbers are 1.87×10^6 at the runner outlet for the BEP.

The turbine runner and generator rotor were mounted on the same shaft therefore, runner angular speed was proportional to the rotor speed. For the variable-speed measurements, a developed LabView program was integrated with the governing system that allowed to regulate both guide vane movement and frequency controller at same time. However, the actual variation may be dependent on the system inertia, water mass acting on the guide vanes and the response time. Frequency response time was much higher than the data logging rate. Therefore, delay in data digitization was almost null as compared to the time-scale of load change.

2.2. Instrumentation and calibration

The Francis turbine was equipped with all instruments required to carry out model testing according to IEC 60193 [48]. Additional