Mechanical Systems and Signal Processing 48 (2014) 162–173

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Non-intrusive detection of rotating stall in pump-turbines

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ARTICLE INFO

Article history:
Received 28 November 2012
Received in revised form
28 February 2014
Accepted 11 March 2014
Available online 6 April 2014

Keywords:
Rotating stall
Pump-turbine
Off-design
Structure-borne noise
Non-intrusive monitoring

ABSTRACT

When operated far from their optimum conditions, pump-turbines may exhibit strong hydrodynamic instabilities, often called rotating stall, which lead to substantial increase of vibration and risk of mechanical failure. In the present study, we have investigated the flow filed in a model of radial pump-turbine with the help of tuft visualization, wall pressure measurement and structure-borne noise monitoring. As the rotation speed is increased, the machine is brought from its optimum operation to runaway with zero torque on the shaft. The runaway operation is characterized by a significant increase of pressure fluctuation at the rotor–stator interaction frequency. As the speed is further increased, the flow exhibits sub-synchronous instability, which rotates at 70% of the rotation frequency. Tuft visualization clearly shows that, as the instability evolves, the flow in a given distributor channel suddenly stalls and switches to reverse pumping mode in periodic way. We have also investigated the monitoring of the rotating stall with the help of vibration signals. A specific signal processing method, based on amplitude demodulation, was developed. The use of 2 accelerometers allows for the identification of the optimum carrier frequency by computing the cyclic coherence of vibration signals. This non-intrusive method is proved to be efficient in detecting the rotating stall instability and the number of stall cells. We strongly believe that it could be implemented in full scale pump-turbines.

1. Introduction

The growing demand for clean and secure energy supply is posing serious challenges to policy makers as well as industrials and researchers. There is a strong need to develop new energy infrastructures and reduce the environmental impacts at the same time. In this context, the hydropower sector is expected to play a major role in addressing the global issue of energy supply. In particular, pumped storage power plants (PSPP), which use reversible pump-turbine technology, provide highly efficient, flexible and secure way to produce and store electric energy by moving water back and forth between two reservoirs. Such power plants offer unique business opportunity in nowadays liberalized and competitive electricity market [1,2]: extra energy may be stored during valley-time and released during peak hours. PSPP are also used for electricity grid stabilization [3,4] and offer a sustainable way to store alternative energies such as solar, wind and tidal. As a consequence, modern pump-turbines are frequently switched from pumping to generating modes with prolonged operation at speed-no-load, far from their best efficiency point. Such operation may lead to large pressure fluctuation and strong vibration with an increased risk of mechanical failure.

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http://dx.doi.org/10.1016/j.ymssp.2014.03.007
0888-3270/

Nomenclature

D	impeller outlet diameter [m]
E	specific energy [J kg^{-1}]
f_n	frequency coefficient [–]
k_s	rotating stall cells number
n	impeller rotational frequency [s^{-1}]
n_{ED}	speed factor [–]
P	pressure monitoring location
p	relative wall pressure [Pa]
$\tilde{p}_E$	pressure fluctuation factor [–]
Q	discharge [m^3 s^{-1}]
Q_{ED}	discharge factor [–]
V	vibration monitoring location.
t	time [s]
T_{ED}	torque factor [–]
T_m	impeller torque [N m]
y	vibration [m s^{-2}]

Greek symbols

ρ	water density [kg m^{-3}]
Δt	delay [s]
$\Delta\varphi$	angle between monitoring points [rad]
ω	angular velocity [rad s^{-1}]

subscripts

m	envelope
o	impeller
s	rotating stall

Abbreviations

BPF	blade passing frequency
OP	operating point
PSPP	pumped storage power plant
RS	rotating stall

The so-called characteristic curve or four-quadrant diagram is the common way to represent the hydraulic performances of reversible radial pump-turbines; Fig. 1b. Depending on the signs of the discharge and rotational speed, various modes may be achieved, such as pump, brake, turbine, runaway, turbine-brake and reverse pump. Owing to IEC 60193 standard [5], dimensionless factors for speed, discharge and torque are defined by Eqs. (1)–(3). When the characteristic curve at constant guide vane opening is S-shaped; i.e. $(dQ_{ED}/dn_{ED}) > 0$ (see Fig. 1c), the operation may become strongly unstable at turbine-brake and runaway where the synchronization to the electricity grid is performed. The machine can switch back and forth from generating to reverse pumping modes involving load rejection, increased pressure fluctuations, strong structural vibrations with possible catastrophic failures, as reported by Martin [6,7].

$$n_{ED} = \frac{nD}{\sqrt{E}} \quad \text{(speed factor)} \tag{1}$$

$$Q_{ED} = \frac{Q}{D^2\sqrt{E}} \quad \text{(discharge factor)} \tag{2}$$

$$T_{ED} = \frac{T_m}{\rho D^3 E} \quad \text{(torque factor)} \tag{3}$$

The so-called rotating stall (RS) is a hydrodynamic instability associated with S-shaped characteristics, which initiates at runaway and develops at turbine-brake mode generating hydraulic unbalance and increasing structural vibrations [8]. This flow instability is thought to result from flow separations in several impeller and guide vane channels leading to propagating blockages or cells. Staubli et al. [9] reported that local vortices formed at the inlet of the impeller channels

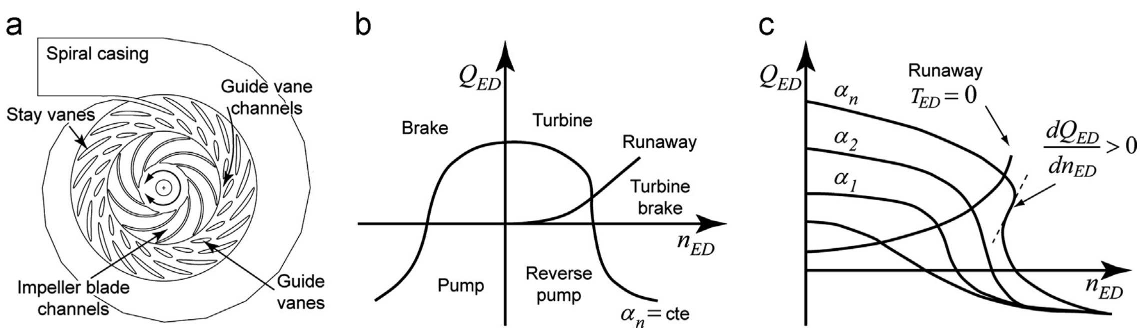

Fig. 1. Reversible pump-turbine and characteristics. (a) Machine sketch and flow paths, (b) four-quadrant diagram indicating the operating modes as a function of the discharge and rotational speed for a constant guide vane opening. (c) Characteristics at constant guide vane opening can be S-shaped, featuring positive slopes in the turbine-brake region. ((a) Reversible radial pump-turbine, (b) Operating models and (c) S-shape characteristics).