Mechanical Systems and Signal Processing 60-61 (2015) 375–390

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A cyclostationary multi-domain analysis of fluid instability in Kaplan turbines

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ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form
15 July 2014
Accepted 27 August 2014
Available online 4 February 2015

Keywords:
Hydraulic instability
Condition monitoring
Cyclostationarity
Order tracking
Rotatordynamics
Kaplan turbine

ABSTRACT

Hydraulic instabilities represent a critical problem for Francis and Kaplan turbines, reducing their useful life due to increase of fatigue on the components and cavitation phenomena. Whereas an exhaustive list of publications on computational fluid-dynamic models of hydraulic instability is available, the possibility of applying diagnostic techniques based on vibration measurements has not been investigated sufficiently, also because the appropriate sensors seldom equip hydro turbine units. The aim of this study is to fill this knowledge gap and to exploit fully, for this purpose, the potentiality of combining cyclostationary analysis tools, able to describe complex dynamics such as those of fluid-structure interactions, with order tracking procedures, allowing domain transformations and consequently the separation of synchronous and non-synchronous components. This paper will focus on experimental data obtained on a full-scale Kaplan turbine unit, operating in a real power plant, tackling the issues of adapting such diagnostic tools for the analysis of hydraulic instabilities and proposing techniques and methodologies for a highly automated condition monitoring system.

1. Introduction

The detection of hydraulic instabilities in Francis and Kaplan turbines for power generation is a key issue to avoid drastic reductions of the turbine life. High vibrations may arise in the shaft as a consequence of those abnormal pressure fluctuations in the flow, in turn causing fatigue problems on the turbine components, as shown by Presas et al. [1], Egusquiza et al. [2]. Moreover, cavitation problems are also associated with such phenomena (see for instance Ausoni et al. [3], Escaler et al. [4]), resulting in a faster degradation of the surfaces of the runner.

Hydraulic instabilities have been studied in the past mainly by means of computational fluid-dynamics (CFD) models and pressure measurements within the flow in prototype turbines. The first mentioning of vortex instabilities in a close conduct is likely due to Kelvin in 1910 [5]. His study, despite neglecting significant factors such as turbulence and viscosity, remained substantially the state of the art until the 1960. Only then, the studies by Hoffman and Joubert [6] and Kreith and Sonju [7], proved, with experimental tests, that their turbulence models could be introduced in the description of vortexes in a pipe.

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http://dx.doi.org/10.1016/j.ymssp.2014.08.026
0888-3270/

Despite the fact that investigation of flow in hydraulic turbines was considered a significant issue, as demonstrated by the experimental investigations on turbine prototypes by Wigle et al. [8], Hosoi [9] and Kolyachev and Lasenko [10], no major breakthrough was made in this application until Ruprecht et al. [11,12] finally introduced in the first years of the this century the full dynamics of a 3-dimensional unsteady turbulent flow in the simulation of a Francis turbine, including the rotor and stator interactions. Later studies, as those by Susan-Resiga et al. [13], Zhang et al. [14] and Liu et al. [15], focused particularly on vortex rope instability, which was described as an unsteady motion of vortices in the draft tube of Francis turbines, often happening in partial load conditions. Fluid-dynamical studies on Kaplan turbines are also available in the literature, such as that by Wang et al. [16], focusing on experimental measurement of the flow, and Liu et al. [17–19], implementing CFD models for the prediction of pressure fluctuations, further verified by means of a turbine prototype.

The possibility to exploit vibrations to detect and investigate the nature of such phenomena has not been analyzed before previous preliminary works by the authors on this topic [20,21]. In those papers, order tracking techniques were applied to isolate the non-synchronous part of the vibration signal and therefore highlight the harmonics which characterized the hydraulic instability in a Kaplan turbine. The preliminary investigations reported in those papers were however limited to simple first order cyclostationary indicators, like the Short Time Fourier Transform and its order domain counterpart, similarly to what is usually employed in the few studies available in the literature for Francis turbine, such as Bajic and Keller [22] and Escaler et al. [23]. In this way, it was possible to characterize the phenomenon only in relation to its periodic/deterministic behavior, while all the information carried in the random part was neglected.

As shown by Antoni [24], second order cyclostationary components are often significant, or even dominant, in the dynamics of many rotating and reciprocating mechanical systems, including fluid machines such as compressors and internal combustion motors. The concepts of cyclostationary analysis were brought from the field of telecommunications to mechanical engineering thanks to the works of Randall et al. [25] and further developed by Antoni et al. [26,27]. The basic idea of cyclostationarity is to look into periodicities of the statistical properties of the signal [28], mainly mean (first order cyclostationarity) and variance (second order cyclostationarity). While the first order tools are substantially coincident with the traditional Fourier analysis ones, the second are able to provide information on signals which have interactions between periodic and random components. In particular, second order cyclostationary tools have proven their effectiveness in describing modulations of random carriers by deterministic components and non-exactly periodic phenomena.

Despite the absence, to the best of the authors' knowledge of any study regarding cyclostationary tools applied to hydraulic turbines, the coupling of unstable and ergodic phenomena, characteristic of turbulent flows, and macroscopic cyclic behaviors, typical of fluid structure interactions, suggest the potential of such techniques for this application.

Therefore, the aims of this paper are:

1. to further detail and describe the application of first order cyclostationary tools for the detection of fluid instabilities, including the necessary domain transformations;
2. to investigate the nature of the hydrodynamic instability by means of second order cyclostationary analysis, providing a further tool for the diagnostics of hydraulic turbines.

This study will take advantage of experimental measurements on a real Kaplan turbine unit installed in an Italian power plant. The sketch of the turbine is shown in Fig. 1.

2. The Kaplan turbine

The turbine unit under investigation is shown in Fig. 2. It consists of a 7 blades runner, able to process a 91 m^3/s flow with nominal speed of 166.67 rpm (2.778 Hz), net head of 27.95 m and a maximum power output of 23.388 MW. The turbine is connected to a 18 poles synchronous generator, thus obtaining the European standard electric frequency of 50 Hz.

2.1. Finite element model

A finite element model (FEM) of the shaft, based on beam elements, has been programmed, as described in the previous work [20], to obtain an estimate of the natural frequencies and eigenmodes of the shaft for the lateral vibrations. Some model data are reported in Annex A. A sketch of the shaft-line model is reported in Fig. 3.

The first two modes, relative to the runner, are shown in Figs. 4 and 5, corresponding to natural frequencies of 6.00 Hz and 15.52 Hz for backward modes, 6.17 Hz and 19.54 Hz for forward modes respectively.

2.2. Measurement setup

The turbine unit is equipped with a series of sensors, including for vibration measurements:

- Two couple of Brüel & Kjær Vibro IN-081 proximitors measuring lateral rotor vibrations in two orthogonal directions. The sensors were installed in two different measuring planes, in correspondence of the unit bearings (turbine journal bearing – Brg. #1 and generator journal bearing Brg. #2 in Fig. 3).