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Hilbert spectrum analysis of unsteady characteristics in centrifugal pump operation under cavitation status

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ABSTRACT

Cavitation has negative influence on nuclear pump operation. In order to detect incipient cavitation effectively, experimental investigation was conducted for acquisition of current and vibration signals during cavitation process. In this research, a centrifugal pump was modeled for nuclear pump research. The data was analyzed by HHT method. The results show that Torque oscillation resulted from unsteady flow during cavitation process could result in energy variation. RMS of IMF in current signal is sensitive to cavitation occurrence. It could be regarded as the indicator of incipient cavitation. RMS variation of IMF in radial vibration signals experiences monotone increasing tendency when cavitation gets severe. Such variation regulation could be selected as the indicator of cavitation stage recognition. Hilbert-Huang transform is suitable for transient and non-stationary signal process. Time-frequency characteristics could be extracted from results of HHT process to reveal pump operation condition. The contents of current work could provide valuable references for further research on centrifugal pump operation detection.

1. Introduction

Nuclear pumps are key components of controlling water circulation in nuclear plants. Centrifugal pumps can be used as the important power equipment in the circuit of Reactor Coolant System. Thermal energy generated during cooling of reactor cores is brought out by pumps and transmitted to steam generator to produce vapor. These pumps operate at high rotating speed under the situation of high temperature and pressure during long time period. Highly efficient operation should be ensured under the situation of start-stop, accidents, earthquake, and even fire disasters. However, nuclear pumps are susceptible to the change of pressure and temperature. Cavitation could be easily induced by loss of coolant accident conditions due to low pressure in pump inlet. During cavitation process, vibration of pump system would intensify. And outlet pressure of nuclear pump would reduce, which means the thermal energy in reactor cores could not be brought off. Reactor fuel rods might melt due to the high temperature of reactor cores after long time period of operation. Thus, it can be seen that pre-alarm and detection of cavitation should be non-negligible part of nuclear plant management. The development of cavitation detection technology is necessary for ensuring the reliability and efficiency of nuclear centrifugal pump operation.

The premise of effective detection is the acknowledgement of cavitation and seal damage characterization. Cavitation is usually resulted from absolute pressure in local domain of liquid drops to a value lower than that of the liquid vapor pressure (Escaler et al., 2006). Vaporization may reduce the efficiency and reliability of pumps. Even worse, the collapse of vapor might cause a high speed micro-jet and have impact on adjacent internal metal surface. In the long time period, such unsteady flow conditions would do harm to internal surfaces of fluid-carry as well as mechanical components, such as volutes, shafts, bearings and so on (Sahdev, 2005, 2004). That is why such unexpected condition could do harm to nuclear centrifugal pumps.

Recently, research work about pump cavitation detection is increasing. There are amount of reference literatures about such research work. Perovic (2000) established a fuzzy recognition system to realize condition of cavitation, impeller crack and pump outlet blocking based on various energy intensity of current frequency. Čudina (2003) measured and analyzed the noise of pumps to prevent cavitation by means of initiating an alarm, shutdown or control signal via an electrical control system. Mohanty et al. (2012) developed a self-diagnostic capability (SDC) framework and diagnosed the impeller condition of a centrifugal pump using motor current signal analysis (MCSA) technology. Adamkowski

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et al. (2016) investigated on the pressure fluctuation spectra under cavitation status. He found that may cause the fractures of pump shafts due to the resonance.

The selection of parameters characterizing faults is significant. Conventionally, cavitation is determined by vigorous increase of noise level which is tested by acoustic emission as well as noise transducers (American Water Works Association, 2001; Stiles, 1974; Tullis, 1989). Such method is easily interfered by other disturbance factors so that could not be widely applied into noisy industrial environment (Neill et al., 1997). Motor Current Signature Analysis (MCSA) technology was utilized in operation detection and impeller crack diagnosis of centrifugal pumps, which could provide reference for cavitation prediction (Sun et al., 2017). Intensive vibration signals induced by cavitation could inversely reflect the characteristics of the fault (Dular and Petkovšek, 2015; Abd-el-Malek et al., 2017).

In general, cavitation is usually detected by pressure, noise, vibration signal transducers. But these transducers are expensive and vulnerable to external interference. In some cases, the installation of sensors are too complicated to achieve reliable data (Benbouzid, 1998). Motor current signature analysis (MCSA) technology developed since 1970s regards induction motors as torque sensors. This means cavitation could also be detected by current signals. In most research work concerning MCSA, current signal is usually processed by Fourier transform. However, all the operation information of motor and pump is reflected in current. Characteristic frequency reflecting cavitation should be retained, while the interference frequency, such as power frequency and noise, should be removed. In addition, FFT is only suitable for periodic and steady signal analysis, which has no temporal sensitivity. Since current signals are transient used in cavitation detection, Hilbert-Huang transform with high adaptive ability could be selected for time-frequency analysis of current.

From the literature review above, it could be concluded that noninvasive detecting techniques are suitable for pump fault detection. On-line detection could be realized by such techniques. Consideration of such techniques could lead to the selection of current and vibration signals as fault characterization parameters. These quantities have the advantages that they could be obtained from any existing pump system without breaking system structure. Moreover, hall sensors (measuring current signals) and acceleration transducers (measuring vibration signals) are cheap and conveniently installed.

In this manuscript, both vibration and current signals were acquired and analyzed by HHT, in order for further validation of the availability and accuracy of MCSA method. Meanwhile, characteristic frequency reflecting cavitation could be extracted in signal Hilbert spectrum.

2. Theoretical analysis

The realization of MCSA (Motor Current Signal Analysis) method is based on the working principle of motor and the interaction with its driven devices. The voltage balance and motion equations are expressed as following:

$$\begin{cases} u = Ri + L\frac{di}{dt} + \frac{dL}{d\theta}\omega i \\ T_e = T_L + \frac{J}{p_n}\frac{d\omega}{dt} \\ \omega = \frac{d\theta}{dt} \end{cases} \quad (1)$$

In the voltage balance equation, the second and third items are electromagnetic induction electromotive force. $L\frac{di}{dt}$ is pulsation variable electromotive force caused by current variation. $\frac{dL}{d\theta}\omega i$ is rotational electromotive force resulted from relative position between rotor and stator which is proportional to rotating speed ω, u, R, I, L are motor voltage, resistance, current and inductance respectively (Zhang, 2006).

Since the power network capacity is quite large, the stator voltage of on-load running is constant, not varying with load change. The stator current would respond to keep balance of the equation when ω is disturbed with load variation.

The motion equation shows the dynamic balance of motor torque. In the equation (Luo et al., 2015a,b), T_e is electromagnetic torque, T_L is load torque including friction torque, J is rotary inertia, p_n is motor pole-pairs, ω is rotating speed, θ is mechanical angle.

From the analysis based on the equations above, ω is disturbed by load variation, which would result in the current change. Torsional vibration of shaft system caused by complicated flow in centrifugal pumps may change the air-gap magnetic field in the motor during pump operation. According to the motion equation, stator current will respond to change of T_e because of the variable load, which could make the equation reach new equilibrium. Thus, unsteady operation characteristics of centrifugal pumps could be reflected in current signal.

3. Experiment

3.1. Pump model

Centrifugal pumps are important components in nuclear power plants used for reactor coolant system. Considering the time and money cost of the experiment investigation, a centrifugal pump IS65-50-160-00 was selected as the pump model for experimental investigation. Specifications of the pump are given in Table 1. And the motor Y160M-2 B3 was selected as the model in pump system. Specifications of motor model is shown in Table 2.

3.2. Test rig

The experiment was carried out in National Research Center of Pumps of Jiangsu University. The test rig is shown in Fig. 1. The scheme of test rig is shown in Fig. 2. It mainly consisted of a water tank, a test centrifugal pump, an electric motor, a vacuum pump, a suction line and a discharge line. All these elements formed a

Table 1
Main parameters of IS65-50-160-00 centrifugal pump.

Name	Symbol	Value
Designed flow rate	Q_d	50 m^3/h
Designed head	H_d	34 m
Rated speed	n	2930 r/min
Efficiency	η	72.8%
Specific speed	n_s	89.51
Impeller inlet diameter	D_1	74 mm
Impeller outlet diameter	D_2	174 mm
Impeller outlet width	b_2	12 mm
Blade number	Z	6
Volute base circle diameter	D_3	184 mm

Table 2
Main parameters of Y160M-2 B3 electric motor.

Name	Symbol	Value
Rated voltage	U	380 V
Rated speed	n	2930 r/min
Efficiency	η	89.4%
Rated power	P	15 kW
Pole Number	n_P	2
Power factor	$cos\varphi$	0.89