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A vibration cavitation sensitivity parameter based on spectral and statistical methods

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ABSTRACT

Cavitation is one of the main problems reducing the longevity of centrifugal pumps in industry today. If the pump operation is unable to maintain operating conditions around the best efficiency point, it can be subject to conditions that may lead to vaporisation or flashing in the pipes upstream of the pump. The implosion of these vapour bubbles in the impeller or volute causes damaging effects to the pump. A new method of vibration cavitation detection is proposed in this paper, based on adaptive octave band analysis, principal component analysis and statistical metrics. Full scale industrial pump efficiency testing data was used to determine the initial cavitation parameters for the analysis. The method was then tested using vibration measured from a number of industry pumps used in the water industry. Results were compared to knowledge known about the state of the pump, and the classification of the pump according to ISO 10816.

1. Introduction

There are 13 well defined fault modes of a pump, some of which are detectable using vibration monitoring. Cavitation is found to be one of the most common fault modes appearing in centrifugal pumps in industry due to the inability of the end user to constantly maintain the minimum needed pressure in the pipelines upstream of the pump. Usually undetectable upon inception, its presence during normal operation of the pump are usually not noticed until its effects have done considerable damage to the pump, (McKee, Forbes, Mazhar, Entwistle, & Howard, 2011a, 2011b).

This paper presents a method utilising adaptive octave band analysis techniques, where the octave bands are centred on the pump running speed, and statistical methods to determine the presence of cavitation using the measured centrifugal pump vibration velocity. A review of the state of the art in cavitation detection is presented in Section 3. Section 4 then explains the theory behind the proposed method. The final sections of the paper then briefly describe the methodology and procedure used, and the results of case studies where the method has been applied to vibration data measured from industrial centrifugal pumps.

2. Cavitation

Cavitation is the formation of vapour bubbles in a moving fluid and their subsequent implosion within the centrifugal pump. The effects of this fault mode may have devastating impacts on the centrifugal pump, such as extreme local heating, high local pressures, energy being released, and extensive pitting on the impeller which would render the impeller inoperable, (Cudina, 2003; Yedidiah, 1996). Cavitation damage, which occurs on the low pressure or the visible surface of the impeller inlet vane, is accompanied by four symptoms: erosion via pitting of the impeller, a sharp crackling noise which is sometimes compared to pumping stones, high amplitude vibration, and a reduction in pumping efficiency, (McKee et al., 2011a, 2011b; Palgrave, 1989; Rayner, 1995).

Pump designers attempt to avoid cavitation by taking into account the high and low capacities of the system when designing pumps, resulting in pumps that are most comfortable operating in the range of 90–110% of their best efficiency point (BEP). However, problems arise since the majority of centrifugal pumps are forced to operate outside of this region, (Forsthoffer, 2011).

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3. State of the art in cavitation detection

Detection of the onset of cavitation is a difficult task to achieve. A large number of methods have been investigated to be able to predict and diagnose cavitation within pumps during operation. Despite the promising results from a number of reference works, no single method has been shown to be able to be deployed in all field situations.

M. Cudina utilised microphones to detect the onset of cavitation. Placing the microphones near the centrifugal pump, it was determined that a discrete frequency tone of half the blade pass frequency was distinct from the noise associated with the pump and thus was a clear indication of the onset of cavitation and its development. In later studies, Cudina et al. determined that this distinct frequency was a function of the pump's design, such as the pump's geometry and material used, (Cudina, 2003; Černetič & Čudina, 2011; Čudina & Prezelj, 2009). The problems with this analysis are (1) it would be difficult for a technician to implement the detection method without knowing intricate information about the pump, and (2) surrounding noise from the environment could cause background noise interference in the signal, thus resulting in difficulty and possible inability of finding the distinct frequency stated by Cudina. The use of vibration analysis to determine faults have been proven to be a more reliable method of fault detection over audible measurements.

Neil et al. and Alfayez et al. performed industrial scale tests to determine if acoustic emission sensors are able to detect cavitation. Both cases were found to show the onset of cavitation, while only one was able to show its existence. As a result, if acoustic emission sensors were to be used on a centrifugal pump, they would have to be attached on the pump from the factory and then observed frequently. They cannot be placed onto a used pump that has an unknown condition since the sensors are only able to reliably show the onset, and not the development of cavitation. In addition, although empirical evidence supports the validity of using acoustic emission sensors to detect incipient cavitation, limited evidence of the effectiveness of this technique for a wide range of industrial environments is found, (Alfayez, Mba, & Dyson, 2005; Neil, Reuben, Sandford, Brown, & Steel, 1997). This is opposed the proposed vibration analysis for cavitation, which can be used to detect cavitation in all its stages, from inception to complete development.

Cavitation models attempt to incorporate all factors involved in an effort to predict the behaviour of the cavitating state. However, despite their high accuracy, models have difficulties modelling the nonlinearities of cavitation as well as being insensitive to the operating point, (Athavale, Li, Jiang, & Singhal, 2002; Hofmann, Stoffel, Coutier-Delgosha, Fortes-Patella, & Reboud, 2001; Kallesoe, Cocquempot, & Izadi-Zamanabadi, 2006; Kallesoe, Izaili-Zamanabadi, Rasmussen, & Cocquempot, 2004; Uchiyama, 1998). As a result, a number parameters needed to accurately tune the model are difficult to obtain, and thus need to be assumed when not readily available. This leads to the development of inaccurate models. The proposed method for detecting cavitation removes the need to determine these modelling parameters and relies solely on the accepted levels of vibration velocities, which can be obtained using robust industrial accelerometers.

Some methods of cavitation detection utilise data other than vibration in their analysis. Methods such as measuring inlet pressure fluctuations are a good indicator of cavitation and have been shown to be more sensitive than comparing the actual net positive suction head (NPSHa) to the required net positive suction head (NPSHr). However, it is sometimes difficult to obtain this data due to the alterations that must be done to the pump to secure the instrumentation, (Franz, Acosta, Brennen, & Caughey, 1990; Jensen & Dayton, 2000; Lee, Jung, Kim, & Kang, 2002; Rapposelli, Cervone, Angelo, & d'Agostino, 2002). Other forms of analysis are able to use methods of non-destructive testing, such as the use of accelerometers, which attach to the outside of the pump without the need to alter it in any way to detect vibration. This saves time in the implementation phase of the method.

Parrondo et al. created an expert system that attempted to detect the existence of six abnormal situations including flow rate greater than the best efficiency flow rate, lower flow rate, cavitation partially developed, cavitation fully developed, presence of an obstacle in the inlet conduit and rotational speed greater than or lower than the specified value. Although its classification of the pump's fault mode was correct on the lab tested setup, the effectiveness of adapting such a system to other industrial pumps was not attempted, (Parrondo, Velarde, & Santolaria, 1998). Similarly, Yang et al. (Yang, Lim, & Tan, 2005) created an expert system for fault detection for centrifugal pumps which also incorporated decision trees. The problem with expert systems is that they are normally system specific. In this case, 6 abnormal situations were attempted on a single system. However, parameters change based on factors such as the environment, size of pump, size of motor, and load; and thus, more investigation is needed to create a more versatile expert system. The proposed method for detecting cavitation is not limited by factors in the environment, and has been shown using experimental data to work on a variety of centrifugal pumps in different environmental conditions. As a result, it has been demonstrated to be more versatile and robust than Parrondo et al.'s expert system.

Sakthivel et al. and Azadeh et al. created a fuzzy logic system to identify up to 19 failure modes of a centrifugal pump. Classification was based on statistical features of a vibration signal, such as mean, standard deviation and kurtosis, as well as a few other measurable quantities, such as flow rate, discharge pressure and temperature. Empirical evidence shows moderate results of classification of the multiple faults, (Azadeh, Ebrahimipour, & Bavar, 2010; Sakthivel, Sugumaran, & Nair, 2010). The difficulty associated with using fuzzy logic systems is the complexity in the creation of the fuzzy rules, which are usually done by hand, and their limits. Despite this problem, the papers only provide verification for their work based on one pump each. The method proposed has been tested on a number of different centrifugal pumps, which shows its robustness in industrial applications.

Sakthivel et al. further created a vibration based fault diagnostic system using a decision tree for a monoblock centrifugal pump. It utilised 9 different statistical features from the data, such as standard error, standard deviation, and kurtosis, to separate the data and detect if one of 5 different fault conditions were present in the pump. The faults that were simulated and tested for are bearing fault, seal fault, impeller fault, bearing and impeller fault together, and cavitation. The C4.5 decision tree algorithm was used to create the decision tree for classification, and resulted in a 100% accuracy for the training data and 99.66% accuracy for the testing data (Sakthivel, Sugumaran, & Babudevasenapati, 2010). Sakthivel et al. had only tested their method on a single pump, and surmise that the same method can possibly be used in general on all pumps. One of the largest problems with using decision trees is training the system. Care must be given so as to not overtrain or under-fit the data. Overtraining will result in good results, such as that given, for the training data, and possibly from the testing data if they all come from the same source. However, taking the newly over-trained decision tree and presenting it with data from an unseen pump may result in poor results. Under-fitting will produce similar results for the test case, but can also produce poor results for the training case as well. The method proposed has been tested over a range of different sized pumps in a range of different conditions to show its robustness.