Fault diagnosis of tilting-pad type fluid film bearings in high-speed rotating machinery

Kyung Ho Sun[1], Dong Hyuk Kang[2], Byeong Ock Kim[3], Jai-Kyung Lee[4],and Donghyun Lee[5]

[1,3,4,5]*Korea Institute of Machinery & Materials, Daejeon, 34103, Korea*

sunkh@kimm.re.kr
kbo2612@kimm.re.kr
jkleece@kimm.re.kr
donghyun2@kimm.re.kr

[2]*Department of Mechanical Engineering, Chungnam National University, Daejeon, 34519, Korea*

dynimite89@cnu.ac.kr

ABSTRACT

Of all fluid film bearing types, tilting pad bearings offer the optimal rotordynamic stability due to their excellent stiffness and damping characteristics. Due to the reduction in cross-coupling stiffness, tilting pad bearings are ideal for use in high-speed and high-load turbomachinery applications, such as industrial compressors and steam/gas turbines. In this investigation, we propose the method to diagnose the main failure mode of tilting pad journal bearings such as babbitt metal wear and pivot wear in bearing pads. Various experimental cases for bearing wear were precisely implemented through a high-speed rotating test rig operating at 10,200 rpm. The vibration and temperature data were obtained through a condition monitoring system and various features from shaft vibration, bearing metal and lubrication temperature data were extracted for the fault diagnosis. In this study, we have shown that even defects due to the abrasive wear of fluid film bearings including general rotor faults, such as unbalance, misalignment and rubbing, can be accurately diagnosed.

1. INTRODUCTION

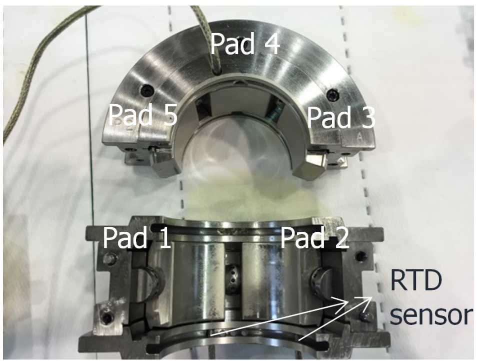
In industrial turbomachinery, such as steam / gas turbines and compressors, bearings are one of the most critical key elements for the reliable operation of the rotating system. Since these turbomachinery require high-speed and high-load capacity, oil lubricated bearings are generally used. Among them, tilting pad bearings which provide the highest rotordynamic stability has been widely used in many applications. In recent decade, PHM (Prognostics and health management) researches on rotating machines have been studied by combining with machine learning and artificial intelligence, and this research trend is expected to accelerated along with the development of IIoT (Industrial internet of things) technology and big data with the advent of the forth industrial revolution era. The data-based PHM researches on rotating machines have been investigated because of high diagnostic efficiency, despite the inherent difficulty of requiring hazardous experiments to obtain the fault data. However, most of the existing researches (Nembhard et al. (2015), Jung et al. (2017)) rarely simulate the lubrication characteristics of a practical rotating system because they use relatively low-speed rotating data for rotor-bearing systems supported by simple bearings. Also, the referred studies have focused only on the fault diagnosis of a rotating shaft in rotor-bearing systems.

In this study, we propose a method to diagnose abrasive wear of tiling pad bearings in addition to general fault diagnosis of the rotating shaft. For this purpose, a high-speed rotating simulator equipped with tilting pad type oil lubricated bearings (Branagan (2015)) mostly used in practical industry applications were designed and manufactured for our PHM research. Fault data were obtained by precisely simulating unbalance, misalignment, and rubbing, which are representative shaft fault modes. The abrasive wear and pivot wear of the bearing were also simulated and used to diagnose the bearing failure. The characteristics of the acquired data were extracted in time and frequency domain, and temperature data related to bearing metal and lubrication were also extracted. We verified the classification accuracy by applying various machine learning algorithms and confirmed that the extracted temperature characteristic is the most important factor in diagnosing fault mode of bearings.

2. EXPERIMENTAL SET UP

As shown in Fig. 1(a), the experimental facility is built to conduct the high-speed and high-load rotating experiments. The facility consists of a driving system, rotor-bearing system, data acquisition system, lubrication system, cooling system and monitoring system. The weight of rotor is 105 kg and the maximum rotating speed is 15,000 rpm. The rated speed used in this experiment is 10,200 rpm and tilting pad bearings have five pads. This type of bearing is typically installed to carry a static load in between pads (LBP) shown in Fig 1(b).

(a)



(b)

Figure 1. (a) Experimental facility and (b) tilting pad bearings inserted with RTD sensors.

In this study, we experimentally simulated three types of shaft fault modes, such as mass imbalance, misalignment, and rubbing, as well as two types of bearing fault modes, such as bearing metal wear and pivot wear. The unbalance fault was implemented according to the standard (ISO 1940-1) by adding an additional known mass and a thin steel shim was inserted down to the base of bearing pedestals to give the desired misalignment effect. The rubbing fault was induced using the contact of a labyrinth seal made of aluminum. The local wear of the bearing metal was partially offset by 10, 20, and 30 μm, and the pivot wear of the tilting pad was machined to a level of 20 μm by grinding as shown in Fig. 2.

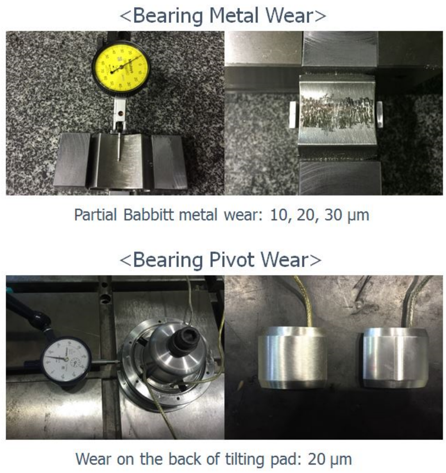


Figure 2. Configuration of the worn bearings

The vibration response of the rotor is measured by four proximity probe in mutually perpendicular ($+45^{\circ} \sim -45^{\circ}$) directions. The bearing metal temperatures are measured by six RTD sensors inserted into tilting pads (pad 1, 2, 4) and lubrication temperatures, such as oil supply & discharge temperature, are measured by thermocouple sensors. All data were acquired in a 10,200 rpm steady-state condition for 120 seconds (60 seconds for the training data and 60 seconds for the testing data).

3. RESULTS

A supervised learning is usually applied to the fault diagnosis of rotating machinery. In this study, as shown in Table 1, eight time-domain features, eight frequency-domain features and five temperature features were selected to separate the obtained data into their respective fault modes. Seven machine learning algorithms, such as k-nearest neighbor (KNN), decision trees, naïve Bayes, discriminant analysis, support vector machine, bagged trees and artificial neural network, were applied to classify the data. In Table 2, it is shown that the best diagnosis result is provided when bearing metal and lubrication temperature related features are used with time and frequency features. This is because fault modes, such as misalignment and bearing wear, that cause oil film thickness changes are highly sensitive to temperature change. Therefore, it is important to carefully monitor the fine temperature changes of the bearings. Figure 3 shows the classification results by using bagged trees algorithms for the six states of normal, unbalance, misalignment, rubbing, bearing metal wear and pivot wear.

Table 1. Time, frequency and temperature features

Time	Feature1	Maximum
	Feature2	Absolute Mean
	Feature3	peak2peak
	Feature4	Skewness
	Feature5	Kurtosis
	Feature6	Crest factor
	Feature7	Shape factor
	Feature8	Impulse factor
Freq-uency	Feature9	Frequency center
	Feature10	RMSF
	Feature11	0.5X/1X
	Feature12	2X/1X
	Feature13	(3X~5x)/1X
	Feature14	(3X,5x,7x,9x)/1X
	Feature15	(2X~10x)/1X
	Feature16	(0.01X~0.99x)/1X
Temp-erature	Feature17	Pad1- supply temp.
	Feature18	Pad2- supply temp.
	Feature19	Pad4 - supply temp.
	Feature20	Pad2 - Pad1
	Feature21	supply temp. - discharge temp.

Table 2. Classification results using seven machine learning algorithms

Features / Machine Learning	Time	Time+ Freq.	Time+Freq .+Temp.	비고
K-nearest Neighbor (kNN)	87.79 %	92.07 %	96.17 %	k=5
Decision Trees	83.71 %	90.26 %	93.52 %	·
Naïve Bayes	76.21 %	74.25 %	92.05 %	kernel
Discriminant Analysis	55.69 %	79.98 %	92.21 %	·
Support Vector Machine	65.29 %	80.43 %	96.38 %	Linear kernel
Ensemble: Bagged Trees	87.26 %	94.02 %	98.67 %	50 learning cycles
Artificial Neural Network (ANN)	79.26 %	90.24 %	96.21 %	# of hidden-layer neurons=60

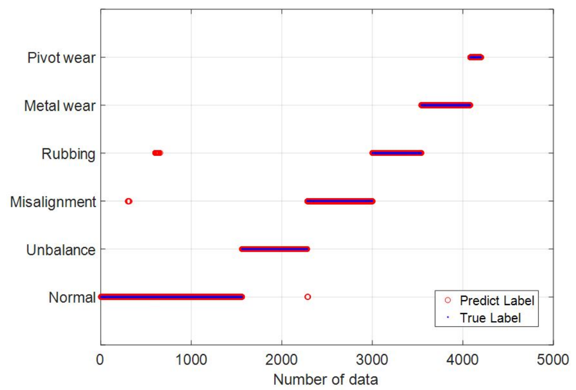


Figure 3. Classification results for health state

4. CONCLUSION

In this study, we have shown that wear of fluid film bearings can be accurately diagnosed, including common rotor defects such as unbalance, misalignment and rubbing. The specific achievements in this investigation may be summarized as:

1. An experimental test rig for high-speed and high-load rotating machinery equipped with tilting pad type oil lubricated bearings was constructed.
2. The fault data of the worn oil lubricated bearings were obtained and used for the first time to diagnose the fault of high-speed rotating machinery.
3. It is important to use the bearing temperature data in addition to the vibration data to fully detect the failure mode of the rotating machinery.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Machinery & Materials (KIMM) Grant No. NK203B.

REFERENCES

Nembhard, A. D., Sinha, J. K. Yunusa-Kaltungo, A. (2015), Development of a generic rotating machinery fault diagnosis approach insensitive to machine speed and support type. *Journal of Sound and Vibration*, vol 337, pp. 321-341. http://dx.doi.org/10.1016/j.jsv.2014.10.033

Jung, J. H., Jeon, B. C., Youn, B. D., Kim, M. & Kim D. (2017) Omnidirectional regeneration of proximity sensor signals for robust diagnosis of journal bearing systems. *Mechanical Systems and Signal Processing*. Vo. 90, pp. 189-207. http://dx.doi.org/10.1016/j.ymssp.2016.12.030

Branagan, L. A. (2015) Survey of damage investigation of babbitted industrial bearings. *Lubricants*. Vol 3, pp. 91-112. Doi:10.3390/lubricants3020091

International Standards Organization (ISO) (2003). Mechanical vibration – Balance quality requirements for rotors in a constant state- part 1: Specification and verification of balance tolerances. In ISO, *ISO1940-1:2003. Guidance for balance quality grades for rotors in a constant state, I. O. f. S.* (ISO), (p. 11). Genève, Switzerland: International Standards Organization.

BIOGRAPHIES

Kyung Ho Sun received his Ph.D. degree in mechanical engineering from Seoul National University, Seoul, Korea, in 2010. Currently, he is a principal researcher at Korea Institute of Machinery and Materials (KIMM). His main research field is the condition monitoring and diagnosis of high-speed rotating machinery, and the optimal design of multiphysics systems including transducers, smart materials and structures.