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Integrity assessment of large rotating machine components based on their resonance characteristics (2)
-- An algorithm for anomaly detection--

大型回転機部材の共振特性に基づく健全性評価 (2)
-- 異常診断アルゴリズム --

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1. Introduction

It is important to shorten the downtime for integrity assessment to extend availability of power generators. Conventionally, a crack inspection of wedges, which are components that lock coils in the rotor of a generator, takes one month or longer because the rotor is required to be extracted from the stator of the generator.

For inspection without rotor extraction, Katayama, et. al. proposed an inspector robot that crawls the rotor surface and inspects wedges by ultrasonic testing[2]. Vibration testing techniques using piezoelectric actuators are also proposed for higher resolutions, where cracks of submillimeter depth are detected from resonant frequency shifts[3].

In the vibration testing techniques, resonant frequencies of target samples are compared to those of a reference sample[4]. However, it is difficult to replicate the installation state of the reference sample due to a large mechanical load. Moreover, resonant frequency detection is sensitive to measurement noises.

In this paper, we propose a new algorithm for robotic wedge inspections using the vibration testing. In our algorithm, cracks of wedges are detected as outliers in frequency responses, so that no normal sample is required as a reference. We also illustrate the validity of our algorithm by experimental results.

2. Algorithm for anomaly detection

First, we introduce a similarity between frequency responses of a pair of wedge samples. Let $X_i(f)$ denote a frequency response of ith sample at a frequency f, and $\bar{X}_i$ denote an average of $|X_i(f)|$ over all measured frequencies $f_1, \dots, f_M$. The similarity between i th and j th sample is defined by

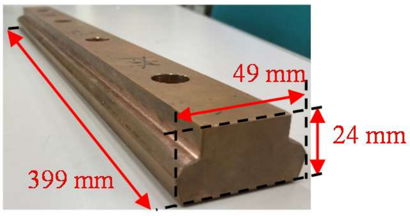

Fig. 1 A wedge for the experiment to illustrate the validity of our algorithm in Section 3.

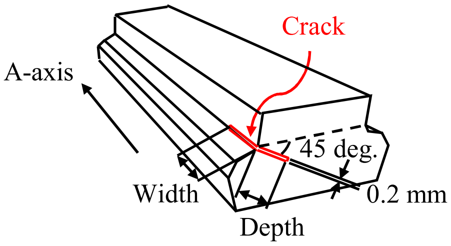

Fig. 2 The position, the size and the shape of an imitated crack.

$$s_{ij} := \frac{\sum_m c_{ij}^m}{\sqrt{\sum_m c_{ii}^m}\sqrt{\sum_m c_{jj}^m}}, \tag{1}$$

where

$$c_{ij} := \left(|X_i(f_m)| - \bar{X}_i\right)\left(|X_j(f_m)| - \bar{X}_j\right). \tag{2}$$

The similarity between a normal sample and a cracked sample is expected to be significantly smaller than that between a pair of normal samples, that is close to 1. In contrast to the resonant frequency detection, the similarity is highly robust to noises by using many frequency bins.

Let us assume that only a few samples have cracks. Then most of similarities in $\{s_{ik}\}_{i \neq k}$ are close to 1 for a normal sample k, but significantly smaller than 1 for a cracked sample k. Therefore cracked samples are detected by the outlier degree defined by

$$A_i := \mathrm{median}_{i \neq j}\, s_{ij}, \tag{3}$$

which is close to 1 for a normal sample, and significantly smaller than 1 for a cracked sample.

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Table 1 Positions and sizes of cracks.

#	Position	Depth	Width
1	Center	0.5 mm	1.0 mm
2			10.0 mm
3		5.0 mm	1.0 mm
4			10.0 mm
5	Edge	0.5 mm	1.0 mm
6			10.0 mm
7		5.0 mm	1.0 mm
8			10.0 mm

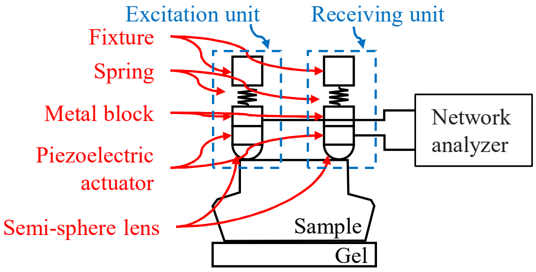

Fig. 3 Measurement system of frequency responses of wedge samples.

3. Experimental results

In this section, we illustrate the validity of our algorithm by an experiment, in which frequency responses of normal and cracked wedges are measured. And it is verified that the cracked wedges are detected correctly.

The wedges, shown in Fig. 1, are made of Beryllium copper, and the shape of the wedges is designed according to lietratures[1,5]. The cracks are imitated by slitting wedges by electric discharge machining as shown in Fig. 2. The position on A-axis, the depth, and the width of the crack is varied for each sample as shown in Table 1.

In Fig. 3, we show the measurement system for this experiment. A wedge sample is isolated in the manner of vibration by a gel sheet, and combined with an excitation unit and a receiving unit by spring whose thrusting force is 15 N. In both units, vibration of the sample is bidirectionally propagated to a piezoelectric actuator (PC4FL, Thorlabs) via a semi-sphere lens (PKFESP, Thorlabs), which contacts on the top surface of the sample beause the surface is accessible by inspector robots. A metal block that weighs 8.7 g is bonded on the back side of the piezoelectric actuator to decrese the gap of acoustic impedance. A network analyzer (AnalogDiscovery2, Digilent) measures the frequency responses between the excitation unit and the receiving unit at every 12 Hz from 30 kHz to 70 kHz. The resonant frequency shifts derived from cracks are known to appear in this range of frequencies[3].

We applied our algorithm to datasets composed of five normal samples with each cracked sample in Table 1. The resulting outlier degrees are shown in Fig. 4. The outlier degrees of cracked samples are less than 0.95, while those of normal samples are all greater than 0.95, so that cracks are correctly detectable by a threshold deciding.

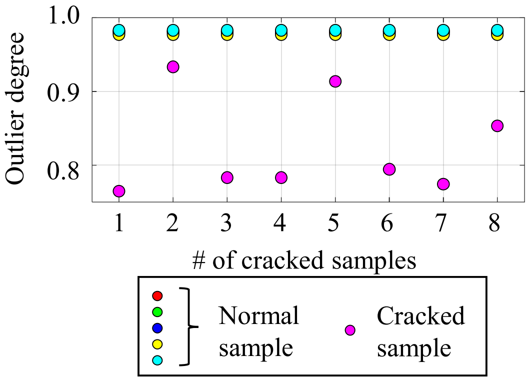

Fig. 4 The resulting outlier degrees of normal and cracked wedges.

4. Conclusion

We have proposed a new algorithm for robotic wedge inspections using the vibration testing. In our algorithm, a cracked wedge is detected based on the outlier degree of each wedge sample. The outlier degree of a sample is calculated from the similarity between the frequency responses of the sample and the others, so that no normal sample is required as a reference. The validity of our algorithm is illustrated by an experiment, in which 8 kinds of imitated cracks are correctly detected.

The minimum depth of detected cracks is 0.5 mm. This result implies high sensitivity of our algorithm enough to practical wedge inspections.

References

1. G. Klempner and I. Kerszenbaum: *Operation and Maintenance of Large Turbo-Generators* (Wiley-IEEE Press, NJ, 2004) p. 274.
2. H. Katayama, F. Sato, Y. Gunji, T. Ishikawa, A. Matsuzaki, and H. Shimada: Water and Energy International **62(7)** (2019) pp. 19-23.
3. H. Mine, J. Wu, Y. Mizuno, and K. Nakamura: Proc. of Symp. on Ultrasonic Electronics, **39** (2018) pp. 29-31.
4. T. Arai, T. Yagi, and H. Torii: JP2008232763A (2008).
5. T. Matsushita and S. Kimata: JP2006296064A (2006).