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Experimental Fault Detection in Rotating Machines Based on the Modal State Observer Approach

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Abstract: *In this paper, a fault detection methodology based on the so-called modal state observer is applied for detecting transversal cracks in a horizontal rotating shaft. The Luenberger state observer is formulated in the modal domain to estimate the rotor vibration responses described in the modal domain. Consequently, the most affected vibration modes due to the crack existence can be determined. The kernel density estimator is applied to quantify the influence of a crack over the dynamic behavior of the rotor. The time domain vibration responses measured directly on the rotating machine are used for comparison purposes. An experimental investigation is presented by considering both breathing and open cracks. The breathing behavior of the crack is simulated according to the Mayes model. The additional flexibility introduced in the shaft by the crack is determined by using the linear fracture mechanics theory. The obtained results demonstrated that the methodology conveyed represents a good alternative technique to detect faults in rotating machines.*

Keywords: rotating machinery, fault detection, transversal cracks, Luenberger state observer, modal state observer.

INTRODUCTION

The development of health monitoring techniques for crack detection in shafts of rotating machines was motivated by a series of accidents, such as the catastrophic failure occurred in a General Electric turbine in the 1970s [1]. Considerable academic effort on crack detection techniques was observed along the 1980s, resulting high economic impact in various industries. Researches on structural health monitoring (SHM) techniques for early fault detection has been growing since then.

According to Cavalini et al. [2], there are several SHM techniques proposed in the literature for crack detection in rotating machines. Some methods have proved to be costly since satisfactory results rely on detailed and periodic inspections [3]. As a full stop of the machinery is required for inspection, production losses proportional to the time spent on inspection is verified. Therefore, techniques based on vibration measurements are recognized as promising SHM tools [2, 4, 5] in the context of rotating machinery.

SHM techniques based on the vibration signals are sensitive to mass, damping, and stiffness changes on the structure, which may indicate the presence of faults [6]. According to Cavalini Jr et al. [7], nowadays it is already possible to identify incipient cracks in rotors by applying sophisticated SHM methods. As mentioned, various SHM techniques can be applied in rotating machines aiming at fault detection. In industry, rotor cracks are commonly detected by changes in the amplitudes of the harmonics, especially on the 2X and 3X vibration components, which are continuously monitored. Additionally, crack detection can be also performed by using model-based methodologies [8], such as combination resonances [9], state observers [10], and approaches in the modal domain, devoted to the monitoring of natural frequencies and mode shapes [11].

It is well known that time domain vibration responses are more sensitive than modal characteristics for performing fault detection in mechanical systems. However, interesting information can be obtained by monitoring modal parameters. Only converting the time domain vibration responses to the modal domain does not ensure that it will become more sensitive to the fault presence. Thus, it is necessary to apply a technique able of deriving the fault signatures from the time to the modal domain. In this sense, the modal state observer (MSO) technique [11] appears as an interesting alternative, combining the main advantages of both time and modal domains analyses.

The MSO is able to convert vibration responses from the time domain to the modal domain. The mathematical model of the healthy system is incorporated into the MSO, which is tuned to estimate the vibration responses of the system for its healthy condition. Then, the estimated modal vibration responses are compared with a baseline (i.e., modal vibration response of the healthy rotor) for crack detection purposes. Additionally, MSO serves as a filter designed specifically for crack detection in combination with the mathematical model of the system [11].

In this context, the present paper aims at detecting transversal cracks existing along the shaft of a horizontal rotating machine by using the MSO technique, as proposed by Cavalini Jr et al. [11]. For this purpose, an experimental investigation is presented aiming at highlighting the efficiency of the MSO technique.

MODAL STATE OBSERVER

The SHM technique based on MSO was proposed by Cavalini Jr et al. [11], in which faults were detected in a truss like structure (numerical investigation). Figure 1 shows the scheme of the SHM technique based on MSO. The representative model of the healthy mechanical system described in modal coordinates has to be identified first. In this case, the model is represented by the block-diagonal state space form [12]. The system condition is continuously monitored by the MSO from the measured vibration responses, which are represented by the vector $\mathbf{y}_u(t)$ in Fig. 1. The vector $\mathbf{y}_h(t)$ represents the vibration responses in the time domain of the healthy system. Any deviation between the obtained modal state vector $\hat{\mathbf{y}}_{mu}(t)$ and the reference $\hat{\mathbf{y}}_{mh}(t)$ (i.e., the modal state vector of the healthy system) is interpreted as fault existence. Then, a damage index is defined. MSO estimates the modal state vectors from the measured vibration responses in the time domain. Thus, the vibration mode most affected by the fault existence can be indicated.

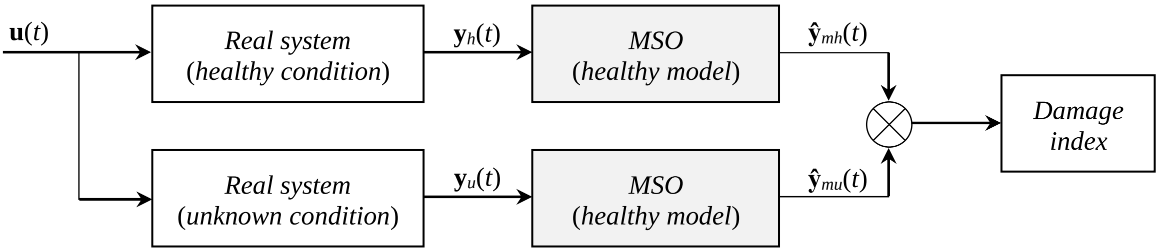
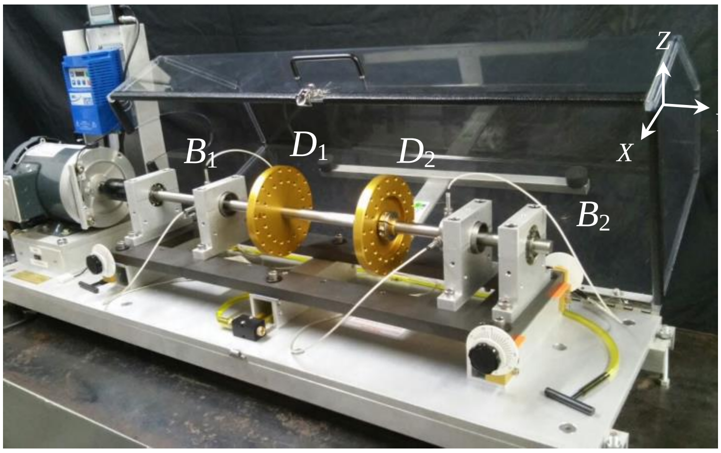


Figure 1. SHM technique based on MSO.

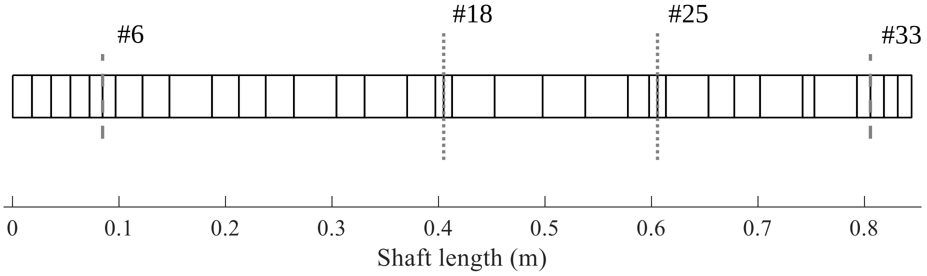
The MSO is based on the association of the Luenberger state observer with features derived from the modal domain. In this case, the MSO estimates the modal states related to the points where, for instance, the vibration responses of the shaft in the time domain were measured [11]. Consequently, it is expected more sensitive modal vibration responses with respect to fault existence stemming from the application of the MSO technique.

EXPERIMENTAL RESULTS

Figure 2a presents the rotor test rig used both in the numerical and experimental applications explored in this work. A FE model with 35 elements (see Fig. 2b) was used to represent the dynamic behavior of the horizontal rotating machine. The flexible steel shaft has 850 mm length and 19 mm diameter (E = 182 GPa, ρ = 7930 kg/m^3, and υ = 0.29).



(a)

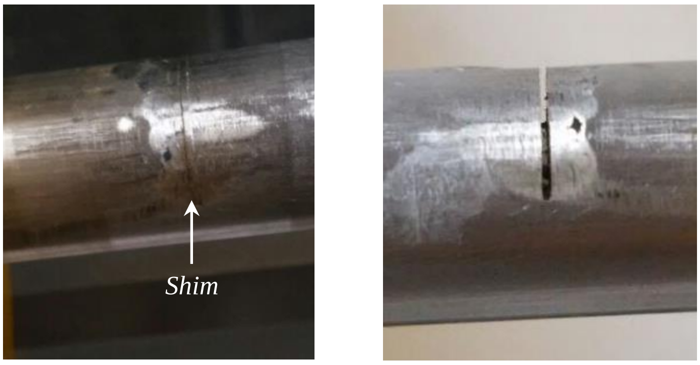


(b)

Figure 2. Rotating machine: (a) rotor test rig; (b) FE model.

Two aluminum discs are coupled to the shaft, namely D_1 (0.658 kg) and D_2 (0.656 kg) located at the nodes #18 and #25 of the rotating machine FE model, respectively. The shaft is supported by two self-alignment ball bearings B_1 and B_2, which are located at the nodes #6 and #33, respectively. Displacement sensors are orthogonally mounted on the nodes #12 (S_{12X} and S_{12Z}) and #29 (S_{29X} and S_{29Z}) to collect the shaft vibration response. An electric DC motor drives the system.

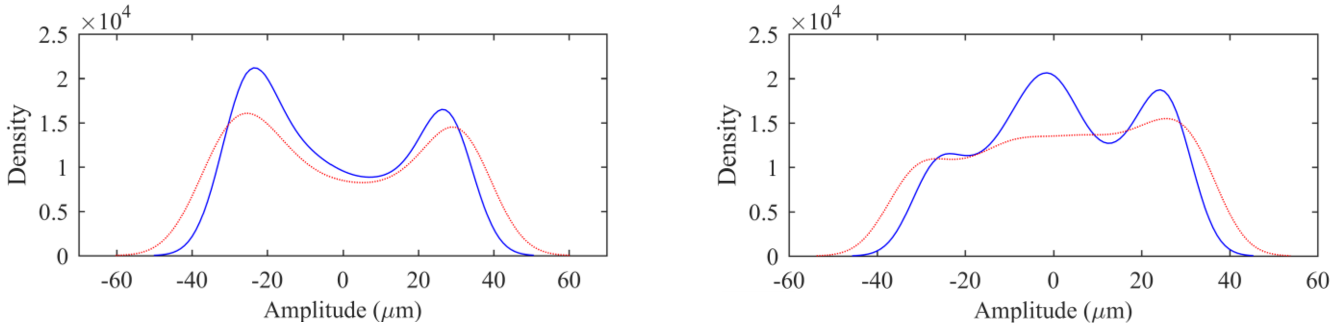
In this case, two different fault conditions are considered, namely a breathing crack and an open crack with 50% depth. The cracks are located between the discs D_1 and D_2 of the rotating machine, corresponding to the element #22 of the FE model (see Fig. 2). The open crack condition is characterized by creating a small notch on the shaft by using a wire electrical discharge machine (see Fig. 3a). During the shaft rotation, the notch edges do not touch each other. The breathing crack condition (see Fig. 3b) was obtained by introducing a shim in the crack area intending to simulate the breathing mechanism.



(a) (b)

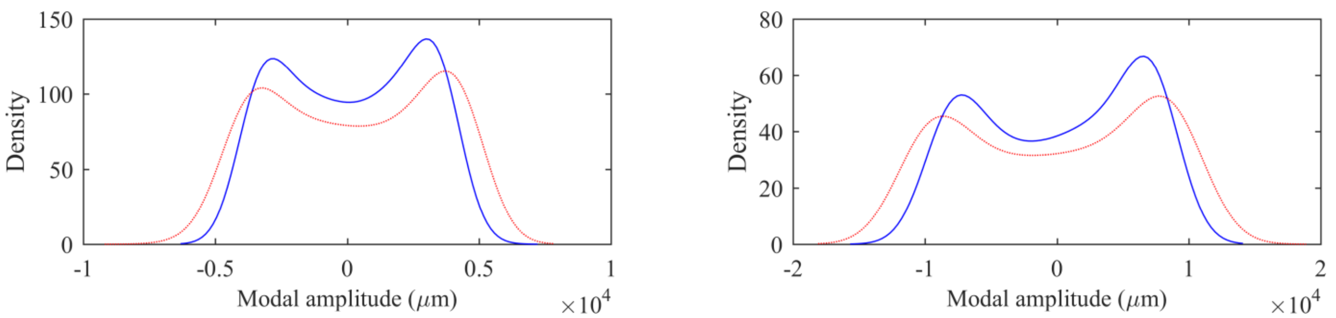
Figure 3. Crack conditions: (a) breathing crack; (b) open crack.

Figure 4 shows the estimated density functions of the time domain vibration responses associated with the two rotor structural conditions. The estimated density functions of the modal displacements shown in Fig. 5. Table 1 presents the damage index associated with the estimated density functions presented in Figs. 4 and 5 (including the sensors S_{29X} and



(a) (b)

Figure 4. Estimated density functions of the experimental time domain vibration responses for the shaft with the breathing crack (——) and the shaft with the open crack (······): (a) sensor S_{12X}; (b) sensor S_{12Z}.



(a) (b)

Figure 5. Estimated density functions of the experimental modal displacements for the shaft with the breathing crack (——) and the shaft with the open crack (······): (a) mode #1; (b) mode #2.

S_{29Z} and the vibration modes #3 and #4). The obtained damage index demonstrates that the modal displacements estimated by using the MSO approach were more sensitive to fault variation than the time domain vibration responses (breathing to open crack behavior).

Table 1. Damage indexes obtained by considering the shaft with breathing and open cracks.

Time domain vibration responses				
Sensor S_{12X} (%)	*Sensor S_{12Z} (%)*	*Sensor S_{29X} (%)*	*Sensor S_{29Z} (%)*	*Mean value (%)*
4.07	4.63	2.18	3.26	3.54
Modal displacements				
Mode #1 (%)	*Mode #2 (%)*	*Mode #3 (%)*	*Mode #4 (%)*	*Mean value (%)*
15.89	7.71	4.14	3.42	7.79

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