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Magnetostrictive patch sensor system for battery-less real-time measurement of torsional vibrations of rotating shafts

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ABSTRACT

Real-time uninterrupted measurement for torsional vibrations of rotating shafts is crucial for permanent health monitoring. So far, strain gauge systems with telemetry units have been used for real-time monitoring. However, they have a critical disadvantage in that shaft operations must be stopped intermittently to replace telemetry unit batteries. To find an alternative method to carry out battery-less real-time measurement for torsional vibrations of rotating shafts, a magnetostrictive patch sensor system was proposed in the present study. Since the proposed sensor does not use any powered telemetry system, no battery is needed and thus there is no need to stop rotating shafts for battery replacement. The proposed sensor consists of magnetostrictive patches and small magnets tightly bonded onto a shaft. A solenoid coil is placed around the shaft to convert magnetostrictive patch deformation by shaft torsional vibration into electric voltage output. For sensor design and characterization, investigations were performed in a laboratory on relatively small-sized stationary solid shaft. A magnetostrictive patch sensor system was then designed and installed on a large rotating propulsion shaft of an LPG carrier ship in operation. Vibration signals were measured using the proposed sensor system and compared to those measured with a telemetry unit-equipped strain gauge system.

1. Introduction

Rotating shafts such as propulsion shafts in large ships and steam turbine shafts might be subjected to a significant level of torsional vibrations during their operations [1–6]. Torsional vibration measurement of those shafts is very important to prevent catastrophic failure in advance. In case of ships, torsional vibrations should be constantly measured to monitor stress to shafts induced by such vibrations [7–9] because shafts are the most important components that transmit mechanical

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power. For real-time monitoring of torsional stress in rotating shafts, stress measurement should be made while shafts are rotating. Generally, commercialized sensor systems based on strain gauges with telemetry units are widely used in ship building industries [8,9]. An example of such sensor system installed on a rotating shaft is schematically shown in Fig. 1.

As shown in Fig. 1, a strain gauge is attached to the surface of a rotating shaft. It is also connected to a battery-powered telemetry system. The measured signal by the strain gauge is sent to a coil wound around the shaft. A fixed receiving antenna which is placed slightly away from the measurement location can detect the signal with wireless communication technique. The whole system except the receiving antenna rotates with the shaft. Photos of a rotating shaft, strain gauge system, and other measurement components are shown in the bottom of Fig. 1. Such strain gauge system was actually used as a reference system for this research [10–12].

The critical disadvantage of the above-mentioned strain gauge system is that rotating shaft to be stopped to replace the battery of its telemetry unit. This process is very time-consuming. In addition, it causes enormous economic loss. Besides, it might be very difficult to use it if shafts rotate at high speed or have small diameters because of undesirable mass unbalance effects caused by its installation. Alternatively, wireless-type slip ring systems can be used to measure vibration signals from the strain gauge bonded on a test shaft. However, the performance of these systems can be easily affected if bending vibrations of a test shaft are significant [13]. Motivated by these observations, the objective of this research was to develop a new sensor system without requiring battery installation while minimizing mass unbalance. If no battery is needed, permanent real-time vibration measurement without shaft stopping could be possible. The proposition is to develop magnetostrictive torsional vibration sensors (MTVSs) that can be installed on a rotating shaft without requiring a battery. Main components of an MTVS are a set of thin magnetostrictive patches, permanent magnets that are directly coupled with a rotating shaft and a solenoid coil wound over the shaft. Magnetostriction, the operating principle of MTVS, refers to the coupling phenomena between mechanical and electromagnetic fields [14,15].

Before mentioning previous studies related to MTVS, other commercialized battery-less sensors for torque or torsional vibration measurement in rotating shafts will be examined first. In the market, sensors using electromagnetic couplings such as a rotary transformer [16] and a capacitive sensor [17] are currently available. A hall sensor measuring magnetic field change induced by a torsional vibration in a ferromagnetic specimen has also been used [18]. One could also consider using sensors based on optics, such as infrared [16] and optical torque sensors [19]. However, these methods do not appear to be appropriate for applications in large propulsion shafts operating under harsh environment with various ambient vibrations. The main disadvantage is that the performance of these sensors can be significantly influenced by bending vibrations of rotating shaft. In addition, they are relatively sensitive to noise and measurement errors resulting from any misalignment of sensor components. Therefore, more advanced signal acquisition equipment would be needed. More importantly, they are not cost-effective compared to MTVS, especially if shafts of large size are considered. One could also consider the use of a magnetoelastic (or magnetostrictive) sensor [20]. However, it is inappropriate for permanent use because it regularly requires pre-magnetizing. In addition, it is sensitive to noise. Moreover, the strain gauge system with telemetry units has been considered as the most reliable method. It is mainly used at present for vibration measurement of large rotating propulsion shafts in the ship building industry even though it uses batteries and wireless modules. Considering these disadvantages of the telemetry strain gauge system and limitations of other sensor systems as mentioned above, an alternative method using MTVS is worthy of investigation as it is cost-effective without requiring battery replacement.

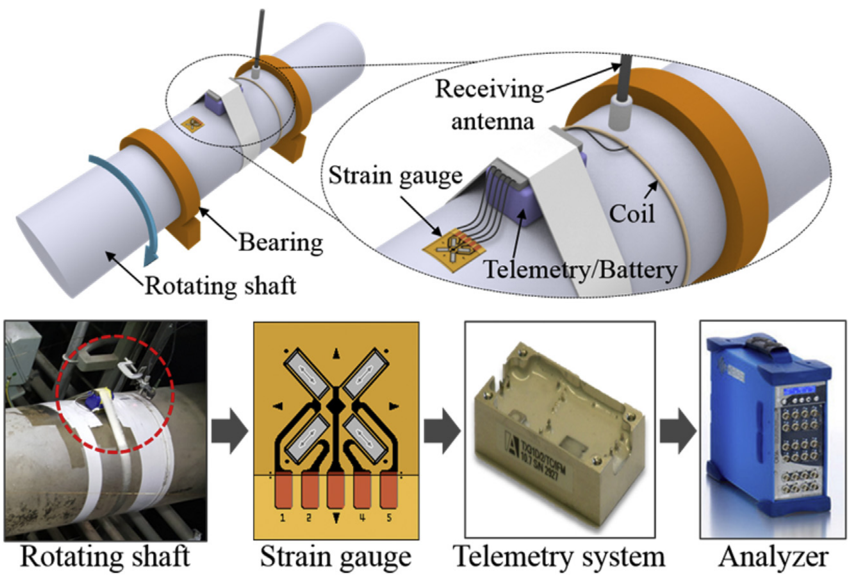

Fig. 1. Schematic configuration of a commercial strain gauge system with a telemetry unit for measuring torsional vibrations in a rotating shaft and its measurement procedure.