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A novel Terfenol-D transducer for guided-wave inspection of a rotating shaft

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Abstract

The purpose of this study is to develop a new ultrasonic transducer capable of transmitting and receiving guided-waves in a rotating shaft. The key idea in this development is the use of wireless capability of the magnetostrictive effect. In this investigation, relatively low-frequency longitudinal waves are generated by Terfenol-D, a giant magnetostrictive alloy (GMA). After an underlying magnetostrictive transducer configuration is presented, the effects of various design parameters on the transducer performances are studied experimentally. The material behavior of Terfenol-D is also briefly discussed. To show the effectiveness of the developed transducer, the transducer is used for guided-wave damage inspection in a rotating shaft having an artificial crack.

Keywords: Ultrasonic transducer; Terfenol-D; Magnetostriction; Non-destructive testing; Guided-wave inspection

1. Introduction

The demand for non-destructive health monitoring of machinery systems has been steadily increasing. Especially in case of rotating machinery, most non-destructive health monitoring techniques are based on vibration signals. In this investigation, we consider the use of longitudinal ultrasonic guided-waves instead of vibration signals for early-stage crack detection in a rotating shaft. However, the generation and measurement of guided-waves should not interfere with shaft rotation. The guided-wave technique has been used in stationary waveguides, such as pipes [1–4], but no guided-wave based health monitoring of rotating shafts has been reported yet.

The only application of guided-waves in a rotating shaft was made by Han et al. [5], but the ultrasonic waves were generated by projectiles shot into one end of a rotating shaft by an impact gun. However, the projectile impact should be avoided for practical use. Guided-waves denote elastic waves propagating along certain waveguides such as cylinders and plates [6]. Traveling along a structure guided by boundaries, guided-waves can propagate relatively long distances so that the whole part of a structure can be inspected at one time. For practical applications of the guided-wave method in rotating shafts, wave generation and measurement should be carried out without affecting shaft rotation motion. Motivated by this need, a new ultrasonic transducer capable of transmitting and receiving guided-waves in a rotating shaft without mechanical contact is developed. Specifically, a transducer based on the magnetostrictive effect is proposed and various design-related issues are investigated.

The magnetostrictive effect denotes the coupling phenomenon between the magnetic field and the strain field of ferromagnetic material [7] and the transducers based on this effect are called magnetostrictive transducers. Magnetostrictive transducers have unique characteristics in that they do not require direct wiring between magnetostrictive materials and sensing/actuating solenoids. For guided-wave generation and measurement, magnetic field is supplied to and measured from magnetostrictive material by solenoids [8,9]. This wireless actuation and measurement property can be very useful, especially when the whole transducer assembly is difficult to attach to the surface of the specimen such as rotating shafts. Recently, Kwun et al. [10], Cho et al. [11] and Kim et al. [12] proposed guided-wave techniques for non-destructive inspection of pipes and cylinders by using the magnetostrictive effect of nickel strips.

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However, nickel strips may not provide sufficient energy to generate guided-waves in rotating shafts especially when they are solid. Thus, we developed a new magnetostrictive transducer using a giant magnetostrictive alloy, called Terfenol-D to inspect rotating solid shafts.

A giant magnetostrictive alloy, Terfenol-D ($Tb_xDy_{1-x}Fe_y$, $x=0.27$–0.3, $y=1.9$–2.0) [13,14], can undergo a significant amount of magnetostrictive strain even under a moderate intensity of the magnetic field. Flatau and Hall [15] developed a vibration generation system taking advantage of the magnetostrictive effect of Terfenol-D. Calkins et al. [16] conducted a research to improve the dynamic performance of a Terfenol-D transducer, and Son and Cho [17] developed an underwater sonar transducer based on Terfenol-D. However, there is no report on the non-contact inspection of the rotating shaft based on Terfenol-D transducer.

After presenting the developed transducer configuration and working mechanism, several important design issues, such as the size of the Terfenol-D element, will be discussed. The material behavior of the specific Terfenol-D used in the present investigation is also briefly discussed. Experiments were conducted to investigate the effects of the bias and excitation magnetic field strength, the damping material, the fill factor, etc. on the transducer performance. To show the effectiveness of the proposed transducer, we used it to carry out the damage inspection of a rotating shaft having an artificial crack.

2. Configuration of the transducer

Fig. 1 shows the schematic diagram of the proposed magnetostrictive transducer used for the damage inspection of a rotating rod. The magnified cut-away view of the figure shows the transducer structure composed of a Terfenol-D element, a matching element, a damping element, a bias magnet, and a bobbin around which a solenoid coil is wound. Because the transducer is placed at one end of a rotating shaft, it can transmit and receive ultrasonic guided-waves along the longitudinal shaft axis. The main body of the transducer should be tightly attached to the rotating shaft, but the solenoid coil bobbin can be detached from the main body of the transducer; this detachment allows wireless actuation and measurement of ultrasonic waves. Fig. 2 shows a prototype of the transducer installed on the rotating shaft.

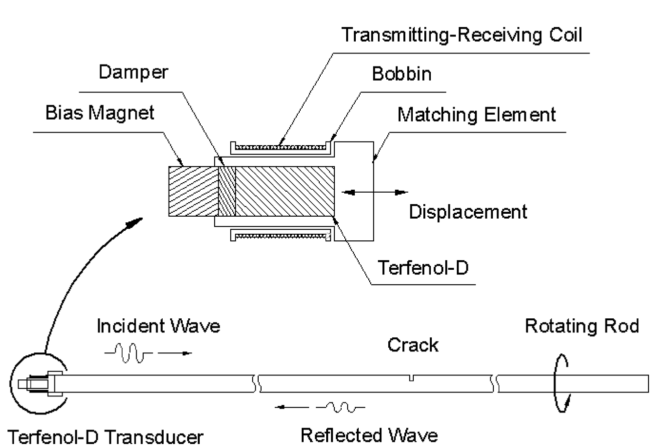

Fig. 1. Schematic diagram of the Terfenol-D transducer.

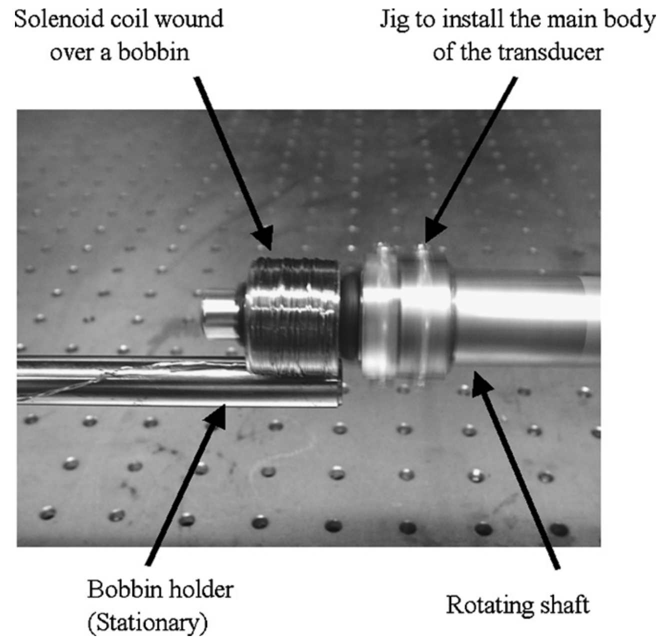

Fig. 2. Terfenol-D transducer installed on a rotating shaft.

2.1. Design issues

In the process of developing the transducer shown in Fig. 1, several design issues were considered. Among them, the following three important issues are addressed in this study:

- Issue 1: wireless inspection

  Several non-contact inspection techniques, such as laser-generated ultrasonic techniques [18], have been used, but these techniques have some limitations in the guided-wave applications for on-line monitoring of a rotating shaft. Therefore, the use of a Terfenol-D transducer that does not require direct wiring is considered. The transducer has sufficient power to generate guided-waves in a rotating solid shaft.

  Due to the magnetostrictive effect of Terfenol-D, guided-waves are generated and measured by a solenoid coil that simply encircles the Terfenol-D element of the transducer. For wave generation, time-varying magnetic field is supplied to the Terfenol-D element by a solenoid while for wave sensing, the field variation resulting from the longitudinal deformation of the Terfenol-D element is picked up by a solenoid. Because the solenoid only needs to encircle the Terfenol-D element, wireless inspection becomes feasible.
- Issue 2: long-range propagation

  The propagating distance of a ultrasonic wave in the structure limits the inspection range of a transducer. The further the ultrasonic wave can reach, the wider the area that can be covered by a single ultrasonic wave launch. When a guided-wave propagates into a bounded medium, its peak amplitude attenuates as it propagates farther, because of dispersion as well as material damping. Therefore, for a long-range inspec-