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Non-contact measurement of axial force in a bolt by remotely exciting a piezoelectric element bonded to a bolt

ボルトに接着した圧電素子の遠隔駆動によるボルト軸力測定

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1. Introduction

Bolt is a very common element in infrastructures and industrial plants, and cost for regular inspection of bolts has been a problem. There is a need for an easy-to-use method of measuring axial force in a bolt. A remote measurement system has been proposed as a convenient method for inspection [1]. In this method, a bolt with a strain gage and a detection circuit is used. At the time of inspection, a specially designed terminal is brought close to the bolt and supplies power to the detection circuit. The detection circuit measures the strain of the strain gage and transmits the data of the strain to the terminal. This system is highly convenient, but it is expensive because of the complex electronic circuitry.

In this study, we propose a simple and low-cost method to measure the axial force of a bolt by remotely exciting a piezoelectric element attached to the head of the bolt. It has been reported that the axial force can be measured by the change in the resonance frequency of the bolt because the resonance frequency decreases as the axial force increases [2]. A method for remotely driving a piezoelectric transducer by electromagnetic induction has also been studied as a sensor in high-temperature environments [3]. In this study, we investigated whether the axial force of a bolt can be measured by remotely driving a piezoelectric element and measuring the resonance frequency of the bolt. Two coils connected to the piezoelectric element and the measuring instrument respectively, are magnetically coupled, and the admittance of the piezoelectric element is measured through the coils. In this report, we demonstrated the feasibility of the proposed remote method.

2. Experimental configuration

The configuration for the experiment is shown in **Fig. 1**. A piezoelectric element (10 mm in diameter and 1 mm thick) was bonded to the head of an M12x100 steel bolt. The piezoelectric element was connected to a flat coil (9 turns and 18 mm in diameter) bonded to the head of the bolt. **Figure 2** shows the photograph of the head of the bolt. A load cell for axial force measurement and a steel plate were inserted between the bolt and nut, and axial

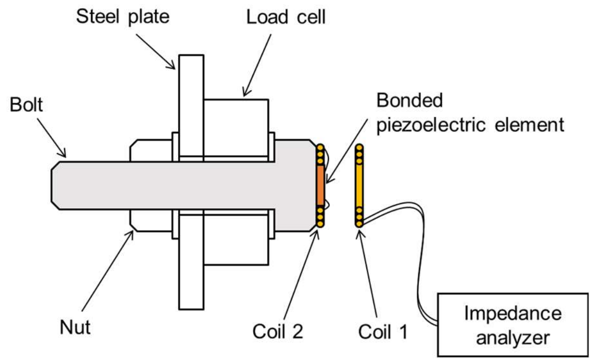

Fig. 1 Schematic of experimental configuration.

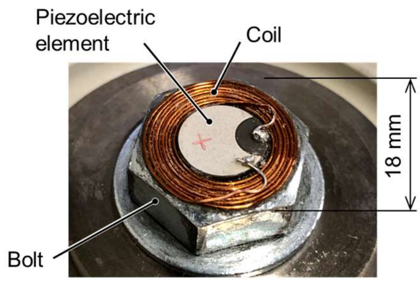

Fig. 2 Photograph of the bolt with the piezoelectric element used for the experiment.

force was generated by tightening the bolt. The distance between the bolt head and the nut was about 60 mm. Another coil (coil 1) of the same shape as the coil (coil 2) bonded to the bolt head was brought closer to the bolt head. An impedance analyzer (4294A, Agilent) was used to measure the frequency response of the admittance of the coil. The measurements were made at frequency ranges near the resonance frequency of the thickness vibration of the piezoelectric element. To simulate bolt looseness, the axial force was relaxed from 18 kN, which is within the elastic range of the bolt.

3. Experimental results

Figure 3 shows the frequency response of the admittance of the coil by changing the axial force. Admittance is normalized to 0-1 range to make it easier to see changes in peaks. The frequency ranges in Figs. 3 (a) and (b) are around the 1st-order and the 3rd-order thickness resonance frequency of the piezoelectric element, respectively. Both Figs. 3 (a) and (b) exhibit peaks every 26 kHz. If the bolt is

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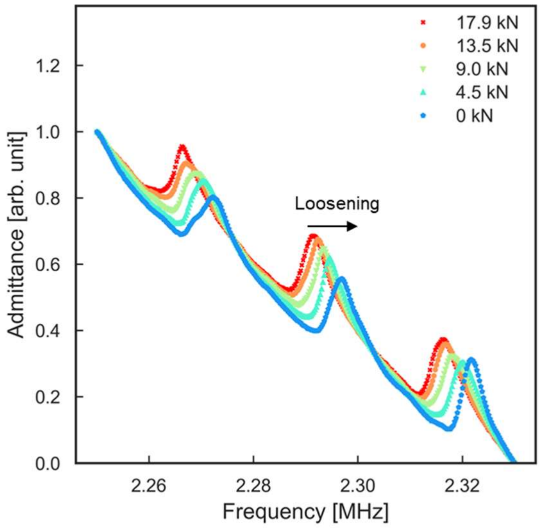
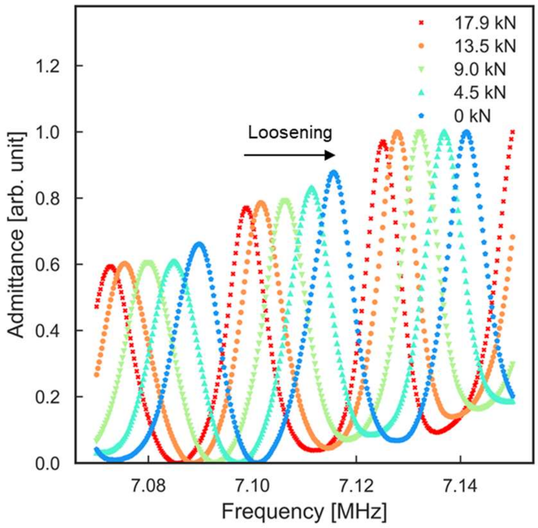


(a)



(b)

Fig. 3 Shifts in admittance peaks due to axial force changes: frequency range of (a) the 1st-order, and (b) the 3rd-order thickness resonances of the piezoelectric element.

treated as a rod, the resonance frequencies of the bolt are [2]:

$$f_\mathrm{n} = \frac{nv}{2L_0} \quad , \qquad (1)$$

where n is a mode number, v is the velocity of acoustic waves, and L_0 is the total length of the bolt. From Eq. (1), the intervals of resonance frequencies are:

$$f_\mathrm{n} - f_\mathrm{n-1} = \frac{v}{2L_0} \quad . \qquad (2)$$

The total length of the bolt is 108 mm (Bolt length of 100 mm and bolt head thickness of 8 mm). The length and the longitudinal velocity of steel (5900 m/s) give the resonance frequency intervals of 27.3 kHz according to Eq. (2). The interval of the peaks corresponds to the resonance frequency interval.

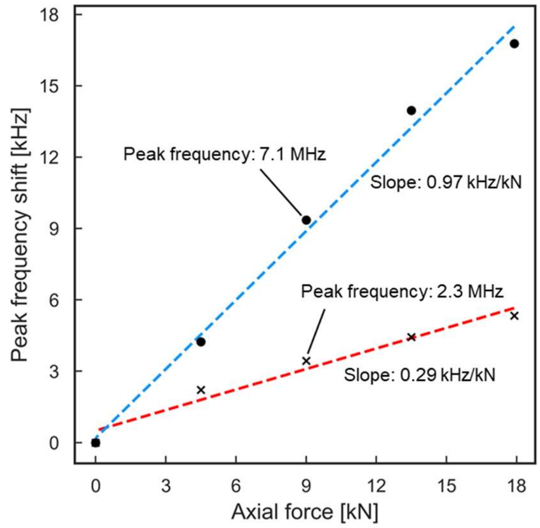


Fig. 4 Peak frequency shifts under different axial forces.

Therefore, these peaks seem to be due to the length resonance of the bolt, and it is indicated that the admittance change of the piezoelectric element due to the resonance of the bolt can be measured through the coils.

Figure 4 shows the dependence of the frequency shift from the peak frequency in the unloaded state on the axial force. The frequency shift is proportional to the axial force, and the fitted lines and the slopes are also shown in the figure. When the peak frequency is 3.1 times higher, the slope of the line is 3.3 times higher. This is reasonably deduced from the nature of harmonic modes. Theoretically, the frequency shift of the bolt is proportional to the axial force and the resonance frequency with no axial force [2]. From these results, we confirmed that the resonance frequency of the bolt and the shift of the frequency due to the axial force can be measured by the remote method.

4. Conclusion

A remote method for measuring an axial force of a bolt is proposed. The shift of the resonance frequency of the bolt due to the axial force can be measured by the method.

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References

1. F. Saigo, R. Sakadume, T. Yamato, Y Suzaki and S. Takahashi: IEICE Tech. Rep. **116** 74 (2016) 19
2. T. Sakai, T. Makino and H. Toriyama: Trans. JSME **43** (1977) 723
3. R. Murayama, M. Kobayashi, KT. Wu and CK. Jen: J. Sens. Technol. **2** (2012) 60.