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Non-contact measurement of bolt axial force using crystal resonator and coil

水晶振動子とコイルを用いたボルト軸力の非接触測定

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1. Introduction

Periodic inspection of bolts is important for maintaining the integrity of structures. It would be useful if the axial force of a bolt could be measured remotely by bringing an inspection device closer to the bolt. In particular, it can be expected that bolts can be inspected using a drone equipped with this inspection device in places where it is difficult to approach, such as high places. A non-contact method that uses ultrasonic waves to detect elongation of a bolt due to axial force was proposed [1].

2. Configuration of the device

In this study, we propose a non-contact bolt axial force measuring method that detects deformation of a bolt head due to axial force. **Figure 1** shows a schematic of the proposed method. A sensing part is attached to the bolt head in advance, and the coil of the inspection device is brought close to the bolt head for inspection. The sensor part consists of a coil, a crystal resonator, a bolt head, and an electrode connected in series. Since the bolt head is deformed by the axial force of the bolt [2], a capacitor whose capacitance changes due to the axial force is formed between the electrode and the bolt head. The change in the resonance frequency of the crystal resonator due to this change in capacitance is detected through the coils by the inspection device.

We showed the possibility that the axial force can be measured remotely by the proposed method by the equivalent circuit analysis and the experiment using a prototype.

3. Equivalent circuit

Figure 2 shows the equivalent circuit of the proposed method. A crystal resonator, a capacitor, and a coil are connected in series. The impedance of the crystal resonator and the capacitor is calculated with $R_m = 0$ for simplicity, and the resonance frequency is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{L_m C_m}\left(1+\frac{C_m}{C_s+C_d}\right)} \quad . \qquad (1)$$

The resonance frequency changes with the change of C_s. It can also be seen that the smaller C_d and the larger C_m, the larger the change in resonance frequency due to the change in C_s.

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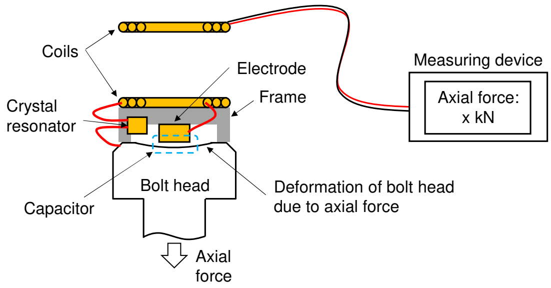

Fig. 1 Schematic of the proposed method.

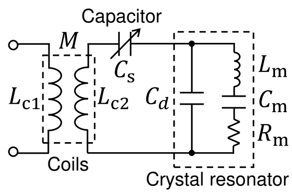

Fig. 2 Equivalent circuit of the proposed method.

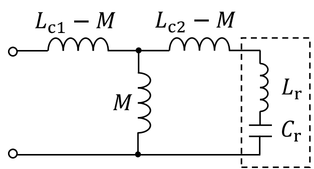

Fig. 3 Simplified equivalent circuit of the proposed method at frequencies near the resonance frequency of the crystal resonator and the capacitor.

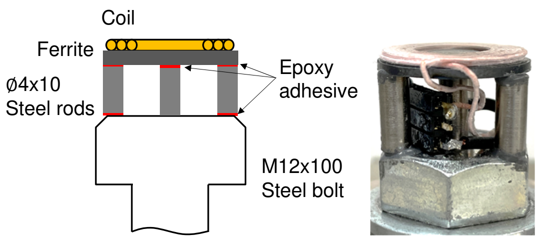

Fig. 4 Prototype of the bolt.

This resonance is observed through the coils. Fig. 3 shows the equivalent circuit of the proposed method, in which the crystal resonator and the capacitor are made into a series circuit of L_r and C_r for the sake of simplicity. The frequencies at which the admittance of this circuit is 0 and ∞ are expressed by the following equations, respectively.

$$f_{dip} = \frac{1}{2\pi}\sqrt{\frac{1}{(L_r+L_{c2})C_r}} \ , \qquad (2)$$

$$f_{peak} = \frac{1}{2\pi}\sqrt{\frac{1}{(L_r+(1-k^2)L_{c2})C_r}} \ , \qquad (3)$$

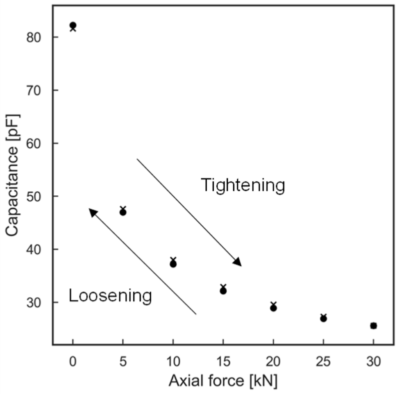

Fig. 5 Shifts in capacitance between the electrode and the bolt head due to axial force changes.

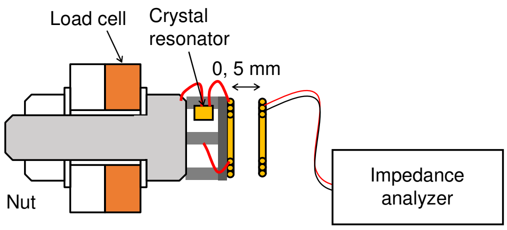

Fig. 6 Schematic of experimental configuration.

where k is the coupling coefficient between the coils. From equations (2) and (3), the admittance peak frequency is affected by the coupling coefficient between the coils, but the dip frequency is not. Therefore, by observing the dip frequency, it is possible to perform a measurement in which the measurement result is not affected by the distance between the coils.

4. Experiment

Figure 4 shows a schematic diagram and a photograph of the sensor part of the prototype bolt. The central steel rod is used as an electrode. An epoxy adhesive was applied to four steel rods, and they were bonded at the same time.

Figure 5 shows the measured results of the capacitance between the electrode and the bolt head with an LCR meter when an axial force is applied to the bolt. The capacitance decreases as the axial force increases regardless of whether the bolt is tightened or loosened.

A 5 MHz crystal resonator was connected to the prototype bolt, and the relationships between axial force, and dip and peak frequencies were measured with the configuration shown in **Fig. 6**. The coil connected to the impedance analyzer was opposed to the coil attached to the bolt head. The distance between the coils was 0 mm or 5 mm.

Figure 7 shows the frequency characteristics of the admittance when the distance between the coils is 0 mm. The dip and peak frequencies increase as the axial force increases. **Figure 8** shows the results of plotting the dip and peak frequencies at

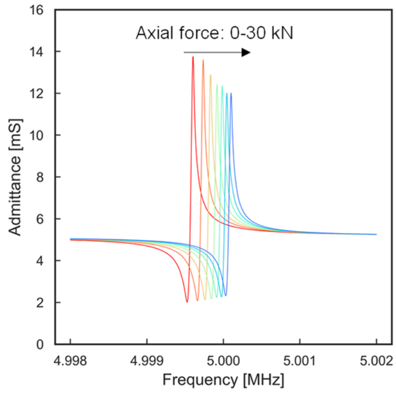

Fig. 7 Frequency response of the admittance of the coil under different axial force when the distance between 2 coils is 0 mm.

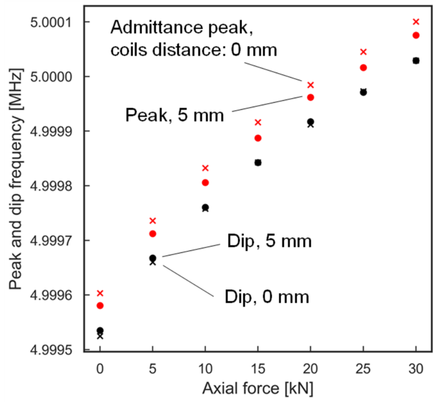

Fig. 8 Peak and dip frequencies under different axial force and distances of the coils.

each axial force. Both the dip frequency and the peak frequency increase monotonically as the axial force increases. Moreover, as shown in Eq. (2), the dip frequency does not depend on the distance between the coils. Therefore, by measuring the frequency of the admittance dip, it is possible to measure the axial force regardless of the distance between the coils by the proposed method.

5. Conclusion

A remote method for measuring the axial force of a bolt is proposed. The axial force can be measured remotely without being affected by the distance between the coils by measuring the dip frequency of the admittance.

Acknowledgement
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References

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