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Development of Vibration Measurement System using a Microcontroller

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Abstract

It is important to interpret resonance in the design to reduce the vibration of mechanical structures, and to verify this resonance phenomenon by experiments and theoretical approach. In the measurement for the vibration of a continuous system, the experience and skill of the observer affect the measurement accuracy of the natural frequencies and vibration modes. Therefore, in this study, a vibration measurement system is developed to stably and quantitatively verify the natural vibration of the beams using a microcontroller and an ultrasonic sensor. The vibration measurement system consists of a microcontroller, a vibration motor and an ultrasonic sensor. The accuracy and validity of the natural frequencies of the beams measured by the system are discussed, and the performance of present system is evaluated on the basis of the measurement results of the natural frequencies and the natural vibration waveforms.

Keywords: Vibration measurement; natural vibration; continuous system; microcontroller; ultrasonic sensor

1. Introduction

Resonance phenomenon is an important issue in the design on the fields of machinery, construction, aerospace, and civil engineering. In order to reduce and control the vibration of the mechanical structures, it is important to comprehend the mechanism of vibration and verify the resonance phenomenon by experimental and theoretical means.

For years, the vibration of the beam as a continuous system has been studied widely and actively. Dickey [1] discussed the free vibration and dynamic buckling of the beams under axial force by describing the solution of the equations of system. Thambiratnam and Zhuge [2] investigated the free vibration analysis of a stepped beam on an elastic foundation by using the finite element method. Tsai et al. [3]indicated the vibration analysis for a beam with distributed internal viscous damping by applying Timoshenko beam theory. Capozucca [4] treated the analysis of vibration of cantilever beams consist of dameged carbon fiber reinforced plastics. Wu et al. [5] proposed a method of analyzing beam vibration by tracking a laser stripe as non-contact measurement technique for vibration of the beams. Lee [6] presented free vibration analysis of a laminated beam with delaminations using a layerwise theory. Lin [7] presented the eigensolutions for an arbitrary number of cracks of a beam with various boundary conditions. Della et al. [8] solved analytically the vibration of beams with double delaminations without resorting to numerical approximation. Lee [9] analyzed mathematically the vibration characteristics of four parallel and uniform beams. Kerboua [10] presented the control and reducion the vibration of beams using smart materials. Sepehri-Amin et al. [11] investigated the vibration response of functionally graded and viscoelastic damped beams.

On the other hand, the researches using a microcontroller have been actively reported in various engineering fields recently. Priohutomo et al. [12] discussed the design of maneuver controls using a microcontroller to avoid the ship from the collision. Sitanayah et al. [13] designed and implemented a low-cost wireless system to count the number of cars and motorcycles in a parking lot using the microcontroller. In addition, Putra et al. [14] showed the design and development of a simulator that can represent the earthquakes using a microcontroller, the hydraulic actuator and the three-axis accelerometer.

In general, the vibration measurement of a continuous system requires an integrated system consists of such as accelerometers, vibrators, analyzers, oscillators and amplifiers. In addition, a system that supports to measure simply and comprehend intuitively the natural frequencies

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and vibration modes of a continuous system is valid in the acquisition for the fundamental of vibration phenomenon.

Therefore, in this study, a vibration measurement system consists of a microcontroller, a vibration motor and an ultrasonic distance sensor was developed to visualize and comprehend intuitively the natural frequencies and vibration modes of beams, which are one of continuous system.

In particular, the natural vibration waveforms in time series for a cantilever beam have been measured by using the present system. Based on the comparison between the measured results and theoretical ones for the natural frequencies of the aluminum beams, the performance of the present system is evaluated and discussed.

2. Test Piece and Modules

2.1. *Test piece (Cantilever beam)*

Figure 1 shows an aluminum beam applied for vibration measurement on present system. Since the beam is flexible, it is appropriate for the detection of the amplitude (vibration displacement), and it is suitable for the verification of natural frequency and vibration mode of the beams. In addition, since a beam is thin form, it is able to observe the vibration displacement even if the excitation force is not powerful.

2.2. *Microcontroller*

Arduino microcontroller demonstrates a superiority in developing the systems that use DC motor, stepper motor, LED diode, piezoelectric sounder and various sensors, etc. Therefore, as shown in Fig. 2, Arduino UNO having 16MHz ceramic resonator has been adopted in this study.

2.3. *Ultrasonic sensor*

Figure 3 shows the ultrasonic distance sensor adapted on present system measuring the vibration displacement of the beam. The sensor has characteristics of operating frequency 40kHz and a measuring distance range from 2cm to 400cm. The ultrasonic sensor enables the non-contact measurement of a beam vibration displacement.

2.4. *Vibration motor*

Figure 4 shows the vibration motor adapted on present system exciting the beam at the resonance frequency. The motor exhibits maximum driving frequency 200Hz and an acceleration 1G at a rated voltage of 3V, and is characterized by its small size and large excitation force. The vibration motor has been mainly used to excite the second-order natural vibration of the beam.

2.5. *Motor driver*

By using the DC motor driver with a bipolar type linear integrated circuit shown in Fig. 5, the vibration motor speed can be controlled using a variable resistor.

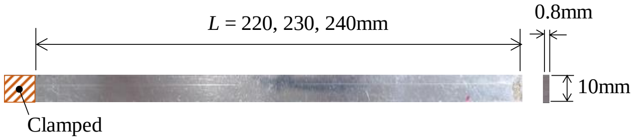


Figure 1. Geometry of an aluminum cantilever beam

Figure 2. Microcontroller (Arduino UNO)

Figure 3. Ultrasonic distance sensor (HC-SR04)

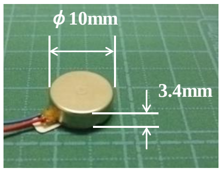


Figure 4. Vibration motor (Uxcell DC micromotor)

Figure 5. Motor driver (Toshiba TA7291P)

3. Vibration Measurement System

3.1. *System for exciting the beam*

Figure 6 presents the block diagram of system for exciting a beam. A vibration motor shown in Fig. 4 has been used for exciting the second-order natural vibration, and a DC motor with a reducer has been applied to induce the fundamental natural vibration of a beam. A program code to control the motor rotation speed (driving frequency) has been developed and applied to Arduino microcontroller. Present system can control the driving (excitation) frequency of the motor with a variable resistor. Also, the excitation frequency [Hz] of the motor can be indicated on the PC monitor. Furthermore, Figure 7 shows the circuit of the system for exciting a beam.

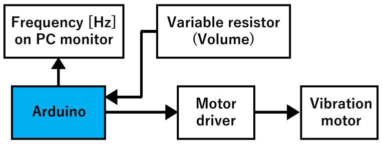


Figure 6. Block diagram of system for exciting a beam

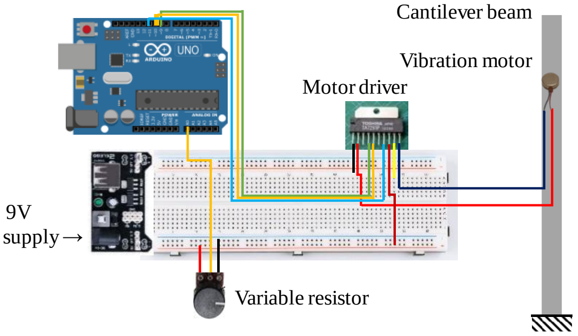


Figure 7. Circuit diagram of system for exciting a beam

3.2. System for measuring the vibration displacement

Figure 8 gives the block diagram of system for measuring vibration displacement of a beam. Two ultrasonic sensors shown in Fig. 3 have been located to measure simultaneously the vibration displacement of a beam at multiple points. A program code to take in the vibration displacement of a beam has been developed and applied to Arduino microcontroller. The acquired displacement data are represented on the PC monitor. Figure 9 shows the circuit diagram for measuring vibration displacement of a beam. Ultrasonic distance sensors have been located near the amplitude of an excited beam, and the vibration displacement data have been acquired in time series. Also, the maximum frequency that can be measured with this system is around 100Hz. It is possible to observe up to the second-order vibration mode with aluminum beam length L= 220mm to 240mm.

3.3. Setting position of sensors and motor

Figure 10 illustrates the setting position of the ultrasonic distance sensors and the vibration motor. Sensor-A and B have been located at the center and near the free end of the beam, respectively. In addition, the vibration motor has been attached with adhesive tape.

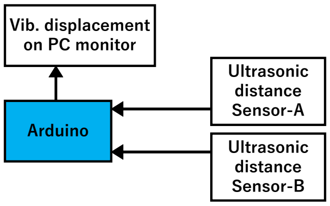


Figure 8. Block diagram of system for measuring vibration displacement of a beam

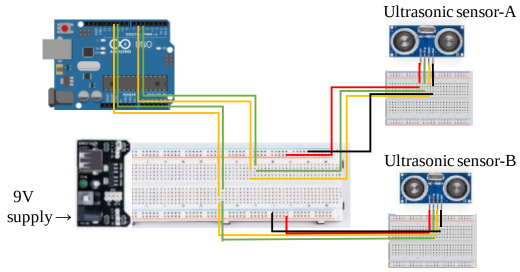


Figure 9. Circuit diagram of system for measuring vibration displacement of a beam

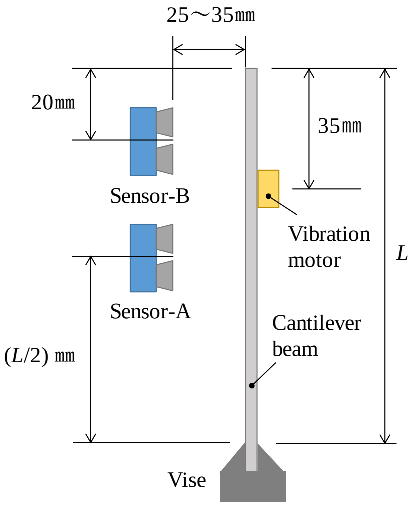


Figure 10. Position of ultrasonic sensor and vibration motor

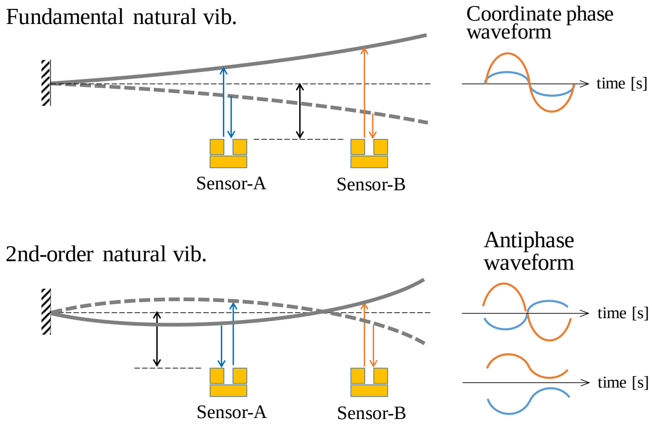


Figure 11. Discrimination for vibration mode of cantilever beam

3.4. Discrimination of vibration mode

Figure 11 demonstrates the concept of discrimination of vibration mode of the beam. Considering the natural vibration mode shapes of cantilever beam, the fundamental and second-order natural vibration can be distinguished from type of waveform having the coordinate phase or antiphase.

3.5. Discrete Fourier transform

The frequency spectrum of natural vibration displacement in time-series can be analyzed by the discrete Fourier transform (DFT) written in Eq. (1).

Also, a program code for numerical calculation of the frequency spectrum was developed according to the flow chart of the DFT processing shown in Fig. 12.

Sampling No.： n (0~N−1)
Sampling number：N
Sampling period：Δt
Frequency： $f_k = k/(N\Delta t)$ (k=0~N/2−1)
Imaginary unit： $i=\sqrt{-1}$

Vibration displacement in time series：$h(t_n) \equiv h_n$
Frequency spectrum：$|H(f_k)| \equiv |H_k|$

$$
\begin{aligned}
H_k &= \sum_{n=0}^{N-1} h_n\, e^{-i\frac{2\pi nk}{N}} = \sum_{n=0}^{N-1} h_n \left(\cos\frac{2\pi nk}{N} - i \sin\frac{2\pi nk}{N} \right) \\
&= \sum_{n=0}^{N-1} h_n \cos\frac{2\pi nk}{N} \;+\; i \left(-\sum_{n=0}^{N-1} h_n \sin\frac{2\pi nk}{N} \right) \\
&= \mathrm{Re}(H_k) + i \cdot \mathrm{Im}(H_k)
\end{aligned}
$$

$$|H_k| = \sqrt{\{\mathrm{Re}(H_k)\}^2 + \{\mathrm{Im}(H_k)\}^2} \qquad (1)$$

3.6. Experiment procedures and setting

Experiment procedures for exciting and measuring of the beam by the present system are as follows:

- Adjust the variable resistor to drive the vibration motor and induce the natural vibration mode of the beam.
- Observe and save the sampling data of the vibration displacement measured by the ultrasonic sensor on the PC monitor.
- Analyze the frequency spectrum (natural frequency) of the beam by applying the Fourier transform to the vibrational displacements in time-series.

4. Measurement Results and Discussion

In this section, the measurement results for the natural vibration of a cantilever beam acquired by present system are illustrated, and the performance of the system will be evaluated.

Figure 13 gives the fundamental and second-order natural vibration displacements in time-series of the cantilever beam obtained by using present system. The vibration displacement waveforms measured by sensor-A and B show “Coordinate phase” in the case of fundamental natural vibration. Also, the vibration displacement waveforms show “Antiphase” in the case of second-order natural vibration. This phenomenon follows the concept of discrimination of vibration mode of a cantilever beam shown in Fig. 11.

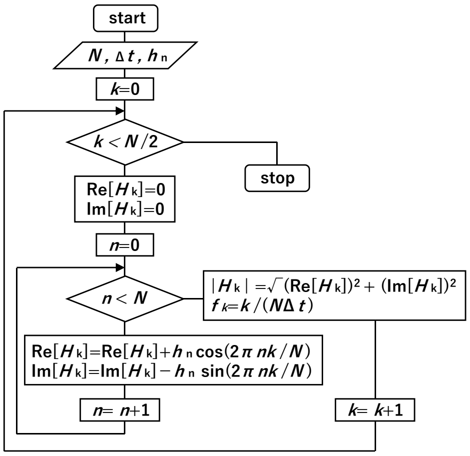
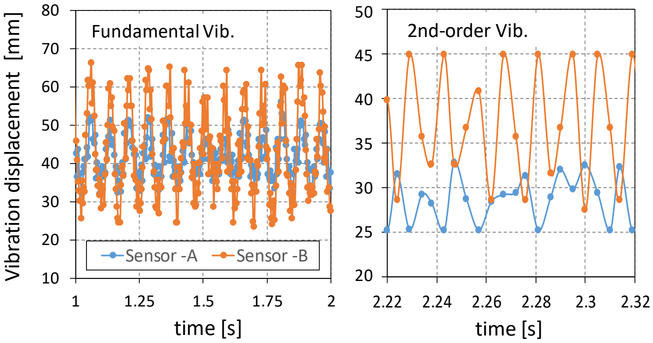
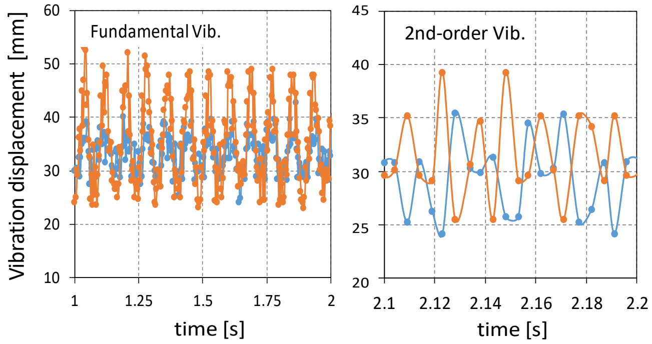


Figure 12. Flowchart of DFT processing

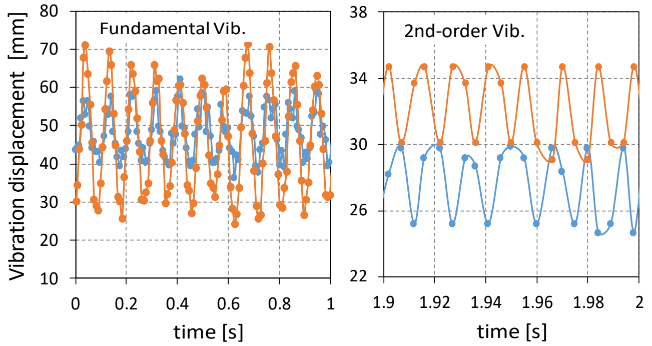
Figure 14 presents the results of the spectrum analysis by the discrete Fourier transform (DFT) for the natural vibration waveform in time-series shown in Fig. 13. The spectrum components of the fundamental and second-order natural frequencies detected by DFT analysis are 12.9Hz and 78.3Hz at *L*=220mm, 11.9Hz and 73.8Hz at *L*=230mm, 10.8Hz and 71.8Hz at *L*=240mm, respectively. As can be clearly seen in Fig. 14, each frequency spectrum components (natural frequencies) of the cantilever beam are expressly extracted even though there are countless noise frequency components.



(a) *L*=220mm

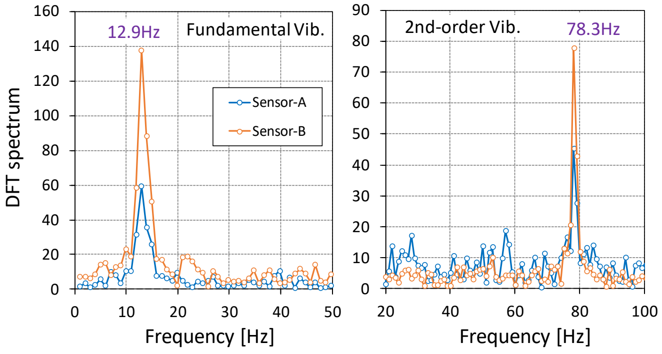


(b) *L*=230mm

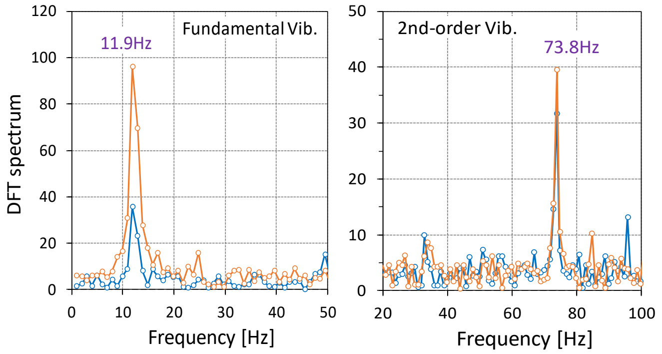


(c) *L*=240mm

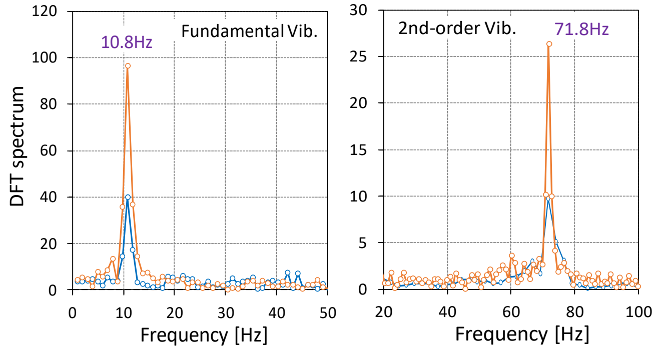
Figure 13. Natural vibration displacements of cantilever beams



(a) L=220mm



(b) L=230mm



(c) L=240mm

Figure 14. Spectrum analysis for natural vibration displacements of cantilever beams

Table 1 demonstrates comparisons of natural frequencies for cantilever beams. Theoretical(exact) solutions for natural frequencies of a cantilever beam are given in Ref. [15], and Young's modulus 70GPa and the volume density 2700kg/m^3 have been employed as the material constants of the aluminum beam in the exact solutions. It is observed that the measured(DFT) results agree well with theoretical(exact) solutions, because the maximum relative difference between the measured results and exact solution is 8.1%. As can be seen, the accuracy and validity of the measured results can be confirmed from the view point of the results for these comparisons between the natural frequencies.

Figure 15 indicates variations of natural frequencies with respect to the length of the cantilever beams. The exact solutions don't include the axial elongation and contraction, the transverse shear deformation of the beam and the mass effect of the vibration motor attached the beam. Therefore, the exact solutions tend to be higher than the measured results. Also, it can be seen that the natural frequencies decrease as the length of the beam increases. In fundamental natural vibration, there is almost no effect of variation of beam length on the relative difference between the measured results and the exact solutions.

Regarding second-order natural vibration, the relative difference between the measured results and the exact solutions seems to be larger for the shorter beam. From this tendency, it is guessed that the measured value is smaller than the exact solution, because the effect of transverse shear deformation is more pronounced for the shorter beam in the case of second-order natural vibration.

5. Conclusions

In this paper, the vibration measurement system for a cantilever beam has been presented, which consists of a vibration motor, a microcontroller and an ultrasonic distance sensor. The natural vibration waveforms in time series for a cantilever beam have been measured by using the present system. Also, the fundamental and second-order natural frequencies, which are the spectrum components of natural vibration waveforms of the cantilever beam have been detected by applying the discrete Fourier transform (DFT).

Comparisons between the measured results and the theoretical(exact) solutions for the natural frequencies of cantilever beams have been demonstrated and discussed. The measured results agreed well with the theoretical solutions, and the accuracy and validity for the natural frequencies of the beams measured by the present system have been confirmed. Also, if the mass of the attached vibration motor could be included as locally point mass in the beam theoretical model, the theoretical solutions would be closer to the experimental results and more accurate.

Table 1. Comparisons of natural frequencies for cantilever beams

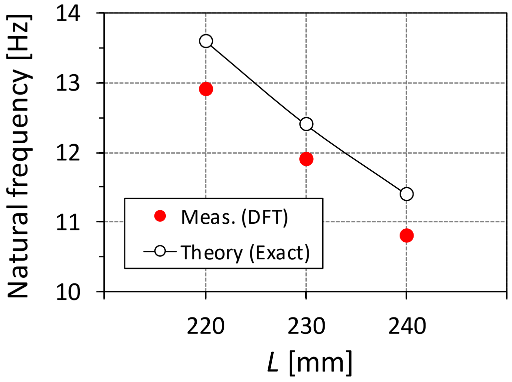
Beam length [mm]	Mode No.	Meas. [Hz] (DFT)	Theory [Hz] (Exact)	Diff.
220	1	12.9	13.6	-5.1%
	2	78.3	85.2	-8.1%
230	1	11.9	12.4	-4.0%
	2	73.8	78.0	-5.4%
240	1	10.8	11.4	-5.3%
	2	71.8	71.6	0.3%

Diff. [%] = { (Meas.－Theory) / Theory }×100

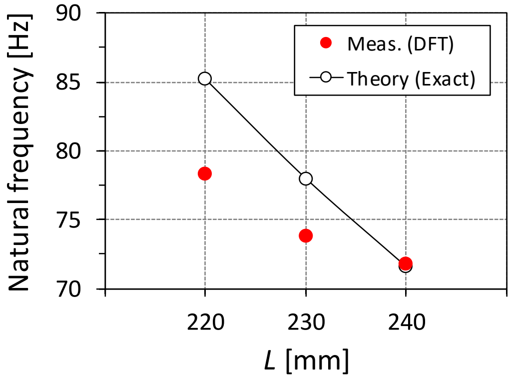
In addition, taking into account the identity taken from the comparisons of natural frequencies, the validity for the performance and the function with respect to the present vibration measurement system using a microcontroller has been evaluated.

Present system has proposed a non-contact measurement technique of vibration displacement. It is expected that the measurement of higher-order natural frequencies of the beam will become possible if more sampling data for the vibration displacement can be acquired with microcontroller having high specification.

The use of this system will be expanded if the measured vibration displacement data can be displayed on the PC monitor in real time, or if a communication module can be connected to the microcontroller to monitor remotely the measured data.



(a) Fundamental natural vibration



(b) Second-order natural vibration

Figure 15. Variations of natural frequencies versus the length of cantilever beams

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