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Use of cut specimen pieces in the vibration method with additional mass (VAM)

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Abstract

The objective of this study was to increase the estimation accuracy of the vibration method with additional mass (VAM). The wood specimen was divided into a cut end and a main body. The cut end was used in VAM. The estimation accuracy of VAM was increased by using the cut end as the additional mass. Hence, the cut end had completely adhered to the main body before cutting. The estimation accuracy reduced with decreasing specimen length. In order to maintain high estimation accuracy, the specimen length should not be too short. The estimation accuracy of the longitudinal vibration was higher than that of the bending vibration because the variation range of the resonance frequency due to end cutting of the longitudinal vibration was lower than that of the bending vibration.

Keywords: Bending vibration, Cut end, Longitudinal vibration, Specimen length, Vibration method with additional mass

Introduction

The vibration test is a simple and nondestructive test for measuring Young's modulus. Density is a necessary input to calculate the Young's modulus. Weighing a specimen is a difficult task in some cases, as it can involve weighing each piled lumber and each cross beam of timber guardrails. For weighing each piled lumber, a place for the weighed lumber as well as a time for weighing are needed. The size of the timber guardrail beam can reach a diameter of 200 mm and a length of 2 m and a mass of 25 kg. A weighing scale is necessary for conducting testing in the field. Therefore, a measuring method that does not involve weighing a specimen for measuring Young's modulus can be a significant improvement in practical uses.

A method for measuring mass, density, and Young's modulus without the weighing of the specimen has been developed based on a frequency equation incorporating the effect of an additional mass bonded to a wooden bar [1–6]. This method is named the "vibration method with additional mass" (VAM) in this study. This method involves decreasing resonance frequency by bonding the additional mass. The ratio of the resonance frequency with the additional mass to that without it is used for the frequency equation incorporating the effect of the concentrated mass bonded on a specimen and its position. And then, the mass ratio (concentrated mass/specimen) is calculated from the frequency equation.

For the application of VAM to actual uses, the suitable mass ratio (additional mass/specimen) [7], the connection between the additional mass and specimen [7], the crossers' position for the piled lumber [8], the specimen moisture content [9], and the bending vibration generation method [10] were examined. It is possible that VAM could be applicable to assess the deterioration of the cross beam of the timber guardrail [11].

The damping associated with attaching the additional mass to a specimen is related to the higher accuracy in the estimation using VAM. If the additional mass is not sufficiently fastened to a specimen, damping occurs at the attaching point [7].

Because a theoretical expression of the bonding state of the specimen and the additional mass is very difficult and a subject for the future study, the simplest case was considered in this study. The specimen was divided into two: the end portion and the main body. The estimation accuracy of VAM was investigated with the end portion used as the virtual additional mass. We assumed that the

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end portion had completely adhered to the body before dividing the specimen.

Theory

Longitudinal vibration and bending vibration under free–free conditions are considered. In the case of a thin beam with constant cross section, the effects of shear deflection and rotary inertia involved in the bending vibrational deflection are negligible, and the Euler–Bernoulli elementary theory of bending can be applied to the bending vibration.

The resonance frequency, represented by f_{n0} (n: resonance mode number, 0: value without the additional mass), is expressed as follows:

$$f_{n0} = \frac{m_{n0}}{2\pi l}\sqrt{\frac{E}{\rho}} \quad \text{(Longitudinal vibration)} \tag{1a}$$

$$f_{n0} = \frac{1}{2\pi}\left(\frac{m_{n0}}{l}\right)^2\sqrt{\frac{EI}{\rho A}} \quad \text{(Bending vibration)} \tag{1b}$$

where l, E, ρ, I, and A are the specimen length, Young's modulus, density, the second moment of area, and the cross-sectional area. m_{n0} is a constant and is expressed as follows:

$$m_{n0} = n\pi \quad \text{(Longitudinal)} \tag{2a}$$

$$\begin{aligned} &m_{10} = 4.730, \quad m_{20} = 7.853, \\ &m_{30} = 10.996, \quad m_{n0} = \frac{1}{2}(2n+1)\pi \\ &(n > 3) \quad \text{(Bending)} \end{aligned} \tag{2b}$$

The resonance frequency is decreased experimentally by attaching the additional mass while the dimensions, density, and Young's modulus are not altered. Hence, it can be said that m_{n0} changes to m_n. As a result, the resonance frequency after attaching the additional mass is expressed as follows:

$$f_n = \frac{m_n}{2\pi l}\sqrt{\frac{E}{\rho}} \quad \text{(Longitudinal)} \tag{3a}$$

$$f_n = \frac{1}{2\pi}\left(\frac{m_n}{l}\right)^2\sqrt{\frac{EI}{\rho A}} \quad \text{(Bending)} \tag{3b}$$

From Eqs. (1) and (2),

$$m_n = \frac{f_n}{f_{n0}} m_{n0} \quad \text{(Longitudinal)} \tag{4a}$$

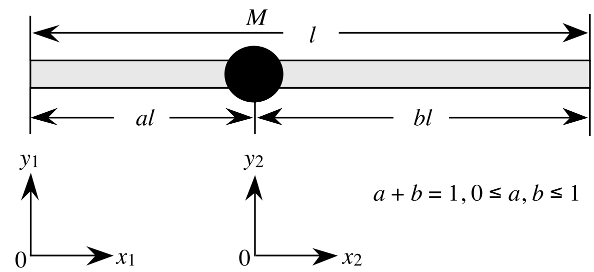

Fig. 1 A beam with additional mass

$$m_n = \sqrt{\frac{f_n}{f_{n0}}} m_{n0} \quad \text{(Bending)} \tag{4b}$$

The frequency equation for the free–free vibration with concentrated mass M placed at position $x = al$ (x: distance along the bar, $0 \le a \le 1$, $a + b = 1$) on a bar (Fig. 1) is expressed as follows:

$$\sin m_n + \mu m_n \cos a m_n \cos b m_n = 0 \quad \text{(Longitudinal)} \tag{5a}$$

$$\begin{aligned} &(\cos m_n \cosh m_n - 1) - \frac{1}{2}\mu m_n \{(\cos a m_n \cosh a m_n + 1) \\ &\times (\sin b m_n \cosh b m_n - \cos b m_n \sinh b m_n) \\ &+ (\cos b m_n \cosh b m_n + 1) \\ &\times (\sin a m_n \cosh a m_n - \cos a m_n \sinh a m_n)\} \\ &= 0 \quad \text{(Bending)} \end{aligned} \tag{5b}$$

where μ is the ratio of the concentrated mass to the mass of the bar, and is defined as

$$\mu = \frac{M}{\rho A l} \tag{6}$$

The measured resonance frequencies f_{n0} and f_n are substituted into Eq. (4) to calculate m_n. The calculated m_n is substituted into Eq. (5) to calculate μ. The specimen mass and density can be obtained by substituting the calculated μ, the concentrated mass, and the dimensions of a bar into Eq. (6). The Young's modulus can be calculated by substituting the estimated density, the resonance frequency without the concentrated mass and the dimensions of a bar into Eq. (1) [1–6].

A measurement of the specimen mass is not required for these calculations. The above is the calculation procedure of VAM.

Materials and methods

Specimens

Twenty rectangular Sitka spruce (*Picea sitchensis* Carr.) bars 30 mm (Radial direction, R) × 15 mm (Tangential direction, T) × 500 mm (Longitudinal direction, L) in dimension were used as the specimens. They were divided into five groups consisting of four replicate specimens each. The ends of the specimens were cut, and the specimen length (mm) for each group was decreased as follows:

Group 1: 500 → 495 → 490 → 485 → 480 → 475 → 470 → 465 → 460 → 455
Group 2: 500 → 450 → 445 → 440 → 435 → 430 → 425 → 420 → 415 → 410 → 405
Group 3: 500 → 400 → 395 → 390 → 385 → 380 → 375 → 370 → 365 → 360 → 355
Group 4: 500 → 350 → 345 → 340 → 335 → 330 → 325 → 320 → 315 → 310 → 305
Group 5: 500 → 300

The specimens were conditioned at 20 °C and 65% relative humidity. All tests were conducted under the same conditions.

Vibration tests

Longitudinal vibration test

Free-free longitudinal vibration tests were conducted on the initial specimens (500 mm long) and the specimens with an end cut using the following procedure: the test bar was placed on a small sponge near its center point. Then, the longitudinal vibration was generated by tapping the RT-plane of one end in the L-direction using a wooden hammer, while the first-mode vibration of the specimen was detected using a microphone placed at the other end. The signal was processed through a fast Fourier transform (FFT) digital signal analyzer (Multi-Purpose FFT Analyzer CF-5220, Ono-Sokki, Co., Ltd., Yokohama, Japan) to observe the high-resolution resonance frequencies. The longitudinal vibration tests were performed, while the specimen was shortened stepwise. A diagram of the experimental setup is demonstrated in Fig. 2.

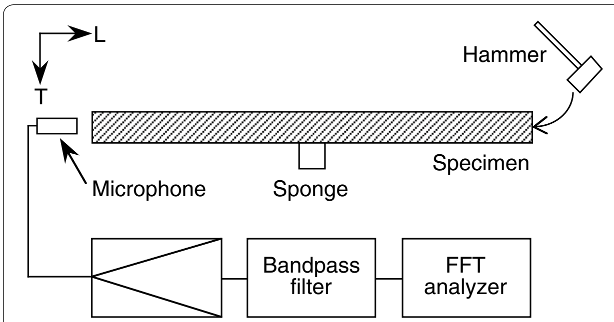

Fig. 2 Schematic diagram of the experimental setup for the longitudinal vibration tests

Bending vibration test

Free–free bending vibration tests were conducted on the initial specimens (500 mm long) and the specimens with an end cut using the following procedure: the test bar was suspended by two threads at the nodal positions of the free–free vibration, corresponding to its first resonance mode. Then, the bending vibration was generated by tapping the LR-plane of specimen in the T-direction using a wooden hammer. The motion of the specimen was detected using a microphone. The signal was processed through the FFT digital signal analyzer to yield the high-resolution resonance frequencies. The bending vibration tests were performed, while the specimen was shortened stepwise. A diagram of the experimental setup is demonstrated in Fig. 3.

Estimation of mass, density, and Young's modulus by VAM

The initial specimen with a length of 500 mm was analyzed together as a combination of the end portion and the main body as shown in Fig. 4. The cut end portion was used as the virtual additional mass in VAM. The measured resonance frequencies before and after the cutting of the end were substituted into Eq. (4). The position of the additional mass used for the calculation of VAM

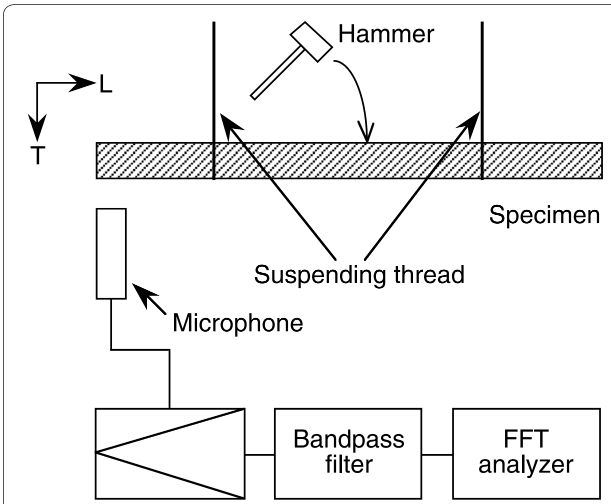

Fig. 3 Schematic diagram of the experimental setup for the bending vibration tests

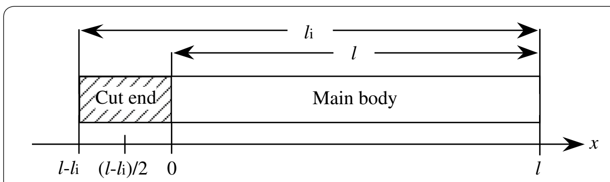

Fig. 4 Schematic diagram of the specimen

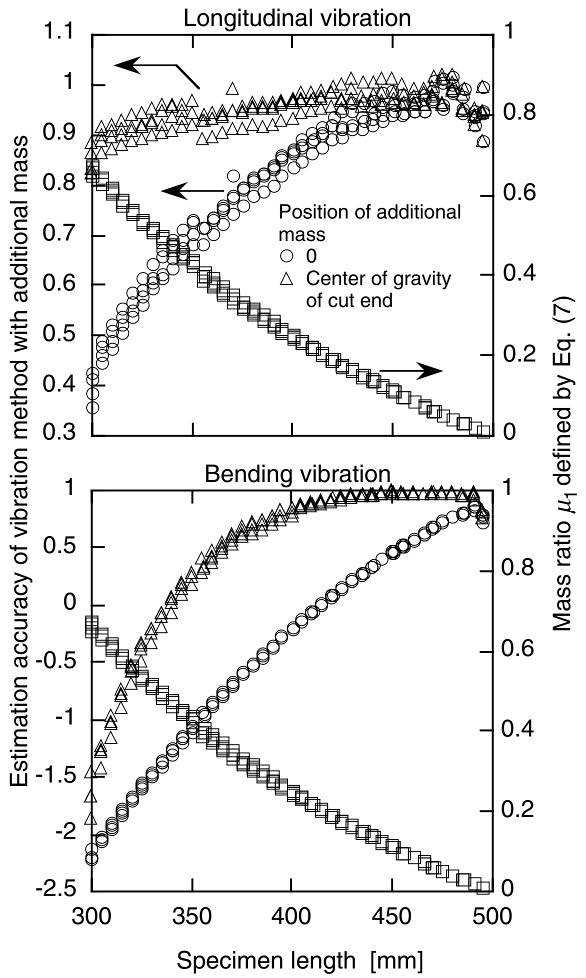

Fig. 5 Experimental estimation accuracy of the vibration method with additional mass (VAM)

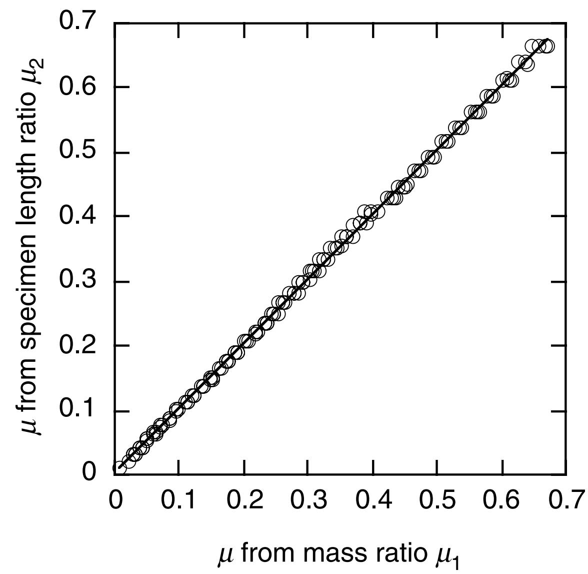

Fig. 6 Inhomogeneity of specimens

was 0 and $(l - l_i)/2$ (<0) (where l_i is the initial specimen length = 500 mm, and l is the specimen length after end cutting). The position $(l - l_i)/2$ is the center of gravity of the cut end. The following mass ratio μ_1 and length ratio μ_2 were used for μ in Eq. (6):

$$\mu_1 = \frac{W_i - W}{W} \quad (W_i: \text{ initial specimen mass, } W: \text{ specimen mass after end cutting}) \tag{7}$$

$$\mu_2 = \frac{l_i - l}{l} \tag{8}$$

The mass ratio (estimated specimen mass from VAM/measured specimen mass $\neq \mu_1$) that means the deviation of the estimated value from the true value was used to assess the estimation accuracy for VAM.

Results and discussion

The average (standard deviation) density and Young's modulus of the initial specimens were 426 (20) kg/m^3, 12.50 (0.75) GPa (longitudinal vibration), and 12.04 (0.75) GPa (bending vibration), respectively.

Figure 5 demonstrates the estimation accuracy of VAM. It was slightly low for the length of 495 mm because the change in the resonance frequency was small. The estimation accuracy was increased by correcting the position of the additional mass from 0 to $(l - l_i)/2$. In a previous study, the estimation accuracy varied from 0.81 to 1.07 (longitudinal vibration, attaching the additional mass to wood: wood screw) for $0.012 \le \mu_1 \le 0.18$, and from 0.26 to 1.11 (longitudinal vibration, attaching the additional mass to wood: adhesive tape) for $0.012 \le \mu_1 \le 0.17$ [7] while it varied from 0.92 to 1.00 [longitudinal vibration, position of the additional mass: $(l - l_i)/2$] for $0.008 \le \mu_1 \le 0.43$ in this study. Hence, it was concluded that the cut end had completely adhered to the main body before cutting because the tissue structure of the wood was continuous.

The estimation accuracy reduced with decreasing specimen length (Fig. 5). The effect of the decrease in the specimen length on the accuracy of estimation was explored theoretically.

Since the resonance frequencies of the longitudinal and bending vibrations are proportional to the specimen length and the square of the specimen length, respectively, the resonance frequencies of the longitudinal and bending vibrations become l/l_i and $(l/l_i)^2$ times that of the initial specimen, respectively. These resonance frequencies (first mode) were substituted into Eq. (4) to calculate μ values, where the μ is expressed by μ_3. The accuracy of estimation can be expressed by μ_2/μ_3. This calculation procedure assumes that a specimen is uniform, where $\mu_1 = \mu_2$. In this study, μ_1 was approximately equal to μ_2 (Fig. 6). There was a high correlation between μ_1 and μ_2 at 99% significant level. The regression equation was as follows:

$$\mu_2 = 1.0021\mu_1 + 0.00333 \quad \text{(Correlation coefficient } = 0.99962) \tag{9}$$

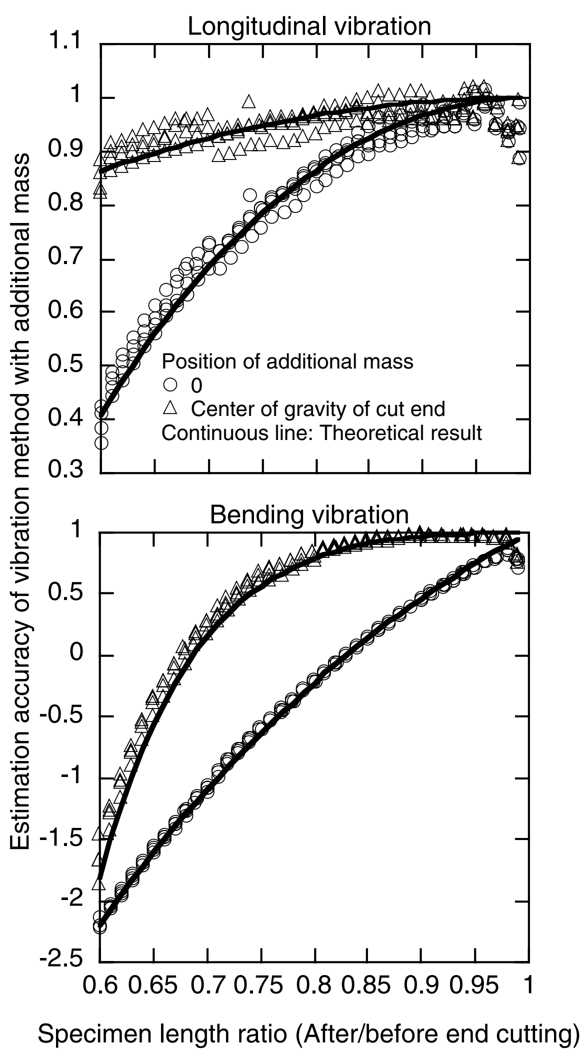

Fig. 7 Theoretical estimation accuracy of the vibration method with additional mass (VAM)

The ratio μ_2/μ_3 is plotted against the specimen length ratio (after/before end cutting) (Fig. 7). In order to maintain high estimation accuracy, the specimen length should not be too short. For example, the estimation accuracy was more than 0.90 when the specimen length ratio was more than 0.83 for longitudinal vibration (position of the additional mass = 0), 0.66 for longitudinal vibration [position of the additional mass = $(l - l_i)/2$], 0.98 for bending vibration (position of the additional mass = 0), and 0.85 for bending vibration [position of the additional mass = $(l - l_i)/2$]. The reason that estimation accuracy of the longitudinal vibration was higher than that of the bending vibration was because the variation range of the resonance frequency due to end cutting of the longitudinal vibration was lower than that of the bending vibration.

The experimental estimations had high overlap with the theoretical estimations (Fig. 7). The averages of the ratio of experimental value to theoretical one that mean the deviation of the experimental values from the theoretical ones were 1.00 (longitudinal, uncorrected), 1.00 (longitudinal, corrected), 0.92 (bending, uncorrected) and 1.01 (bending, corrected), respectively.

Conclusions

The specimen was divided into a cut end and the main body. The cut end was used as the additional mass for VAM. The following results were obtained:

1. The estimation accuracy for VAM was increased by using the cut end as the additional mass. Hence, the cut end had completely adhered to the main body before cutting.
2. The estimation accuracy decreased with the decreasing specimen length.
3. In order to maintain high estimation accuracy the specimen length should not be too short.
4. The estimation accuracy of the longitudinal vibration was higher than the bending vibration because the variation range of the resonance frequency due to end cutting of the longitudinal vibration was smaller than that of the bending vibration.

Abbreviations

VAM: vibration method with additional mass; FFT: fast Fourier transform; L: longitudinal direction; R: radial direction; T: tangential direction.

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Authors' contributions
All authors designed the experiments. YK performed the experiments, analyzed the data, and was a major contributor in writing the manuscript. All authors contributed to interpretation and discussed results. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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