MASS ESTIMATION OF PILED ROUND BARS THROUGH VIBRATION TESTS

*Yoshitaka Kubojima**

Researcher
Forestry and Forest Products Research Institute
Ibaraki, Japan
E-mail: kubojima@ffpri.affrc.go.jp

Satomi Sonoda

Researcher
Toyama Prefectural Agricultural,
Forestry & Fisheries Research Center
Toyama, Japan
E-mail: satomi.sonoda@pref.toyama.lg.jp

Hideo Kato

Researcher
Forestry and Forest Products Research Institute
Ibaraki, Japan
E-mail: KATO_Hideo@ffpri.affrc.go.jp

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Abstract. A simple method was developed to estimate the mass of each piled round bar using a vibration test. Specimens used in the tests were Japanese cedar (*Cryptomeria japonica* D. Don) round bars (diameter = 180 mm, length = 2000 mm) with a pith and a back split. Vibration tests were conducted, and the effect of sticker positions on the vibration test was investigated. The vibration tests were conducted for each piled round bar and the estimation accuracy of the vibration method with additional mass (VAM) was examined. By placing the round bar on the stickers, the resonance frequency of the longitudinal vibration was stable while that of the bending vibration decreased with the increase in the distance between the sticker and the specimen end and stabilized when this distance was greater than or equal to 0.2 l (l: specimen length). When the round bars were piled with no stickers, the bending resonance frequency could not be identified and the VAM estimation accuracy of the longitudinal vibration depended on the specimens. The estimation accuracy of VAM for the longitudinal vibration of the piled round bars while using stickers made of wood and rubber was superior to that without stickers. The estimation accuracy of VAM for the bending vibration was sufficiently high. These results were attributed to the reduction of the vibration restraint by the stickers and the contact between adjacent round bars.

Keywords: Additional mass, density, piled round bars, rubber, sticker, vibration test, Young's modulus.

INTRODUCTION

Evaluating the strength of the log is effective for estimating the strength of lumber obtained from a log. Since there is a high correlation between the Young's modulus and the strength of wood (Nakayama 1968), the strength can be predicted using the Young's modulus. Hence, it is possible that the strength of the lumber is estimated using the Young's modulus of the log. However, classifying based on log shapes such as diameter, length, and warp is required in log markets and Young's modulus is not used for classifying logs.

Because a vibration test is a nondestructive and simple testing method for measuring the Young's modulus, it is expected to be promising for classifying logs using the Young's modulus in log markets. Calculation of the Young's modulus based on the vibration theory needs density (mass) of the log. In the case of piled logs, because the log is large and heavy, handling it is difficult, and determining the

* Corresponding author

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output of a scale is time consuming. Space is required to place the logs when the pile is dismantled.

Various testing methods for the piled logs were proposed (Aratake et al 1992; Aratake et al 1994; Kiribayashi et al 2016; Urabe et al 2017; Kishi et al 2019). The higher resonance frequencies of longitudinal vibration of piled logs were effective for estimating the modulus of rupture, the modulus of elasticity of lumber, and the MC of lumber and logs (Aratake et al 1992; Aratake et al 1994). The stress wave propagation times of piled logs were also effective for estimating the change in weight of the logs (Kiribayashi et al 2016). Calculation methods for the Young's modulus of the log without measuring its density were used (Urabe et al 2017; Kishi et al 2019). In these studies, the density was estimated based on the constant oven-dried density and the MC.

In the authors' previous study, a method was proposed for measuring the mass of wood lumber in piles using a vibration test without weighing the wood lumber (Kubojima et al 2020a). The specimen mass was estimated without weighing it using the method based on the difference of the resonance frequency when a concentrated mass is added to and subtracted from wood (Skrinar 2002; Türker and Bayraktar 2008; Kubojima and Sonoda 2015; Matsubara et al 2015; Kubojima et al 2016; Matsubara et al 2016; Sonoda et al 2016; Kubojima et al 2017a; Kubojima et al 2017b; Kubojima et al 2018a; Kubojima et al 2018b; Kubojima et al 2019; Kubojima et al 2020a; Kubojima et al 2020b; Kubojima et al 2021). Hereafter, this method is referred to as the "vibration method with additional mass (VAM)."

This study aims to obtain the basic data for applying VAM to piled logs. For this purpose, round bars were used as the specimens.

THEORY

Here, longitudinal and bending vibrations under free-free conditions are considered. The effects of shear deflection and rotatory inertia on the bending vibrational deflection of a thin beam with a constant cross section are negligible, and the Euler–Bernoulli elementary theory of bending can be applied to the bending vibration.

The resonance frequency, denoted by f_{n0} (n refers to the resonance mode number and 0 reflects the value without the additional mass), can be 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 can be expressed as follows:

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

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

The resonance frequency is experimentally reduced 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. Thus, 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,

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

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

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) can be expressed as follows:

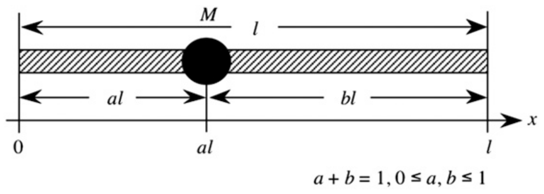

Figure 1. Beam with an additional mass.

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

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

where μ is the ratio of the concentrated mass to the mass of the bar and can be defined as follows:

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

To calculate m_n, the measured resonance frequencies (f_{n0} and f_n) are substituted in Eq 4. The calculated m_n is substituted in Eq 5 to calculate μ. The specimen mass and density can be obtained by substituting the calculated μ, concentrated mass, and dimensions of a bar in Eq 6. The Young's modulus can be calculated by substituting the estimated density, resonance frequency without the concentrated mass, and dimensions of a bar in Eq 1 (Skrinar 2002; Türker and Bayraktar 2008; Kubojima and Sonoda 2015; Matsubara et al 2015; Kubojima et al 2016; Matsubara et al 2016). The specimen mass is not required for these calculations.

These calculations are the VAM procedure. In this study, the estimation accuracy of VAM was expressed by the ratio of the specimen mass estimated by VAM (M_{VAM}) to the measured specimen mass (M_0). VAM can be applied in the MC range of air-dried MC (12%) to high MC (134% and 238%) (Kubojima et al 2017b; Kubojima et al 2021).

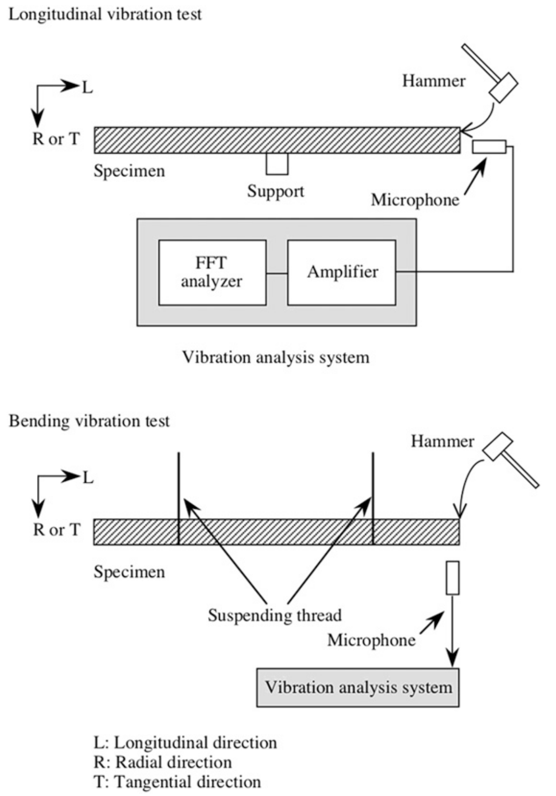

Figure 2. Schematic diagram of the experimental setup for the vibration tests (first specimen-placing conditions).

The estimation accuracy of VAM is considered sufficiently high at $0.9 \leq M_{\mathrm{VAM}}/M_0 \leq 1.1$ in this study.

MATERIALS AND METHODS

Specimens

Specimens used in the tests were Japanese cedar (*Cryptomeria japonica* D. Don) round bars (10 bars, diameter = 180 mm, length = 2000 mm) with a pith and a back split. VAM can be applied to round bars with and without the back split (Kubojima et al 2018b). The length/diameter ratio of 2000/180 in this study is appropriate to VAM according to our previous studies (Kubojima et al 2018b; Kubojima et al 2020b). The vibration tests for the Japanese cedar logs were conducted in a

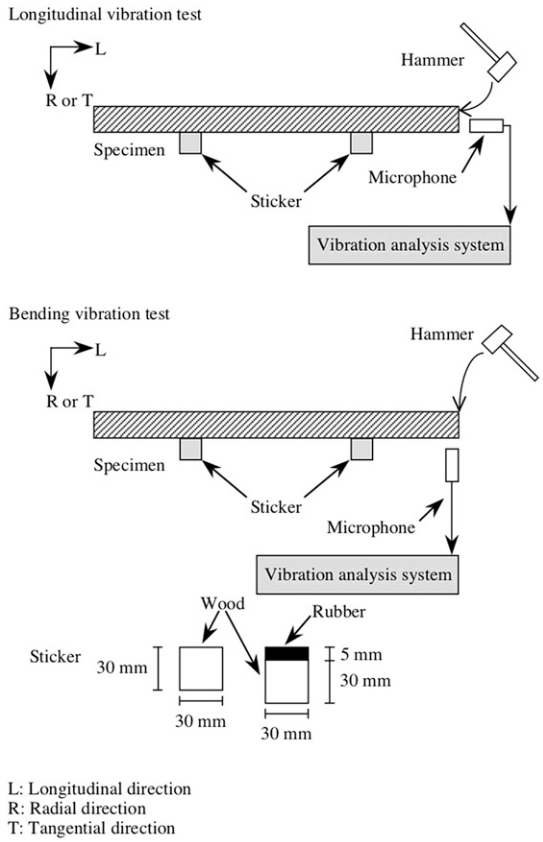

Figure 3. Schematic diagram of the experimental setup for the vibration tests (second specimen-placing conditions).

sawmill building with no control over the temperature and RH.

Specimen-Placing Conditions in the Vibration Tests

To examine the effect of the vibration restraint on the measurements, the following three cases were investigated.

The first case (Fig 2) involved placing the round bars around the nodal position of the free-free longitudinal vibration corresponding to their first resonance mode (0.5 *l*) and suspending them by two threads at the nodal positions of the free-free bending vibration corresponding to the first resonance mode (0.2242 *l* and 0.7758 *l*). The support for the longitudinal vibration test in Fig 2 was a cushioning material. Ten specimens were used under these specimen-placing conditions.

The second case (Fig 3) involved placing the round bars on two stickers at 0, 100, 200, 300, 400, 450 (≈0.2242 *l*), and 500 mm from both ends. Two types of stickers were used: one was made of Japanese cedar wood (30 mm × 30 mm × 500 mm) and the other was composed of the aforementioned wooden sticker and rubber (30 mm × 5 mm × 500 mm, Rubber sheet GR-17, Wakisangyo Co., Ltd). Three specimens were used under these specimen-placing conditions.

The third case (Figs 4-7) involved piling the round bars with and without stickers. When the stickers were not used, the round bars located at the bottom layer (No. 1-4) were in direct contact with the floor, and the adjacent round bars were in direct contact with each other. When the stickers were used, they were placed at the nodal positions of the free-free bending vibration corresponding to the first resonance mode (0.2242 *l* and 0.7758 *l*). The round bars located at the bottom layer (No. 1-4) were placed on the stickers that were the aforementioned complex of the wooden sticker and rubber, and the rubber with the dimensions of 30 mm × 5 mm × 300 mm and 30 mm × 5 mm × 150 mm (aforementioned rubber) were inserted between the adjacent round bars. The rubber with the length of 150 mm and that with the length of 300 mm were placed vertically and horizontally, respectively, as shown in Fig 4(b). Ten specimens were used under these specimen-placing conditions.

Longitudinal Vibration Tests

In the aforementioned three specimen-placing cases, the longitudinal vibration was initiated by hitting the RT(radial tangential)-plane of the round bar using a hammer with an iron head. Round bar motion was detected using a microphone (MI-1235; Ono Sokki Co., Ltd, Yokohama, Japan) at the same end (Figs 2-4). The microphone was pointed in the L (longitudinal)-direction of the specimen. The signal was processed through a Fast Fourier transform (FFT) digital signal analyzer (FFT Analyzer CF-9200; Ono Sokki Co., Ltd,

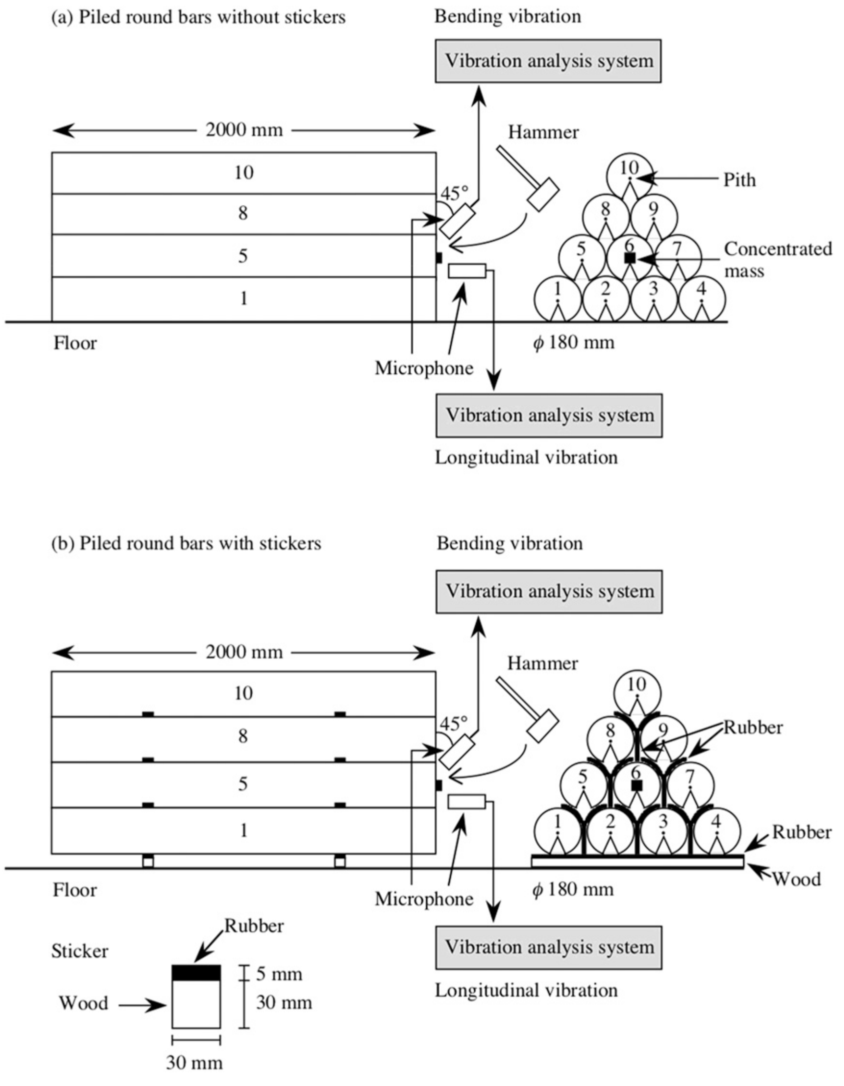

Figure 4. Schematic diagram of the experimental setup for the vibration tests (third specimen-placing conditions).

Yokohama, Japan, Frequency resolution = 0.25 Hz, Preamplifier MI-3111; Ono Sokki Co., Ltd, Yokohama, Japan) to yield high-resolution resonance frequencies. The round bars without the concentrated mass were used under the first and second specimen-placing conditions (Figs 2 and 3). The round bars with and without the concentrated mass were used under the third specimen-placing conditions (Fig 4). A steel plate (dimensions = 70.1 mm × 70.1 mm × 9.2 mm, mass = 352.84 g) was used as the concentrated mass and was fastened to the RT-plane of the round bar using a set of four wood screws through the holes of the plate.

Bending Vibration Tests

The bending vibrations were initiated by hitting the LT-plane of the round bar with the aforementioned hammer under the first and second specimen-

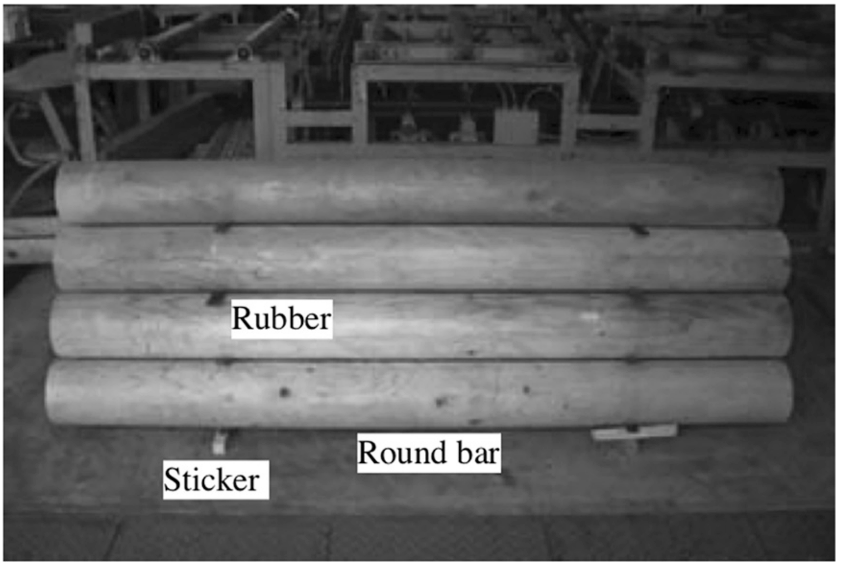

Figure 5. Round bars, stickers, and rubber sheet.

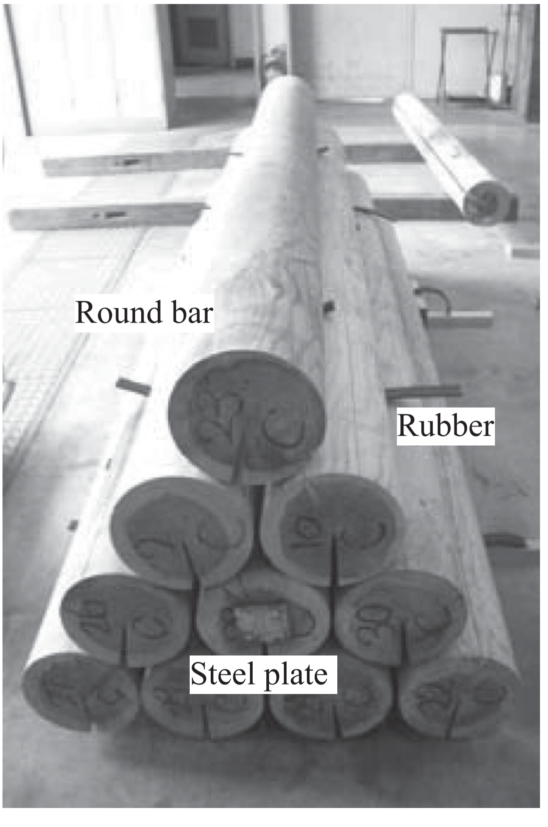

Figure 6. Round bars, stickers, rubber sheet, and the steel plate.

placing conditions (Figs 2 and 3), and by hitting the RT-plane of the specimen with the hammer under the third specimen-placing conditions (Fig 4). The motion of the round bar was detected by the aforementioned microphone at the same end. The microphone was pointed in the vertical direction under the first and second specimen-placing conditions and was pointed at 45 degrees with respect to the vertical direction under the third specimen-placing conditions. The signal was processed through the aforementioned FFT digital signal analyzer to yield high-resolution resonance frequencies. The round bars without concentrated mass were used in the first and second specimen-placing conditions. The round bars with and without the concentrated mass were used for the third specimen-placing conditions. The aforementioned steel plate was used as the concentrated mass and was fastened to the RT-plane of the round bar with a set of four wood screws through the holes of the plate.

RESULTS AND DISCUSSION

The mean and standard deviation of the density of 10 specimens subjected to the first specimen-placing conditions, ie the free-free condition

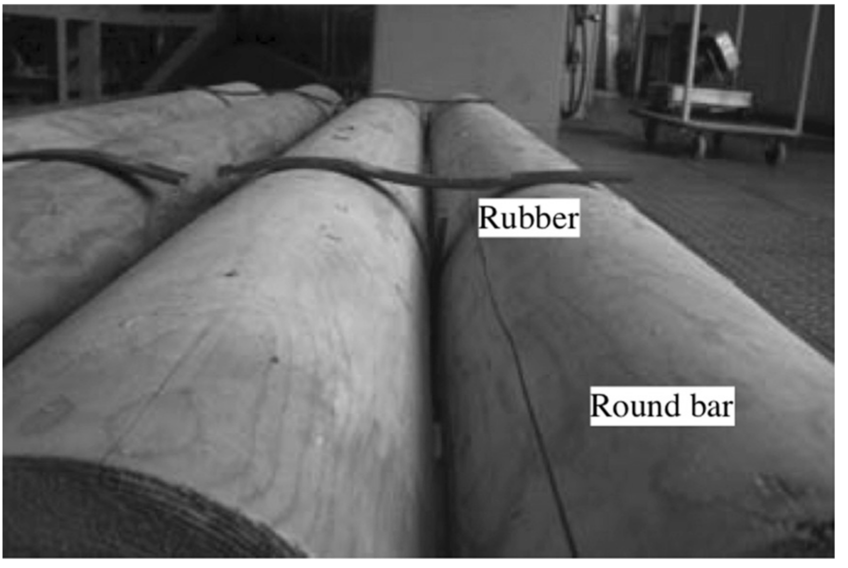

Figure 7. Round bars and rubber sheet.

corresponding to the first resonance mode, were 414 and 30 kg/m^3, respectively, while those of Young's modulus were 8.43 and 1.45 GPa (longitudinal vibration) as well as 7.95 and 1.51 GPa (bending vibration), respectively.

Figure 8 is the result of the second case in the section "Specimen-placing conditions in the vibration tests" and shows the relationship between the resonance frequency and the distance from the sticker to the specimen end (*d*). The horizontal axis of Fig 8 is the ratio *d/l*. The resonance frequency of the longitudinal vibration was near that obtained under the free-free condition; on the other hand, the resonance frequency of the bending vibration depended on the position of the sticker: it decreased with the increase in *d* and was stable near the value obtained under the free-free condition when the sticker was placed at $d \geq 0.2\ l$. Thus, the resonance frequency was far from the value obtained under the free-free condition when the vibration restraint at the position of the sticker was strong, whereas it was near the value obtained under the free-free condition with weak vibration restraint at the position of the sticker. Thus, the restraint of the bending vibration was stronger than that of the longitudinal vibration because the vibration direction in case of bending and longitudinal vibrations was parallel and perpendicular to the gravity of the round bar, respectively, and the restraint of the bending vibration weakened when the position of the sticker approached the nodal position of the free-free vibration corresponding to the first resonance mode ($d = 0.2242\ l$). Based on these results, the positions of sticker were 0.2242 *l* and 0.7758 *l* for the third specimen-placing conditions.

Table 1 shows the estimation accuracy of VAM conducted on the piled round bars without using the stickers. Since no clear frequency spectrum (Fig 9) was observed, the bending resonance frequency could not be identified. This suggests that the bending vibration was restrained because the round bar was in contact with the floor and adjacent round bars. The resonance frequency of the longitudinal vibration without the concentrated mass was larger than that obtained under the free-free condition and this was similar to the results obtained in the previous study (Aratake et al 1992). The estimation accuracy of VAM for the longitudinal vibration varied widely. It was suggested that low and high estimation accuracies of VAM were caused by the strong and weak restraints of vibration, ie

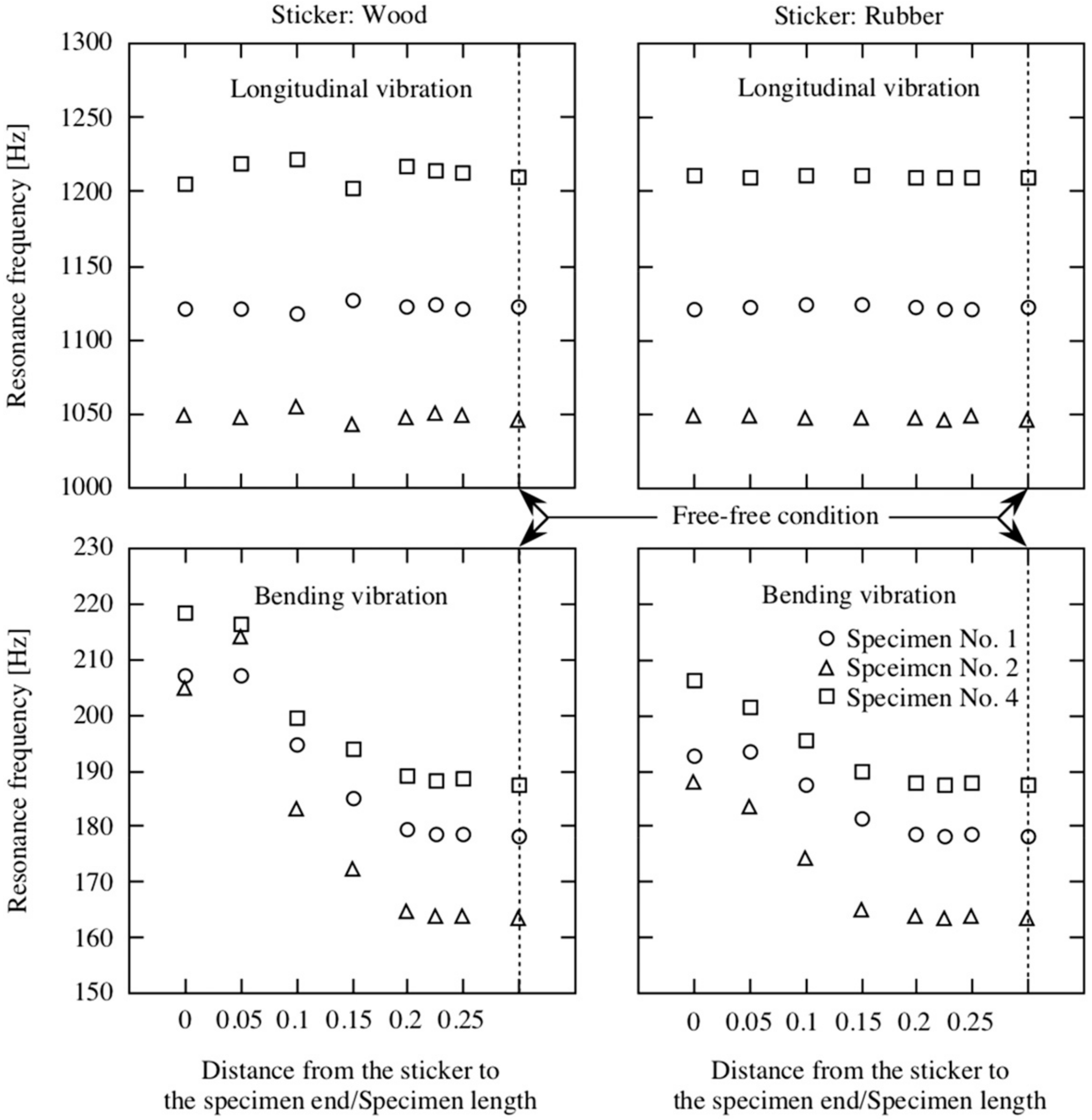

Figure 8. The relationship between the resonance frequency and the position of the sticker.

the adjacent round bars were in sufficient or insufficient contact, respectively, with each other, which was confirmed with the naked eye.

Table 2 shows the estimation accuracy of VAM conducted on the piled round bars when the stickers made of wood and rubber were used. The resonance frequencies of the longitudinal vibration without the concentrated mass were almost in agreement with those under the free-free condition. Hence, when the Young's modulus is estimated through VAM, the resonance frequency without the concentrated mass measured under the condition with the rubber is more appropriate than that measured under the condition without the rubber. The estimation accuracy of VAM for the longitudinal vibration was improved using the stickers. Since clear frequency spectra (Fig 9) could be obtained for

Table 1. The accuracy of vibration method with additional mass (VAM) used for the piled round bars with no stickers (longitudinal vibration).

Specimen	M_0 [g]	f_{FF} [Hz]	f_{10} [Hz]	f_{10}/f_{FF}	f_1 [Hz]	M_{VAM} [g]	M_{VAM}/M_0
1	20,920	1124.000	1177.400	1.05	1165.600	34,842	1.67
2	20,530	1051.000	1091.800	1.04	1072.400	19,484	0.95
3	21,977	1177.000	1221.200	1.04	1199.400	19,392	0.88
4	20,234	1214.000	1268.000	1.04	1248.400	22,456	1.11
5	23,596	1239.000	1284.200	1.04	1274.400	45,875	1.94
6	20,550	1138.000	1167.400	1.03	1148.800	21,774	1.06
7	17,743	1083.000	1140.000	1.05	1111.600	13,782	0.78
8	19,324	1212.000	1245.800	1.03	1221.200	17,493	0.91
9	19,815	1182.000	1222.000	1.03	1204.600	24,411	1.23
10	19,842	1088.000	1098.600	1.01	1070.600	13,462	0.68

M_0, Measured mass; f_{FF}, Resonance frequency under the first specimen-placing conditions (the free-free conditions); f_{10}, Resonance frequency without the concentrated mass; f_1, Resonance frequency with the concentrated mass; M_{VAM}, Mass estimated through VAM.

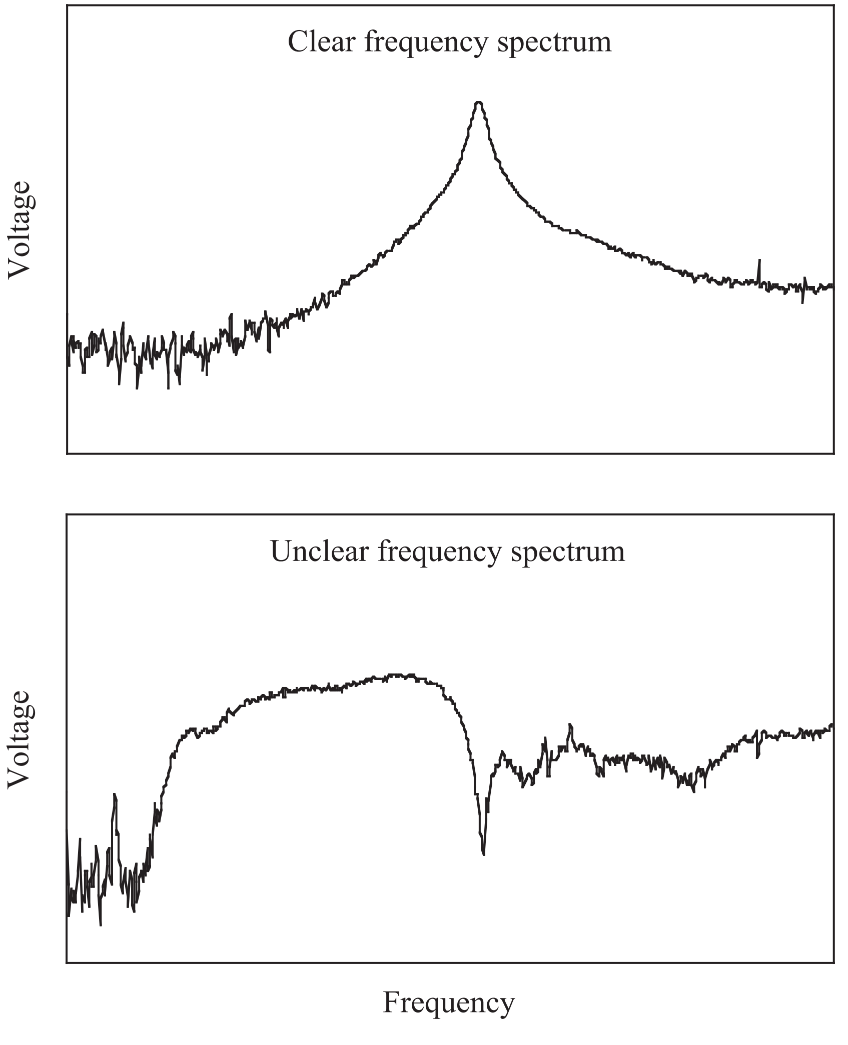

Figure 9. Examples of clear frequency spectra and unclear frequency spectra.

Table 2. The accuracy of vibration method with additional mass (VAM) used for the piled round bars with the stickers made of wood and rubber.

Specimen	M_0 [g]	f_{FF} [Hz]	f_{10} [Hz]	f_1 [Hz]	M_{VAM} [g]	M_{VAM}/M_0
			Longitudinal vibration			
1	20,938	1123.000	1126.600	1105.000	18,029	0.86
2	20,574	1049.000	1048.800	1032.000	21,656	1.05
3	21,987	1177.000	1176.800	1156.600	20,183	0.92
4	20,275	1213.000	1214.200	1190.000	17,328	0.85
5	23,620	1238.000	1239.400	1220.000	22,171	0.94
6	20,573	1138.000	1141.000	1120.200	18,982	0.92
7	17,775	1082.000	1082.200	1059.000	16,082	0.90
8	19,330	1211.000	1212.600	1188.600	17,452	0.90
9	19,827	1182.000	1183.000	1160.000	17,773	0.90
10	19,886	1088.000	1088.000	1067.000	17,906	0.90
			Bending vibration			
1	20,938	170.000	178.800	173.250	20,538	0.98
2	20,574	164.500	163.700	159.000	22,382	1.09
3	21,987	181.750	181.800	176.750	23,207	1.06
4	20,275	187.750	188.200	182.450	20,901	1.03
5	23,620	193.750	193.700	188.750	25,415	1.08
6	20,573	174.000	173.650	168.450	21,369	1.04
7	17,775	168.250	168.500	162.750	18,484	1.04
8	19,330	187.500	187.250	181.100	19,290	1.00
9	19,827	181.250	180.800	175.450	21,651	1.09
10	19,886	169.250	168.750	163.500	20,487	1.03

M_0, Measured mass; f_{FF}, Resonance frequency under the first specimen-placing conditions (the free-free conditions); f_{10}, Resonance frequency without the concentrated mass; f_1, Resonance frequency with the concentrated mass; M_{VAM}, Mass estimated through VAM.

the piled round bars by tapping the RT-plane in the L-direction similar to those obtained in our previous studies for piled lumber (Kubojima et al 2018a; Kubojima et al 2020a), the bending resonance frequency corresponding to the first mode could be identified. The estimation accuracy of VAM for the bending vibration was sufficiently high because the rubber reduced the vibration restraint. The estimation accuracy of VAM for the bending vibration was higher than that for the longitudinal vibration, which can be attributed to the error in measuring the resonance frequencies with and without the concentrated mass, ie m_1 for the longitudinal vibration (Eq 4[a]) is more sensitive to the change in resonance frequency than that for the bending vibration (Eq 4[b]) (Kubojima et al 2017b).

Since measurements without stickers were performed on the day after the measurements with stickers, the measured masses and longitudinal resonance frequencies under free-free conditions, which are listed in Table 2, were different from those listed in Table 1. The differences between the measured masses and longitudinal resonance frequencies under free-free conditions listed in Table 1 and those listed in Table 2 are thought to be very small.

CONCLUSIONS

The effects of position of sticker and piling on the vibration tests of round bars were examined, and the following results were obtained:

1) By placing the round bar on the stickers, the resonance frequency of the longitudinal vibration was near the value obtained under the free-free condition, while that of the bending vibration decreased with the increase in the distance from the sticker to the specimen end and was stable near the value obtained under the free-free conditions when this distance was larger than or equal to 0.2 *l*. This can be attributed to

the difference in the level of vibration restraint between longitudinal and bending vibrations.

2) In case of the piled round bars with no stickers, the bending resonance frequency could not be identified. The estimation accuracy of VAM for the longitudinal vibration depended on the specimens. This was attributed to the difference in the level of vibration restraint between longitudinal and bending vibrations. This restraint resulted from the contact between the adjacent round bars.
3) The bending resonance frequency corresponding to the first mode for the piled round bars with stickers could be identified by tapping the RT-plane in the L-direction.
4) When the stickers made of wood and rubber were used, the estimation accuracy of VAM for the longitudinal vibration was superior to that without the stickers. The estimation accuracy of VAM for the bending vibration was sufficiently high. These results were attributed to the reduction of the vibration restraint by stickers and the contact between the adjacent round bars.

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