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ESTIMATION OF STIFFNESS OF STANDING TREES BY VIBRATION CHARACTERISTICS

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ABSTRACT: The area of Japanese forests planted with trees has remained constant in contrast to the increase in the area logged. This is due to the fact that forest owners are unable to quantitatively evaluate the value of standing tree. The value of timber used for building materials in the Japanese timber distribution system is determined by measuring Young's modulus only after the timber has been cut from the mountain, leaves the forest owner's hands, and is sawn into lumber at a sawmill. The ultimate goal of this study was to estimate Young's modulus in the standing tree condition after sawing, so that the value of the timber could be determined at a stage when the owner of the forest could know the value of the timber. In order to clarify the possibility of estimating Young's modulus from vibration characteristics using natural frequencies in standing tree, forced bending tests of standing tree were conducted and compared with Young's modulus calculated from the load-displacement relationship of the tree. As a result, a correlation between natural vibration and stiffness was obtained. In this study, the position of the center of gravity and weight of the tree were estimated values, but if the estimated values can be clarified, it may be possible to measure them more precisely.

KEYWORDS: Young's modulus, Nondestructive inspection, Wood distribution, Vibration, Bending test

1 – INTRODUCTION

1.1 BACKGROUND

In 2021, The Act for Promotion of Use of Wood in Public Buildings was revised and the "The Act for Promotion of Use of Wood in Buildings to Contribute to Realization of a Decarbonized Society" came into effect. As the scope of the law expanded from public buildings to all buildings, the proportion of wooden buildings has increased. This increase in wooden buildings reflects the growing use of wood. The area of timber harvesting in domestic forests has also been on the rise year by year since around 70,000 ha in 2013. However, the area of replanting has remained steady at about 20,000 ha. [1] This low reforestation rate has led to an increase in neglected forests after logging and poorly managed mountain forests, which could result in a decrease in the supply of domestic timber in the future. One of the causes of the decline in reforestation rates is thought to be the inability of forest owners to quantitatively assess the value of standing tree in their forests.

1.2 OBJECTIVES

Currently, the timber in circulation is harvested by forest owners, landowners, or forestry cooperatives, and shipped to the log market as logs. These logs are then purchased at prices evaluated by sawmills or other processing facilities, and after being transported to the sawmill, they are processed into lumber. The wood used in construction materials is dried after being processed, and its Young's modulus is measured using methods such as longitudinal vibration tests, which is when strength-based quantitative assessments are made. While forest owners perform tasks such as thinning and pruning to improve the value of timber, they are unable to assess the value of each individual tree or the overall timber value of the forest until it is processed into lumber. Therefore, by enabling forest owners to make decisions about the value of timber, it is believed that a more accurate understanding of the forest's value can be achieved, which may contribute to the proper maintenance of the forest.

The ultimate goal of this study is to enable forest owners to clearly understand the value of timber and receive appropriate compensation, thereby promoting the active maintenance and management of forests.

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1.3 POSITIONING OF THIS STUDY

One method to investigate the stiffness of standing trees is the forced bending test of the tree. [2] Previous studies have estimated the Young's modulus by forcibly bending the standing tree, and it has been shown that there is a correlation with the bending Young's modulus of logs. Additionally, other studies [3], [4] have revealed a correlation between the Young's modulus of logs and sawn timber using the longitudinal vibration method, as well as a correlation between the propagation speed of elastic shock waves in logs and the bending Young's modulus of sawn boards. However, the forced bending test of standing trees requires large testing equipment, making it inefficient. Therefore, in this study, we attempted to establish an efficient method for estimating the stiffness of standing trees by measuring their natural vibration characteristics and deriving a relationship between stiffness and natural frequency.

2 – MEASUREMENT

2.1 MEASUREMENT THEORY

This study focused on th e natural frequencies det ermined by the stiffness of standing trees. Natural frequencies are generall y determined from the m ass and stiffness of an ob ject. The natural frequen cies of standing trees swa yed by natural wind are c alculated, and Young's mo dulus is estimated from these values. The Young's modul us is compared to the Young's modulus of logs and sawn l umber in forced bending tests, which have been correlate d with the Young's modulus of logs and sawn lumber in p revious studies. Replacing the standing tree with a one-m ass vibration model as shown in ***Figure 1***, the following e quation (1) is used to calculate Young's modulus from the natural frequencies.

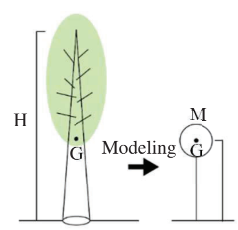

Figure 1 *: Single Point System Modeling of Standing Trees*

$$E = \frac{4mf^2L^3}{3I}\pi^2 \qquad (1)$$

E : Young's Modulus (N/mm^2), m : mass (N),
L : length (mm) f : natural frequency (Hz=/s),
I : cross-sectional secondary moment (mm^4)

2.2 MEASUREMENT METHOD

To estimate Young's modulus, the natural frequencies of standing trees are measured by constant microtremors. Forced bending tests were conducted on standing trees for which previous studies have shown a correlation between Young's modulus of logs and lumber. As a confirmatory test, the elastic shock wave velocity of propagation, which has been shown to correlate between logs and lumber, was measured at the same time. In these three tests, a Scope Radar DL350 (Yokogawa Test & Measurement Corporation) was used for data recording. Detailed measurement methods are described below.

2.2.1 NATURAL FREQUENCY MEASUREMENT TEST

To measure natural frequencies, a high-sensitivity accelerometer (ARGL-10A, Tokyo Measuring Instruments Laboratory Co., Ltd.) is attached to a standing tree to measure the acceleration generated by natural wind-induced shaking. The natural frequency is identified by performing a Fourier transform on the acceleration obtained. Since it is impossible to attach the accelerometer directly to the tree, it was fixed to the tree using a lashing belt and a jig made of a metal plate between the jig and the tree, as shown in ***Figure 2***. The installation point was approximately 1,200 mm above the ground surface on the upper side of the slope relative to the standing tree. For specimens that were difficult to install, the test was conducted by shifting the installation location without changing the orientation. The accelerometer was fine-tuned with bolts attached to a metal plate jig to ensure that it was parallel and perpendicular to the ground.

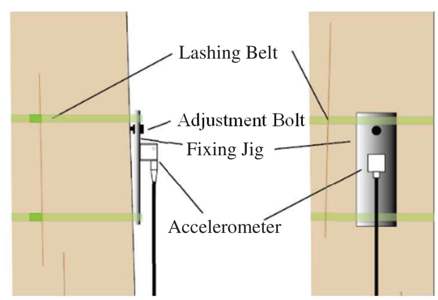

Figure 2 *: Detailed diagram of the measuring instruments*

2.2.2 FORCED BENDING TEST OF STANDING TREES

Forced bending test of standing trees is conducted to compare Young's modulus calculated from natural frequency similarly to the elastic shock wave test. as shown in ***Figure 3***, a jig for applying load and a jig for measuring displacement are installed directly on the standing tree, and Young's modulus is calculated from the load-displacement relationship.

The installation position of the measurement jig is generally on the upper side of the slope, with the loading fixture placed in that direction, except in cases where installation is difficult due to warping or other conditions. The displacement transducer fixing jig should be installed at 180 degrees from the load jig using a lashing belt. The

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load jig is fixed at a higher position than the displacement transducer fixture using a lashing belt and ratchet. The following equation (2) is used to estimate Young's modulus.

$$E = \frac{s^2 L}{2\pi r^4} \cdot \frac{P}{\delta} \quad (2)$$

$\frac{P}{\delta}$: Slope of the linear portion of the load-displacement curve (N/mm)

r : radius at breast height (mm) , s : Span of displacement transducer fixing jig (mm)

L : Sum of load fixture span and breast height radius (mm)

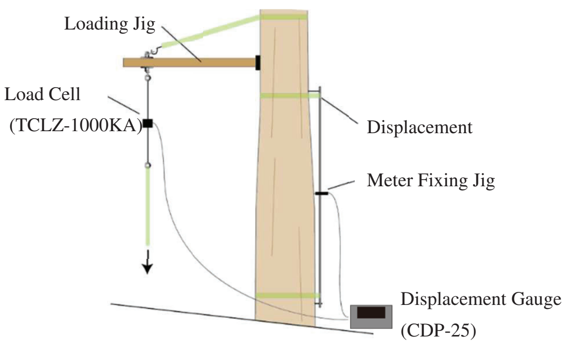

Figure 3 *: Forced Bending Test Setup Diagram*

The loading jig shown in ***Figure 4*** is a device used to apply a bending moment to the standing tree. Made of wood, it prevents rotation at the contact surface with the tree by arranging short pieces of wood in a Y-shape. A belt for applying the load to the opposite end and an eyebolt to connect the belt to secure it to the standing tree were fixed. The displacement measurement fixture shown in ***Figure 5*** is used to fix the displacement gauge for measuring the displacement of the log when the bending moment is applied to the standing tree. Two bolts were fixed at each

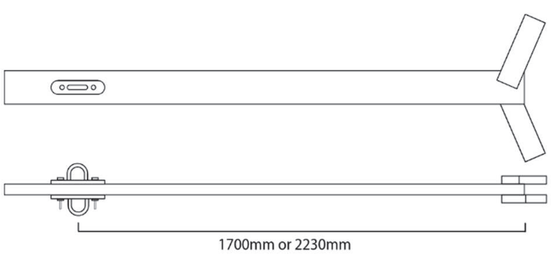

Figure 4 *: Loading Jig*

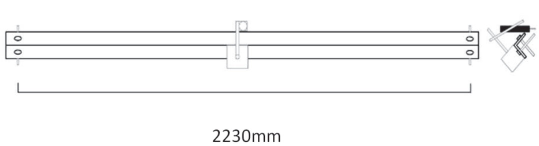

Figure 5 *: Displacement Meter Fixing Jig*

end of the L-shaped angle to clearly define the contact points on the tree. The displacement gauge fixed at the center was a CDP-25 (Tokyo Measuring Instruments Laboratory Co., Ltd.), and the load cell was a TCLZ-1000KA (Tokyo Measuring Instruments Laboratory Co., Ltd.).

2.2.3 TREE DETERMINATION

Measurements of standing tree were conducted in summer and winter, and the results of Young's modulus measurements obtained from the natural frequency test and the forced bending test were compared. In the summer measurements, each of the tests described in Chapter 2 were conducted from July to September.

3 – VIBRATION MEASUREMENT OF STANDING TREES

3.1 SUMMER MEASUREMENT

The summer measurements were conducted in a forest near the lumber mill owned by Matsuba zen Lumbermill (445-1 ChiChuoni-Chou, Izumi City, Osaka Prefecture) in Izumi City, Osaka Prefecture, with their cooperation. Matsuba zen Lumbermill gave us permission to conduct measurements in two areas of their forest: a forest of cypress trees 30-60 years old, and a forest of cedar trees over 60 years old. In each area, 30 cypress trees and 30 cedar trees each were selected for measurement, and their height and diameter at breast height were measured.

3.1.1 PROCEDURE FOR MEASURING TREE HEIGHT

The measurement method of tree height is calculated from the distance and angle as shown in the measurement schematic in ***Figure 6*** using trigonometric functions.

The measurement procedure is as follows.

(1) The measurer stands at a position where the boundary between the crown of the selected tree and the ground is visible.

(2) The horizontal distance L from the measurer's eye level to the standing tree was measured using a laser distance meter. A Bosch laser distance meter was used for the measurements.

(3) From the same location, the elevation angle θ1 to the tree crown and the depression angle (or in some cases, the elevation angle) θ2 to the boundary with the ground were measured using a digital level. The digital level was made by Shinwa Rules Co., Ltd.

(4) The tree height was calculated from the measured values using a trigonometric function.

(5) The above procedure was performed three times at different locations, and the average value was used as the tree height.

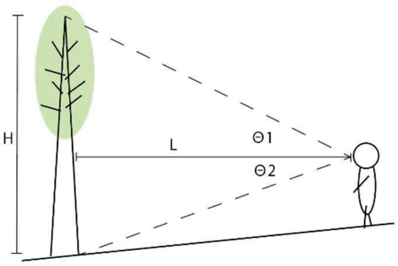

***Figure 6** : Diagram of tree height measurement*

$$H(\text{height of a tree}) = L(\frac{1}{tan\theta_1} + \frac{1}{tan\theta_2} \qquad (3)$$

3.1.2 ESTIMATE OF TREE TRUNK VOLUME AND WEIGHT

To calculate tree trunk volume, we used the “Tree Trunk Volume Calculation Program” [5] made available by Forestry and Forest Products Research Institute. This program calculates trunk volume from tree species, region, breast height diameter, and tree height using a user-defined function that calculates trunk volume of standing trees on a worksheet in Excel spreadsheet software. From this program, tree trunk volume was determined using the tree height and breast height diameter measured in the basic measurements.

Since the approximate weight could be obtained if the trunk volume was calculated as described above and the density could be estimated, the moisture content and density were estimated by referring to a previous paper, “Seasonal changes in water content in living stems of four conifer species and five hardwood species”. [6]

3.1.3 NATURAL FREQUENCY MEASUREMENT TEST

Young's modulus was calculated using the vibration of a single mass system, as described in Chapter 2 for the natural frequency measurement.

The measurements were recorded at 10 Hz for 10 minutes. The measurement was taken on a day when there was no wind or when the wind speed was high enough to clearly determine the period, because too strong a natural wind can affect the period.

To identify the natural period from the measured data, FFT analysis was performed on the recorded acceleration data using the analysis software MATLAB.

Since the acceleration used was highly sensitive and there were many cases where the acceleration did not reach zero at the end of the measurement due to the displacement of the accelerometer during measurement caused by tree shaking, a function in MATLAB was used to perform a baseline correction using a sixth-order approximation function to eliminate residual displacement of the data at the end of the measurement.

In the frequency analysis, after baseline correction of the data was performed using the method described above, the natural frequency peaks were obtained by dividing the FFT results obtained from the accelerometers installed on the standing trees by those obtained from the accelerometers installed on the ground, excluding vibrations on the ground. An example is shown below.

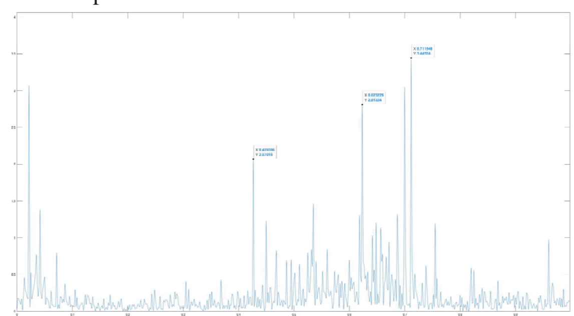

***Figure 7** : Natural period after FFT analysis*

Although the eigenperiods were identified from the data obtained, there were several cases where multiple peaks appeared, or where a prominent peak appeared but the values were clearly different.

This may be due to the fact that not only the first-order mode of the tree trunk vibration but also the second-order mode of the eigenfrequency was recorded, and these peaks may have appeared as a result of the recording. It is also possible that the accelerometer detected the swaying of the branches in the canopy area when they were blown by the wind. For these, the natural frequency was identified by comparing it with the natural period measured with a stopwatch by visual observation.

Young's modulus was calculated from Equation (1) described in Chapter 2. In this case, the cross-sectional secondary moment was calculated as the cross-sectional secondary moment of a circle by approximating the cross-sectional area as a circle based on the measured diameter at breast height, and the mass was estimated from the tree trunk volume and then converted.

3.1.4 FORCED BENDING TEST OF STANDING TREES

The forced bending test of standing tree was measured as the most reliable method of investigation, since previous papers have shown a correlation with logs.

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In principle, the load fixture was placed on the upper side of the slope. The measurement time was 30 seconds, and the measurement frequency was 200 Hz.

Measurements were taken by two persons. One person applied weight to a belt attached to the end of the load cell to apply a bending moment to the tree via the jig. The other operated the data logger to verify that load and displacement were detected. These processes were performed three times on each specimen standing tree and the average value was obtained. From the measured load and displacement, a load-displacement curve was drawn and Young's modulus was calculated using equation (2). ***Figure 8*** shows an example of a graph of the load-displacement curve.

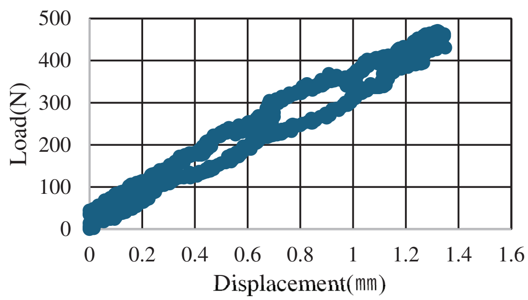

Figure 8 *: Example of Load-Displacement Curve*

When load-displacement curves were drawn for the entire recorded range, it was impossible to obtain an appropriate approximation of P/δ because it included noise areas where the displacement was almost zero without load and areas where the displacement returned after unloading. Therefore, as shown in ***Figure 9***, A straight line connecting the part of the displacement gauge where the displacement is measured and the part where the maximum load is applied is considered to be P/δ.

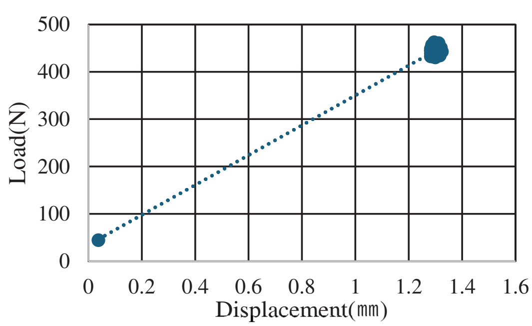

Figure 9 *: Example of Load-Displacement Curve*

Measurements were made on 14 standing trees, although some specimens could not be measured due to their large diameter, although trees were selected.

Measurements of standing trees were conducted in summer and winter to eliminate measurement errors due to season, and Young's modulus obtained from the natural frequency and the measurement results of the two measurement methods were compared. In order to eliminate measurement errors due to regional differences, summer measurements were conducted from July to September at two sites in Izumi City, Osaka Prefecture (cedar and cypress) and Motoyama Town, Kochi Prefecture (cedar and cypress), and winter measurements were conducted from November to December at three sites: Izumi City, Osaka Prefecture (cedar and cypress); Chihaya Akasaka Village, Osaka Prefecture (cedar); and Kaizuka City, Osaka Prefecture (cypress). (cedar and cypress) in each season.

3.2 WINTER MEASUREMENT

3.2.1 BASIC MEASUREMENT OF STANDING TREES

For winter measurements, in addition to Izumi City, Osaka Prefecture, 30 cedar trees from a forest in Chihaya Akasaka Village, Osaka Prefecture, and 30 cypress trees from a forest in Kaizuka City, Osaka Prefecture, were added, and the height and breast height diameter of the trees were measured and the volume and weight of the tree trunks were estimated in the same manner.

3.2.2 NATURAL FREQUENCY MEASUREMENT

Natural frequencies were measured in the same manner as the summer measurements, peaks were identified by FFT analysis, and Young's modulus was calculated.

3.2.3 FORCED BENDING TEST OF STANDING TREES

Forced bending tests on standing trees were also conducted in the same manner as the summer measurements, and Young's modulus was calculated. In the two newly added areas, forced bending tests could be performed on 16 of 30 standing trees in Chihaya-Akasaka Village and 23 of 30 trees in Kaizuka City.

3.2.4 COMPARISON AND SUMMARY OF WINTER MEASUREMENT RESULTS

Figure 10 shows the Young's modulus obtained from the measured natural frequencies and the results of the forced bending test. A comparison of the results from the three measured areas shows a certain correlation, regardless of the area or species. the Young's modulus in bending was higher than the Young's modulus calculated from the natural frequencies in all results. This may be due to the use of estimated values for the center of gravity and weight. In addition, the results for Japanese cypress are relatively consistent, while the results for Japanese cedar appear to be more varied than those for Japanese cypress. However, the age of the cedar trees in Chihaya-Akasaka Village varied, so it is not clear at this stage whether this is due to differences by species or by age.

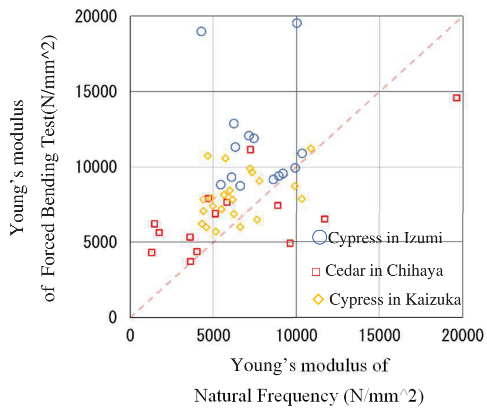

Figure 10 *: Young's Modulus of Natural Frequency – Forced Bending in Winter*

3.3 COMPARISON OF SUMMER AND WINTER MEASUREMENT RESULTS

The results for Izumi cypress, for which natural frequency and forced bending tests could be performed in both summer and winter, are shown in ***Figure 11***. Comparing the summer and winter results, a correlation can be seen in both cases, but there is a slight variation in the results. Since some of the same specimens showed significantly different results depending on the season, it is thought that there may be an effect of moisture content and other factors.

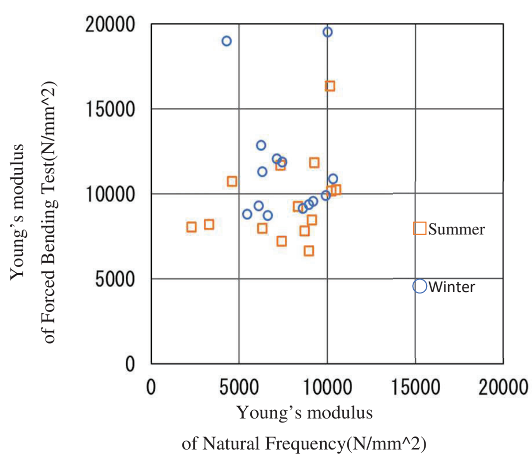

Figure 11 *: Seasonal Comparison: Young's Modulus of Natural Frequency – Forced Bending*

3.4 ADDITIONAL MEASUREMENTS

Although some correlation was observed between the Young's modulus obtained from the natural frequency test and the forced bending test in the summer and winter tests, some variation was observed, additional measurements were made to increase the number of specimens. These measurements were conducted in July, they are treated as summer data.

3.4.1 BASIC MEASUREMENT OF STANDING TREES

For additional measurements, a total of 36 trees, 16 cedar and 22 cypress, were selected from a forest in Motoyama-cho, Kochi Prefecture, and measured. Similarly, tree height and breast height diameters were measured, and tree trunk volume and weight were estimated.

3.4.2 NATURAL FREQUENCY MEASUREMENT

In the summer and winter measurements, natural frequencies were measured from vibrations caused by natural wind. However, it was difficult to correctly measure the peak natural frequencies of some standing trees due to the low wind volume, so the jig shown in ***Figure 12*** was used to force the trees to vibrate and the natural frequencies were measured from the free vibration generated.

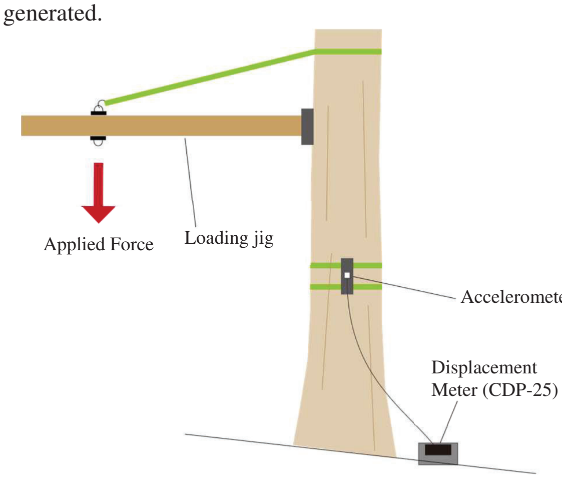

Figure 12 *: diagram of natural frequency measurement test*

Additional measurements were taken in two directions, Perpendicular to the slope direction and slope direction, respectively, to investigate the variation of Young's modulus with direction.

The measurements were recorded at 200 Hz for 30 seconds, and the free vibration was measured by forcing the sample to vibrate three times during each recording.

When conducting the analysis, the baseline correction was set to first order. To prevent the natural vibration peaks from being obscured by the artificial vibration and branch vibration during force application, a low-pass filter was applied in MATLAB to reveal the peaks due to free vibration.

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3.4.3 FORCED BENDING TEST OF STANDING TREES

Forced bending tests of standing trees were performed in the same procedure as summer and winter measurements, and Young's modulus was calculated.

3.4.4 COMPARISON AND SUMMARY OF ADDITIONAL MEASUREMENT RESULTS

Figure 13 shows the Young's modulus obtained from the measured natural frequencies and the results of the forced bending test. Comparison of the results in different directions shows that almost the same results are obtained in different directions. The larger the Young's modulus, the larger the scatter. Comparing the X = Y graph with the red dashed line, the Young's modulus in bending was higher than the Young's modulus calculated from the natural frequencies, as in ***Figure 10***. Some of the Young's modulus values calculated from the natural frequencies were much higher than the Young's modulus of typical wood. This may be due to the fact that the peaks of the natural frequencies were changed by the branches of the standing trees or by the snagging between the standing trees.

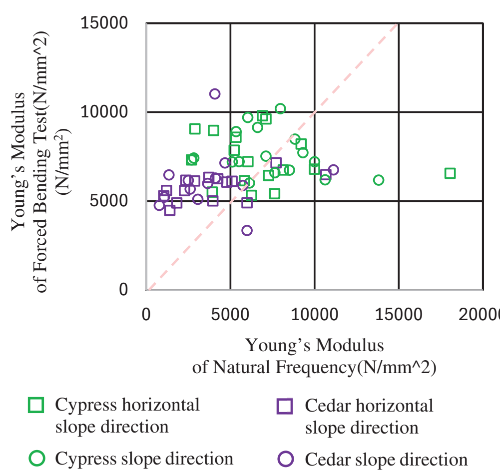

***Figure 13** : Comparison of measurement directions: Young's Modulus of Natural Frequency – Forced Bending*

4 – LOG AND SAWN LUMBER CUTOUT TEST

4.1 EXPERIMENT SUMMARY

Some of the specimens for which Young's modulus estimation of standing trees has been performed in the previous chapters are cut from the mountain forest to measure Young's modulus in bending in the log and sawn conditions and Young's modulus by the longitudinal vibration method. Three specimens were selected from among the Izumi cypress trees for which bending tests could be performed.

4.2 MEASUREMENT OF TREE HEIGHT AND WEIGHT

In order to determine the error in the estimated height and weight of the standing trees measured in Chapter 3, the length and weight of the cut specimens were measured. ***Table 1*** shows estimated and measured tree heights and estimated and measured weights.The measurement error of tree height was about 5%, indicating that the height of the trees was generally measured by this method. On the other hand, the measurement error of weight was about 10-20%, indicating a slight error.

***Table 1** : Comparison of Height and Weight*

No.	Estimated Height(mm)	Actual Height(mm)	Estimated Weight(kg)	Actual Weight(kg)
IH01	12799	12435	138	146
IH08	15216	16230	262	245
IH12	14931	15790	296	154

4.3 LOG AND LUMBER BENDING TEST

Immediately after cutting, logs and lumber were subjected to bending tests. as shown in ***Figure 14***, logs and lumber were fixed with an angle and weight was applied to the center of the logs and lumber to measure displacement and calculate Young's modulus. The test was conducted at a recording frequency of 200 Hz for 30 seconds. This operation was repeated three times, and the Young's modulus was calculated using the average value of the displacements.

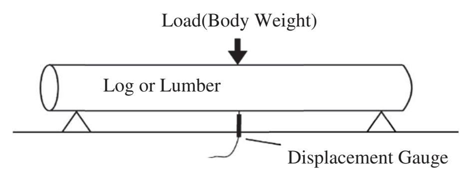

***Figure 14** : diagram of Log and lumber bending test*

4.4 VERTICAL VIBRATION TEST OF LOGS AND LUMBERS

Immediately after cutting, longitudinal vibration Young's modulus measurement tests were conducted on the logs and sawn timber. As shown in ***Figure 15***, a microphone was fixed to the log and sawn timber, and the end face opposite to the microphone was struck with a hammer to record the sound. The recorded sound was analyzed using FFT to identify the natural frequency, and an attempt was made to calculate the Young's modulus. During the test, the end face was struck five times over a 10-second recording period at a sampling frequency of 1 MHz, and the peak frequency was identified through FFT analysis to calculate the Young's modulus.

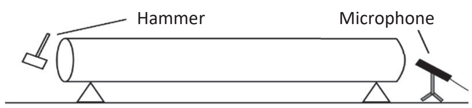

Figure 15 *: Longitudinal Vibration Test Diagram of Log and Lumber*

4.5 RESULTS OF LOGGING AND SAWING TEST

Figure 16 shows the Young's modulus calculated from each of the log and lumber tests. The lower value for the log bending test may be due to the inaccurate fixation of the specimen and the displacement transducer. Young's modulus values obtained from the longitudinal vibration test were close to the values obtained for both logs and lumber, proving the validity of the longitudinal vibration test for both logs and lumber. The reason for the difference in Young's modulus between logs and sawn lumber is thought to be that the sapwood portion of the log's outer circumference was heavily shaved when the log was sawn, changing the ratio of sapwood to heartwood.

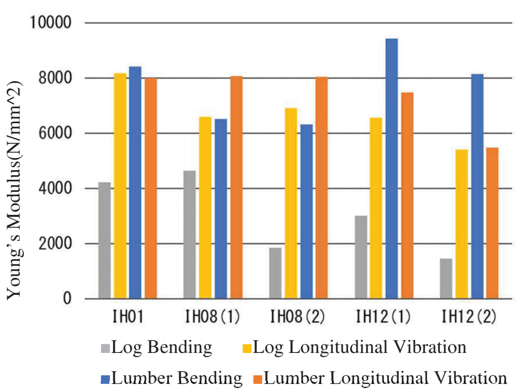

Figure 16 *: Young's Modulus of Log and Lumber*

5 - CONCLUSIONS

The overall results are shown in ***Figure 17***. The results show a correlation between natural vibration and stiffness. On the other hand, some issues were found. The natural frequencies in this study were calculated using estimated values for weight and center of gravity position, but cut-out tests showed that there was some variation in the results. If these estimates can be clarified, the relationship between natural frequencies and stiffness will become clearer. Further investigation of the post-sawing results is also needed.

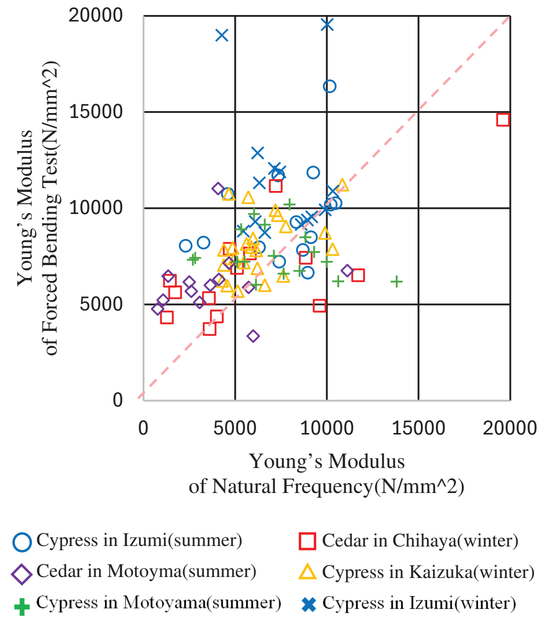

Figure 17 *: Young's Modulus of Natural Frequency - Forced Bending*

ACKNOWLEDGEMENT

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