Analysis of vibration characteristics of Japanese cedar from Nara Prefecture for string instruments

Katuhiro Maki$^{1,*}$ and Maiko Ariyama$^{2}$

$^{1}$Faculty of Human Informatics, Aichi Shukutoku University, 2–9 Katahira, Nagakute, 480–1197 Japan

$^{2}$Wood Utilization Section, Nara Forest Research Institute, Kibi 1, Takatori, Nara, 635–0133 Japan

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Abstract: We measured the vibration characteristics of Japanese cedar (Cryptomeria japonica) from Nara Prefecture, which has a narrow, uniform, and straight wood grain that is a suitable appearance for violin tops. Then, we compared them with those of spruce (Picea spp.) to evaluate the potential utility of Nara cedar as an alternative to spruce for the sound boards of string instruments, including violin tops. The results of an evaluation with multiple indexes based on material density, specific dynamic modulus of elasticity, and loss tangent showed that Nara cedar has similar suitability to spruce species as sound boards. In addition, the results of an equivalence statistical test with index of vibration characteristics for Nara cedar and spruce also support this finding. As such, we were able to identify a possible native supply of wood with suitable characteristics for string instrument construction in Japan.

Keywords: Wood, Sound board, Young’s modulus, Internal friction, Spruce

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1. INTRODUCTION

In the fabrication of sound boards for string instruments, including violin tops, very limited types of spruce in the genus *Picea*, such as Norway spruce (*Picea abies*) and Sitka spruce (*Picea sitchensis*), are used. These trees grow slowly in cold areas, which leads to a narrow ring width and, in turn, decreases density and increases firmness (modulus of elasticity). Therefore, European wood is considered the best for such applications [1–5]. The vibration characteristics of these woods for use in violin construction have been examined in detail [1–3,6–8].

The supply of spruce is predicted to dwindle in the future owing to environmental factors and logging restrictions. As such, it is necessary to identify alternatives to spruce [2,9,10]. In the case of Japan, there is little production of spruce suited to violin construction, but Japanese cedar grown in and around the Yoshino forestry area of Nara Prefecture produces clear lumber with a narrow and uniform ring width and straight wood grains owing to dense planting, multiple thinnings, and long rotation operation. Such attributes of Nara cedar are suited to the fabrication of tops for violins [11]. However, the vibration characteristics of cedar from Nara have not been elucidated [11]. As an alternative to spruce, the data-driven utilization of Nara cedar could result in it being added to the pool of candidate alternatives.

In this study, to evaluate the utility of Nara cedar as an alternative to spruce, we measured the vibration characteristics of Nara cedar having a good appearance by the free-free flexural vibration method [12–14] and compared the results with those of spruce species. Although wood is anisotropic and has different properties in the fiber, radial, and tangential directions, in this study, we focused on the fiber direction of the wood, which is the direction that determines its appropriateness for use in musical instruments [3,6].

2. EXPERIMENTAL METHODS

2.1. Materials and Measurement Methods

We used nine samples of Nara cedar (Cryptomeria japonica D. Don) with high-quality rings and grains (see Introduction), grown in and around the Yoshino Forestry area and naturally dried. We prepared three specimens from the heartwood of each of these nine samples. In addition, we prepared three specimens from the sapwood of...
eight of the nine samples. However, it should be noted that some heartwood was found among some of the sapwood specimens.

We used ten samples of spruce (Picea spp., unknown species) grown in Europe (Northern Italy or the Alps) and sold in radial cuts as material for violin tops. Of these samples, five were handled as high-grade material by the supplier, while the other five were normal grade. We prepared three specimens from each sample. Because it was difficult to visually distinguish the heartwood from the sapwood in the spruce species, we did not make a distinction between them.

We cut the wood 180 mm in the fiber direction, 25 mm in the radial direction, and to a thickness of 8 mm in the tangential direction for both the cedar and spruce. After acclimatizing the specimens to a temperature of 20°C and a relative humidity of 65%, we measured the vibration characteristics of each specimen under the same conditions (described later). The moisture content at the time of measurement was determined using all drying methods in the part that was continuous with the specimen in the fibrous direction for which the vibration characteristics were measured. The mean moisture content was 14.0% for cedar and 11.9% for spruce.

We used the free-free flexural vibration method to measure the vibration characteristics of the specimens [12–14]. A schematic diagram of the measuring apparatus is shown in Fig. 1.

As shown in Fig. 1, each specimen was suspended from two silk threads at a distance of “0.224” from each end, where the overall length is “1” in a state in which both ends are free. The center of each specimen was then lightly tapped with a wooden mallet. The tapping sound was detected by a 1/2-inch microphone (M1-1235, Ono Sokki) with a preamplifier (M1-3111, Ono Sokki) powered by a power supply/amplifier (SR-2210, Ono Sokki) and then saved to a PC via an A/D converter (DS-3200, Ono Sokki).

The dynamic Young’s modulus (E) was calculated in the fiber direction by the Euler–Bernoulli method [13] from the first-order mode resonance frequency obtained by a software-based FFT analyzer with sufficient frequency resolution. In addition, the loss tangent (tan δ) in the fibrous direction was obtained by calculating the logarithmic decay rate (δ) from the damped free vibration curve at the first-order mode resonance frequency in the time domain and taking its tangent. The data for each specimen were collected three times, and the mean was used as the representative data for each specimen (see Table 1).

In this study, for comparison, we used the vibration characteristics data of Norway spruce, Sitka spruce, Western red cedar (Thuja plicata), hemlock (Tsuga sp.), and Norway maple (Acer platanoides) from a previous study [15] and analyzed these results along with the experimental results of this study. Western red cedar has similar characteristics to spruce and is used for guitar tops [8]. In addition, hemlock is used as an alternative to spruce [7]. In contrast, Norway maple is not used as an alternative to spruce, but it is a representative backplate material for violins. In this study, we purposely used data from Norway maple that is not used as top material to facilitate easier judgment of the closeness of its properties to those of Nara cedar and spruce.

### 2.2. Data Analysis

2.2.1. Method of comparison between vibration characteristics of tree species

Wood species suited for use in sound boards for string instruments, such as Norway spruce and Sitka spruce, are lighter and firmer, and their vibrations are not easily attenuated compared with other woods. This implies that their density (ρ) is low, their dynamic Young’s modulus (E) is large, and their loss tangent (tan δ) is small. Therefore, materials with a large specific dynamic modulus of elasticity (E/ρ) and low loss tangent (tan δ) are suitable for sound boards of musical instruments [1–3,6–8]. In Sect. 3.2, we will analyze the relationship between the specific dynamic modulus of elasticity and the loss tangent.

By calculating $Q^{-1}/(E/\rho)$, where the internal friction ($Q^{-1}$) is divided by the specific dynamic modulus of elasticity, we can uniaxially evaluate the suitability of materials as sound boards [2]. Here, internal friction ($Q^{-1}$) is an alternative expression for the loss tangent (tan δ), and these two values are the same. When $Q^{-1}/(E/\rho)$ is small, the sound board is superior. Thus, in Sect. 3.3, we calculated $Q^{-1}/(E/\rho)$ for each wood species and uniaxially evaluated their suitability for sound boards.

Yoshikawa examined the vibration characteristics of various materials for musical instruments and reported that
Table 1 Measurement results of density (\(\rho\)), dynamic Young’s modulus (\(E\)) in fiber direction, and loss tangent in fiber direction (\(\tan\delta\)) for Nara cedar and European spruce. \(f_{1st}\) indicates the first-order mode resonance frequency of the specimen (see Sect. 2.1). \(N\) indicates the number of samples and SD is standard deviation.

|                         | \(N\) | \(\rho\) (kg/m\(^3\)) | \(E\) (GPa) | \(\tan\delta\) \((\times10^{-2})\) | \(f_{1st}\) (Hz) |
|-------------------------|-------|-------------------------|-------------|----------------------------------|------------------|
| Japanese cedar from Nara (sapwood) | 8     | 370 ± 28                | 8.0 ± 1.5   | 0.71 ± 0.07                      | 1,233.8 ± 81.2   |
| Japanese cedar from Nara (heartwood) | 9     | 400 ± 20                | 9.4 ± 1.3   | 0.67 ± 0.08                      | 1,190.0 ± 75.4   |
| Spruce from Europe (high grade)      | 5     | 435 ± 20                | 11.8 ± 1.5  | 0.73 ± 0.04                      | 1,343.3 ± 83.3   |
| Spruce from Europe (normal grade)    | 5     | 430 ± 12                | 12.9 ± 0.4  | 0.72 ± 0.05                      | 1,410.0 ± 43.8   |

c\(Q\) and \(\rho/c\) of wood species used for sound boards have different linear relationships from those used in the frame, such as the back plate [7]. In addition, he showed that wood species used for sound boards and frames can be classified using these properties. Hereafter, \(c\) represents the speed of sound transmitted through a material in the unit of m/s and \(Q\) is the inverse of the loss tangent (\(\tan\delta\)) or the inverse of the internal friction (\(Q^{-1}\)). Therefore, by examining the relationship between \(cQ\) and \(\rho/c\) of materials, the similarities between the properties of each wood species can be evaluated in terms of their use as sound boards. Thus, in Sect. 3.4, we examine the relationship between \(cQ\) and \(\rho/c\) for each wood species and evaluate the similarities between the properties of each wood species regarding their use as sound boards.

2.2.2. Method to verify equivalence

In Sect. 3.2, to evaluate the utility of Nara cedar as an alternative to spruce, we verified the equivalence of \(Q^{-1}/(E/\rho)\) for Nara cedar (sapwood and heartwood) and spruce [16]. In this verification, the equivalence margin (\(\pm\Delta\)) was used to verify the equivalence of the two materials as follows. First, we pooled data on European spruce measured in this study (\(N = 10\)) and spruce data (Norway spruce, \(N = 10\); Sitka spruce, \(N = 13\)) reported in a previous study (\(N = 33\), Fig. 3). Through random selection, we divided the pooled data into two groups (16 in group A and 17 in group B with no overlap between groups). Next, we calculated the 95% confidence interval for the difference between the means of each group. Similarly, we repeated the preparation of the two groups from the pooled data through random selection and calculated the 95% confidence interval 1,000 times. If we assume that this calculation verifies the equivalence of “spruce species,” and we assume that the “spruce species” are equivalent, the 1,000 confidence intervals should include the lowest and the highest equivalence margins. In other words, if the spruce materials are equivalent, there should be an equivalence margin that contains all 1,000 confidence intervals. Therefore, we set the minimum and maximum of these 1,000 confidence intervals as the equivalence margin (\(\pm\Delta\)) to verify the equivalence of Nara cedar and spruce.

In the verification of the equivalence between Nara cedar and spruce, we calculated the 95% confidence interval for the difference in the mean of 17 randomly selected data (no overlap) from the aforementioned pooled data of spruce (\(N = 33\)) and Nara cedar (\(N = 17\)). We then determined whether this confidence interval is within the preset equivalence margin (\(\pm\Delta\)). Similarly, calculation of this confidence interval was performed 1,000 times by repeating the random selection of the spruce data from the pool (\(N = 17\)) relative to the same Nara cedar data (fixed, \(N = 17\)).

### 3. EXPERIMENTAL RESULTS

#### 3.1. Basic Statistics of Measured Data

Table 1 shows the measurement results for density, dynamic Young’s modulus, loss tangent, and first-order mode resonance frequency of Nara cedar and European spruce.

Table 1 shows that the mean density and dynamic Young’s modulus were higher for heartwood than for sapwood of Nara cedar, while the mean loss tangent was smaller for heartwood than for sapwood. In the European spruce, the mean dynamic Young’s modulus was higher for the normal grade than for the high grade, and the mean density and loss tangent were similar for both the high grade and normal grade.

When comparing Nara cedar (sapwood and heartwood) and spruce (high grade and normal grade), the mean loss tangent was similar for both. However, the mean dynamic Young’s modulus was clearly higher in spruce than in cedar.

For each of the data of density, dynamic Young’s modulus, loss tangent, and first-order mode resonance frequency, multiple comparisons were made between groups of the four types of wood shown in Table 1. In this statistical test, the adjustment of the false discovery rate (\(q\)) was performed by the Benjamini–Hochberg (BH) method [17] to reduce the possibility of a type II error (\(\beta\)).
error or false negative). For the density, significant differences were found between pairs of the sapwood and heartwood of Nara cedar ($q < 0.005$) and pairs of Nara cedar (sapwood and heartwood) and spruce from Europe (normal and high grades) ($q < 0.0001$–0.005). For the dynamic Young’s modulus and the first-order mode resonance frequency, significant differences were observed between pairs of Nara cedar (sapwood and heartwood) and spruce from Europe (normal and high grades) ($q < 0.0001$–0.005). For the loss tangent, no significant differences were found for any pairs.

3.2. Relationship between Specific Dynamic Modulus of Elasticity and Loss Tangent

Figure 2 shows the relationship between the specific dynamic modulus of elasticity ($E/\rho$) and the loss tangent ($\tan \delta$) of Nara cedar (sapwood and heartwood) and European spruce (high grade and normal grade) (see Sect. 2.2.1). In addition, Fig. 2 shows data of Norway spruce, Sitka spruce, Western red cedar, hemlock, and Norway maple, which were reported in a previous study [15], for comparison. In Fig. 2, materials with a high specific dynamic modulus of elasticity ($E/\rho$) and low loss tangent ($\tan \delta$) are the most suitable for sound boards (see Sect. 2.2.1).

Figure 2 shows that there is a negative correlation between the specific modulus of elasticity and the loss tangent for each tree species. It has already been reported that this correlation is observed regardless of tree species [2,6]. The Pearson product-moment correlation coefficient ($r$) for the relationship between these two parameters was calculated for tree species that yielded five or more samples and ranged from $-0.8$ to $-0.5$ (sapwood of Nara cedar: $r = -0.754$, $p = 0.031$; heartwood of Nara cedar: $r = -0.78$, $p = 0.013$; high-grade European spruce: $r = -0.674$, $p = 0.212$; normal-grade European spruce: $r = -0.56$, $p = 0.324$; Norway spruce: $r = -0.53$, $p = 0.116$; Sitka spruce: $r = -0.67$, $p = 0.013$; Norway maple: $r = -0.523$, $p = 0.121$).

Figure 2 shows that the specific dynamic modulus of elasticity appears to be small for cedar (sapwood and heartwood) relative to spruce overall; however, the loss tangent does not appear to exhibit much difference. With Western red cedar (+ sign), there are some small samples with a smaller loss tangent than each spruce species, but the specific dynamic modulus of elasticity tends to be smaller than in each of the spruce species. Two samples of hemlock (× symbol) are within the data group of each spruce species and the Nara cedar. In the case of Norway maple (× symbol), the specific modulus of elasticity is smaller, while the loss tangent is clearly larger than those of cedar and each spruce species.

For the data of specific dynamic modulus of elasticity (Fig. 2), a multiple comparison test was performed on each pair for Nara cedar (sapwood and heartwood), spruce from Europe (normal and high grades), Norway spruce, Sitka spruce, and Norway maple groups, which all have 10 or more data. As a result, significant differences were found between Norway maple and all other groups ($q < 0.0001$, multiple comparison by the BH procedure), but no significant differences were found for any other pairs, including the pair of Nara cedar and Norway spruce ($q > 0.05$, multiple comparison by the BH procedure).

In a comparison of each species of spruce, we found large individual variations even within the same species; nevertheless, the specific dynamic modulus of elasticity was large, and the loss tangent was low in the Norway spruce. In other words, many samples of Norway spruce are suited for use as sound boards.

3.3. Uniaxial Evaluation of the Utility of Materials as Sound Boards

To perform uniaxial evaluation of wood materials as sound boards, we calculated $Q^{-1}/(E/\rho)$ for each wood species (see Sect. 2.2.1). In Fig. 3, materials with smaller $Q^{-1}/(E/\rho)$ are superior as sound boards.
Figure 3 indicates that although there are individual differences between wood species, some samples of Norway spruce and Western red cedar had $Q^{-1}/(E/\rho)$ below 0.2 ($\times 10^{-3}$). In other words, these samples are highly suitable for use as sound boards. With regard to Nara cedar (sapwood and heartwood), European spruce (high grade and normal grade), Sitka spruce, Western red cedar, and hemlock, the number of data samples varied and was small. Thus, it was difficult to make simple and direct comparisons. However, the data distribution of each wood species does not show any notable differences, although the magnitude of the data variation differs depending on the wood species. However, $Q^{-1}/(E/\rho)$ of the Norway maple was clearly higher than that of the other wood species regardless of the individual sample.

To evaluate the utility of Nara cedar as an alternative to spruce, we verified the equivalence of Nara cedar (sapwood and heartwood) and spruce (see Sect. 2.2.2). Figure 4(A) shows examples of repeated calculations of the 95% confidence interval for the difference in the mean data of spruce species, which were performed to determine the equivalence margin ($\pm \Delta$) to verify equivalence. When this equivalence margin was set between the minimum and maximum of the confidence interval calculated from the data of spruce species (see Sect. 2.2.2), the result was $\pm 0.00012$, and the 95% confidence interval of the difference in the mean of the data for Nara cedar and spruce was only just within this margin.

3.4. Similarities Based on the Classification of Materials for Musical Instruments

To evaluate the similarities of the properties of each
Among them, there are samples located approximately on this straight line. The area of the data distribution of each wood species straddle the line $y = 143x - 18.9$ (dot-dash line). The line $y = -50.25x + 11.4$ (dotted line) describes the linear relationship between $cQ$ and $\rho/c$ for wood species used for sound boards of musical instruments, while the line $y = 143x - 18.9$ (dot-dash line) shows the linear relationship between $cQ$ and $\rho/c$ for wood species used for frames of musical instruments [7].

Figure 5 shows that for the wood materials, excluding Norway maple (× symbol), the variation in $\rho/c$ is small while the variation in $cQ$ is large. In addition, the data distributions of each wood species straddle the line $y = -50.25x + 11.4$ (dotted line) and are close to this line. Among them, there are samples located approximately on this straight line. The area of the data distribution of each wood species and the distance between the line $y = -50.25x + 11.4$ (dotted line) and the data of each wood species are unclear; however, they appear to be similar for all spruce species, including Nara cedar (sapwood and heartwood) and Norway spruce. This implies that their sound board properties are similar.

On the contrary, with hemlock (× symbol), the results were on the right side of the data margin for all spruce species, that is, in the direction of the dot-dash line reflecting the characteristics of frame materials. This implies that the characteristics of hemlock as a sound board are slightly different from those of the spruce species. In the case of Western red cedar (+ symbol), two of the three samples show data far from the dotted line, and their properties are clearly different from those of spruce for some samples. With Norway maple (× symbol), the data distribution was considerably different from those of other wood species, and the data were distributed near the line $y = 143x - 18.9$ (dot-dash line).

### 4. DISCUSSION

#### 4.1. Evaluation Results

In this study on the use of Nara cedar for sound boards, including violin tops, we examined its vibration characteristics and compared the results with those of spruce used for the same purpose.

In Sect. 3.2, we examined the relationship between the specific dynamic modulus of elasticity and the loss tangent and found that there was a difference in the significance probability; however, the correlation coefficient of all wood species ranged between −0.8 and −0.5. A previous study revealed that the strength of the negative correlation does not depend on the wood species [2]. Therefore, we assumed that the differences in the correlation coefficient and the significance probability between the wood species used in this study were related to the number of samples.

In the uniaxial evaluation of utility as a sound board using $Q^{-1}/(E/\rho)$, as shown in Sect. 3.3, some Norway spruce had a smaller value than the other wood species, except for Western red cedar. In other words, they exhibited superior properties as sound boards. Because Norway spruce is considered to be the best wood for violin tops [1, 18], this result is consistent with the expectation.

In the verification of equivalence described in Sect. 3.3, we considered all spruce species (Norway spruce, Sitka spruce, and European spruce) as the same category of wood material. These spruce species are all limited spruce species in the genus *Picea* that are used as sound boards, including violin tops. Therefore, in a comparison with Nara cedar, which belongs to the Cupressaceae family, placing these spruce species into the same category should not cause any problems.

In the biaxial evaluation using dynamic Young’s modulus and loss tangent described in Sect. 3.2, Nara cedar exhibited a similar loss tangent to that of the spruce species, but the specific dynamic modulus of elasticity was generally lower; in other words, Nara cedar is inferior (Fig. 2). However, in the uniaxial evaluation using $Q^{-1}/(E/\rho)$ described in Sect. 3.3, it did not appear inferior to the spruce species (Fig. 3), and in the verification of
equivalence, Nara cedar and the spruce species were determined to be equivalent. These results can be further examined to reveal that the loss tangent of Nara cedar is smaller than that of the spruce species. This characteristic was most apparent in Western red cedar, which is in the same Cupressaceae family, with a small loss tangent (Fig. 2). Nara cedar is as suitable as spruce for sound board fabrication, but it tends toward a similarity to Western red cedar.

In the evaluation using $cQ$ and $\rho/c$ in Sect. 3.4, there was no clear difference between Nara cedar and spruce species, including Norway spruce. In addition, the data of Nara cedar was distributed in a very similar manner to those of Norway spruce.

From the results of evaluations in Sects. 3.2–3.4, it can be concluded that Nara cedar is slightly inferior to particularly excellent individuals of Norway spruce. However, as a sound board material, it is as suitable as other spruce species such as other Norway spruce species, Sitka spruce species, and spruce species from Europe sold as violin top (high grade and normal grade) materilas.

4.2. Utility of Nara Cedar

The use of spruce is not limited to violins. It is used for the tops of other instruments of the violin family, such as violas and cellos, and guitars. Thus, Nara cedar can be used for these musical instruments as well. In Japan, there is little production of materials for string instruments. Therefore, Nara cedar has the potential to become a valuable material for string instruments. It is of international significance that we were able to show data connected to the expansion of the range of tree species that could be utilized as an alternative to spruce. As the supply of spruce continues to decrease owing to environmental factors and logging restrictions [2, 9, 10], the use of such alternatives will likely increase.

4.3. Comparison of Western Red Cedar, Hemlock, and Maple

Western red cedar of the Cupressaceae family, which is the same family as Nara cedar, has a smaller loss tangent than spruce. In this respect, it is superior to spruce (Fig. 2). In the evaluation in Sect. 3.3, some superior samples similar to Norway spruce were observed (Fig. 3). Western red cedar with such characteristics is used in sound boards for guitars [8]. However, from the evaluation results in Sect. 3.4 (Fig. 5), we can conclude that Nara cedar is a more suitable alternative to spruce than Western red cedar. Similar results were found for hemlock.

In the evaluations described in Sects. 3.2, 3.3, and 3.4, only Norway maple showed notably different properties from other wood species (Figs. 2, 3, and 5). Because maple is used as a back plate material and has different vibration characteristics from spruce, which is used for tops [7], such a result was expected.

4.4. Individual Differences in Materials and Selection Method of Materials for Musical Instruments

In a previous study, it was reported that the materials chosen by makers of musical instruments do not necessarily have superior vibration characteristics [18]. This is because makers also value the appearance of the wood.

In this study, we observed little difference in the vibration characteristics of high- and normal-grade European spruce for sale. Instead, individual differences within the same grade were more notable (Figs. 2, 3, and 5). In addition, the mean dynamic Young’s modulus of Nara cedar shown in Sect. 3.1 showed a difference between sapwood and heartwood, but this was not seen in the evaluations in Sects. 3.2, 3.3, and 3.4, where the differences in individual samples were more notable (Figs. 2, 3, and 5). Furthermore, there were variations between individual samples even within the same wood species (Figs. 2, 3, and 5), similar to the spruce species. Therefore, in the step following the selection of wood suitable for use in sound boards, we must determine a method for easily selecting an individual sample with superior vibration characteristics within a wood species. This is a future task.

4.5. Necessity of Comparison with Cedar from Other Areas

The conventions of violin manufacturing dictate that materials for the top should have a narrow and uniform ring width and straight grain. In other words, materials that do not meet these conditions, such as materials with an uneven ring width, are not used for violin tops. This takes into consideration the appearance of the violin as a finished product. In terms of the vibration characteristics of wood, methods that improve performance through post-processing, such as chemical treatment and aging with bacteria, have been developed [5, 19]. However, because the ring width and wood grain cannot be corrected, the wood used for violins, especially for the top, must satisfy these conditions before its vibration characteristics are considered. Cedar produced in and around the Yoshino Forestry area in Nara is characterized by a large population size that meets these conditions (see Introduction). However, in other areas, there are not many specimens that satisfy these conditions. Thus, in this study, we did not compare the high-grade Nara cedar that satisfied the aforementioned requirements with cedar that did not satisfy the requirements produced in Nara and other areas.

5. CONCLUSIONS

In this study, to verify the utility of Nara cedar as an alternative to spruce, we measured its vibration character-
istics and compared them with those of spruce. Evaluation results with multiple indexes based on density, specific dynamic modulus of elasticity, and loss tangent showed that Nara cedar is suitable for use in sound boards of musical instruments, including violin tops, and is comparable to Norway spruce, Sitka spruce, and European spruce sold for violin tops (high grade and normal grade). As such, we were able to identify a possible supply of valuable string instrument material within Japan as well as a wood species that can be utilized as an alternative to spruce.

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