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ORIGINAL ARTICLE

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Internal friction measurement of tropical species by various acoustic methods

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Abstract A batch of 54 tropical species was analyzed using free-vibration and forced-released vibration tests. The free-vibration tests were conducted by bending and compression using nylon thread or elastic thread as supports. The wood species used cover a broad spectrum of density values and were obtained from the CIRAD wood collection. Samples were stabilized at a mean moisture content of 11.1%. The goals of the study were (a) to observe the effects of nylon or elastic supports on the measurement of vibration damping, (b) to compare the damping measurements obtained through free vibration in bending and in compression, (c) to understand the relationship between temporal damping and internal friction based on free-vibration and forced-vibration bending tests, and (d) to observe the effect of frequency on bending free-vibration damping on a rosewood specimen (*Dalbergia* sp., Madagascar). In this study we were able to demonstrate that (a) the type of support has a significant influence on the measurement of the temporal damping, (b) the temporal damping measurements obtained during bending free vibration are linearly linked to those obtained during compression vibration, (c) the expression of internal friction η_V according to temporal damping α was identical during compression and bending free vibration: $\eta_V = \alpha/(\pi f)$, and (d) changes in temporal damping α according to frequency f can be modeled in the form $\alpha = \beta_1 f^2 - \beta_2 f^4$. This form is theoretically justified as the first-order form obtained from the generalized differential equation of linear viscoelasticity.

Key words Acoustic · Vibration · Damping · Internal friction · Viscoelasticity

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Introduction

A perfectly elastic material subject to cyclical stress will oscillate without loss of energy, except by external friction with its support and with the atmosphere or surrounding fluid. In reality, vibrations are dampened more rapidly than in the case of energy loss due solely to external friction. Internal friction is the property possessed by solid materials of transforming mechanical energy to heat when they are subjected to cyclical stress. This effect develops in the case of small deformations characteristic of elastic phenomena (Martinez-Vega and Rivière[1]).

The internal friction of wood was studied by Ono and Norimoto[2] for 25 softwood species with air-dry specimen dimensions of 10 × 20 × 300 mm (T, R, L axes). Measurements were performed in forced-released bending vibration using electromagnetic excitation at between 250 and 750 Hz (experimental device proposed by Fukada in 1950[3] and by Hearmon[4]). A relationship between internal friction and specific modulus was observed. Based on the results obtained, it was concluded that internal friction is determined, for the major part, by the angle of cellulose microfibrils in the cell wall S2 layer. Ono and Norimoto[5] then compared 30 hardwood species with air-dry specimen dimensions of 10 × 20 × 300 mm (T, R, L axes). Bending vibrations are used at between 300 and 700 Hz. A comparable relationship to that of the previous study was found.

Ono and Norimoto[6] also studied six species (one softwood and five hardwoods) in the three main material directions of wood, with dry specimen dimensions of 10 × 10 × 100–230 mm. Forced vibrations in compression were used by magnetic excitation between 4000 and 21 000 Hz. Internal friction was measured by bandwidth of resonance curves along the three main directions. The following order relation was observed for internal friction: $L \ll R < T$. The differences observed between the axes can be explained by structural factors. Concerning Sitka spruce, a remarkable study consisted in observing the frequency dependence of internal friction by superimposing bending and longitudinal vibration measurements. A broad frequency range was covered by the reducing specimen length. It was observed that, at between approximately 100 and 2000 Hz, internal friction is virtually frequency independent; beyond 2000 Hz it starts to clearly increase (up to a factor of 2 for frequencies of about 10 kHz). However, in bending, the apparent frequency dependence of internal friction also reflects the contribution of shear and rotary inertia, depending on the slenderness and anisotropy of specimens.[7–9]

Norimoto et al.[10] then analyzed the variations in specific Young's modulus and in internal friction by means of a mechanical model taking microfibril angles into account. He concluded that microfibril angle is the leading factor in the variation of vibrational properties. Obataya et al.[9] extended the analysis using a model based on microfibril angle variations. Sampling consisted of Sitka spruce (*Picea sitchensis* Carr.) with air-dry dimensions of 3 × 15 × 150 mm (T, R, L axes). The vibration measurement was analogous to that proposed by Hearmon.[4] The bending vibration frequency range was 600–850 Hz. It was observed that longitudinal damping coefficient increased with microfibril angle, whereas the opposite applied to damping in shear.

In addition to the general effects of orientation (either material directions of wood or microfibril angle), internal friction is strongly modulated by variations in the chemical composition, either in the polymeric characteristics of the "matrix" of hemicelluloses and lignin, or in additional chemical modifications which can be artificial (chemical treatments) or "natural," such as in the case of high contents of some extractives. The influence of methanol extractives on internal friction was studied by Yano[11] on *Thuja plicata* samples more than 100 years old. Bending vibrations were used (Hearmon[4]) over the 486–744 Hz range. Microfibril angle was also measured in the sapwood and heartwood. Specimen dimensions were 2 × 12 × 120 mm (T, R, L axes). It was observed that the distribution of microfibril angles does not explain why internal friction in the sapwood is twice that in the heartwood. After methanol extraction, internal friction increased for the heartwood and decreased for the sapwood. Matsunaga et al.[12] compared the internal friction of Pernambuco (*Caesalpinia echinata* Sipreng.) to that of massaranduba (*Manilkara bidentata* A.Chev.), keranji (*Dialium* sp.), Pao rosa (*Swartzia, fistuloides* Harms), and Blackbutt (*Eucalyptus pilularis* Sm.). Air-dry specimen dimensions were 2 × 10–12 × 100–150 mm (T, R, L axes). Bending vibrations were used over the 300–1200 Hz range. It was concluded that the presence of extractives in Pernambuco decreases its internal friction. The chemical composition and location of the extractives also has an impact on internal friction.[12] The effect of water-soluble extractives on the internal friction of reed *Arundo donax* L. was studied by Obataya et al.[13] Bending vibrations were used (Hearmon[4]) over the 300–600 Hz range. Air-dry specimen dimensions were 1 × 10 × 100 mm (R, T, L axes). Extractives increase internal friction in reed and there is a linear relationship between internal friction and mass loss during extraction. The main constituents of reed extractives are simple sugars.[13]

These different studies indicate that extractives are clearly able to modify internal friction; however, their effects are dependant on their chemical nature. When no secondary chemical modification is considered, the viscoelasticity of wood mainly reflects lignin behavior. Dynamic temperature- and frequency-based tests indicate that lignin viscosity is dependent upon its monomer composition, which determines network density and hence molecule flexibility.[14] Vibrational tests under ambient hygrothermy and at audible frequencies indicate that changes in lignin composition are also determinant in this range of experimental conditions.[15]

The viscoelastic properties were studied by Jiang et al.[16] for temperatures between 30° and 280°C at frequencies ranging from 0.5 to 10 Hz on *Cunninghamia lanceolata* Lamb. The dynamic mechanical analysis (DMA) of forced oscillations was used. Specimen dimensions were 1 × 12 × 35 mm (T, R, L axes) and were initially green. The study revealed the existence of two internal friction peaks at temperatures of 90°C and 240°C. The 90°C peak was ascribed to the molecular movement of lignin, while the 240°C peak was ascribed to the micro-Brownian motion of the noncrystalline cell wall fraction. The authors, however, remarked that the crystalline fraction of cellulose began to decrease in this temperature range. It is remarkable to note that, at very low frequency, viscosity increases as frequency decreases from 10 to 0.5 Hz.[14,16]

Through different studies, different measurement methods and expressions of internal friction (η) are used. Common expressions are the quality factor Q and the loss tangent tan δ. Acousticians often use the temporal damping α. Although some experimental parameters have been studied for individual methods, relatively few authors compared values obtained by different experimental protocols on diverse species. The aim of this study was to compare—experimentally and theoretically—temporal damping and internal friction measurements obtained by bending free vibration, compression free vibration, and forced-released bending vibration, with various types of specimen supports. The broad range of properties of tropical species should prove suitable for these comparisons.

Materials and methods

Plant material

The species were taken from the CIRAD's wood collection. A batch of 54 tropical species was selected in such a manner as to cover a broad range of densities (218–1254 kg/m^3). These species are identical to those chosen for our previous studies (Brancheriau et al.,[17,18] Aramaki et al.[19]). In most cases, samples were collected from the same log. The name, density, and acoustic properties associated with each specimen are given in Table 1.

Experimental methodology

For each species, a specimen was prepared that was 350 mm long, 20 mm wide, and 8 mm thick along the material's L, R, and T axes. The dimensions of the specimens were deter-

Table 1. Wood species used and experimental results obtained

Database no.	Botanical name	Density (kg/m^3)	$\alpha_1/f_{1\text{Flex}}$	$\alpha_1/f_{1\text{Comp}}$	$\Delta f/f_1(=Q^{-1})$	$\alpha_1/f_{1\text{Studies}}$
4271	*Scottellia klaineana* Pierre	635	0.024	0.025	0.0076	0.024
5329	*Ongokea gore* Pierre	851	0.028	0.031	0.0095	0.028
6704	*Humbertia madagascariensis* Lamk.	1254	0.031	0.026	0.0093	0.026
6779	*Ocotea rubra* Mez	626	0.021	0.019	0.0069	0.023
6966	*Khaya grandifoliola* C.DC.	682	0.029	0.031	0.0087	0.027
7021	*Khaya senegalensis* A.Juss.	792	0.030	0.025	0.0084	0.029
7299	*Coula edulis* Baill.	1058	0.023	0.022	0.0070	0.028
11136	*Tarrietia javanica* Bl.	589	0.015	0.015	0.0048	0.020
14238	*Afzelia bipindensis* Harms	820	0.013	0.012	0.0039	0.020
14440	*Swietenia macrophylla* King	631	0.021	0.019	0.0064	0.019
14814	*Aucoumea klaineana* Pierre	379	0.021	0.018	0.0067	0.028
15377	*Faucherea thouvenotii* H.Lec.	1075	0.016	0.019	0.0053	0.021
15719	*Ceiba pentandra* Gaertn.	294	0.028	0.022	0.0087	0.026
16136	*Commiphora* sp	355	0.015	0.013	0.0044	0.014
16184	*Monopetalanthus heitzii* Pellegr.	446	0.018	0.020	0.0060	0.022
16211	*Dalbergia* sp	933	0.013	0.013	0.0043	0.013
16624	*Hymenolobium* sp	668	0.016	0.018	0.0053	0.017
16627	*Pseudopiptadenia suaveolens* (Miq) Brenan	856	0.023	0.022	0.0072	0.020
16643	*Parkia nitida* Miq.	401	0.021	0.021	0.0062	0.017
16664	*Bagassa guianensis* Aubl.	679	0.023	0.027	0.0047	0.023
16727	*Discoglypremna caloneura* Prain	419	0.027	0.024	0.0088	0.037
16796	*Brachylaena ramiflora* Humbert	1015	0.019	0.018	0.0051	0.022
17431	*Simarouba amara* Aubl.	426	0.019	0.019	0.0061	0.020
18077	*Gossweilerodendron balsamiferum* Harms	436	0.028	0.024	0.0086	0.034
18127	*Manilkara mabokeensis* Aubrev.	939	0.023	0.023	0.0070	0.024
18283	*Shorea-rubro squamata* Dyer	576	0.025	0.023	0.0082	0.022
18284	*Autranella congolensis* A.Chev.	998	0.032	0.034	0.0108	0.039
18412	*Entandrophragma angolense* C.DC.	479	0.019	0.023	0.0063	0.021
18752	*Distemonanthus benthamianus* Baill.	744	0.017	0.017	0.0043	0.020
19038	*Entandrophragma cylindricum* Sprague	634	0.026	0.023	0.0083	0.027
19041	*Terminalia superba* Engl. et Diels	361	0.027	0.028	0.0080	0.024
20030	*Nesogordonia papaverifera* R.Cap.	719	0.027	0.030	0.0090	0.028
20049	*Albizia ferruginea* Benth.	617	0.020	0.021	0.0059	0.023
20982	*Gymnostemon zaizou* Aubrev. et Pellegr.	382	0.030	0.030	0.0091	0.018
21057	*Anthonotha fragrans* Exell et Hillcoat	717	0.024	0.019	0.0077	0.025
25971	*Guibourtia ehie* J.Leon.	769	0.023	0.023	0.0075	0.027
27319	*Pometia pinnata* Forst.	847	0.024	0.025	0.0077	0.024
27570	*Pericopsis elata* Van Meeuw	717	0.018	0.019	0.0058	0.020
27588	*Glycydendron amazonicum* Ducke	650	0.015	0.016	0.0052	0.019
28071	*Cunonia austrocaledonica* Brong. et Gris.	934	0.028	0.025	0.0095	0.030
28082	*Nothofagus aequilateralis* Steen.	1098	0.030	0.032	0.0101	0.038
28086	*Schefflera gabriellae* Baill.	569	0.020	0.019	0.0061	0.029
28089	*Gymnostoma nodiflorum* Johnst.	1154	0.027	0.028	0.0087	0.034
28100	*Calophyllum caledonicum* Vieill.	722	0.020	0.018	0.0064	0.018
28102	*Gyrocarpus americanus* Jacq.	218	0.037	0.034	0.0112	0.030
28103	*Pyriluma sphaerocarpum*	772	0.024	0.024	0.0073	0.033
28163	*Cedrela odorata* L.	446	0.024	0.018	0.0066	0.024
28338	*Dysoxylum* sp	962	0.020	0.023	0.0064	0.021
29468	*Moronobea coccinea* Aubl.	916	0.012	0.017	0.0041	0.021
29503	*Goupia glabra* Aubl.	960	0.026	0.013	0.0078	0.041
29509	*Manilkara huberi* Standl.	1188	0.021	0.024	0.0069	0.025
30231	*Micropholis venulosa* Pierre	709	0.019	0.019	0.0062	0.020
30258	*Cedrelinga catenaeformis* Ducke	461	0.020	0.023	0.0064	0.021
30679	*Vouacapoua americana* Aubl.	839	0.018	0.020	0.0058	0.023

The mean fundamental frequency f_1 ($n = 54$) was 303, 6524, 303, and 998 Hz for bending free vibration (nylon threads), compression free vibration (nylon threads), forced released bending vibration (silk threads), bending free vibration (elastic threads in previous studies)

$\alpha_1/f_{1\text{Flex}}$, temporal damping to frequency ratio in bending free vibration; $\alpha_1/f_{1\text{Comp}}$, temporal damping to frequency ratio in compression free vibration; $\Delta f/f_1(=Q^{-1})$, inverse of the quality factor in forced released bending vibration; $\alpha_1/f_{1\text{Studies}}$, temporal damping to frequency ratio in bending free vibration (previous studies)

mined in such a manner as to be able to conduct the tests with the free-vibration device and the forced-released vibration device. All specimens were, as far as possible, taken along the grain, with no knots or defects. Samples were stabilized in a climate-controlled room with 65% relative humidity and a temperature of 20°C, with a theoretical moisture content at equilibrium of 12%.

A 20-mm-wide and 8-mm-thick sample of rosewood (*Dalbergia* sp., origin: Madagascar) was added to the 54 specimens. The length was varied between 1000 mm and

130 mm by sawing off 30-mm lengths. Mean sample density was 960 kg/m^3.

Specimens were always tested flat, i.e., with the vibration deflection occurring in their L-T plane. The different tests conducted and their respective goals are presented below:

– Bending and compression free-vibration tests with nylon threads and elastic (rubber) threads on a specimen. The aim was to study the effect of the different supports on internal friction.
– Bending and compression free-vibration tests with nylon threads. The aim was to compare the results obtained between dynamic bending and compression tests.
– Bending tests under free vibration (nylon thread) and forced-released vibration (silk thread) conditions. The aim was to compare the results obtained with the two types of dynamic test.
– Bending free-vibration tests with nylon thread conducted on the Madagascar rosewood sample. The aim was to study changes in temporal damping with frequency.

Repeatability tests were performed on one specimen under bending and compression conditions on nylon threads with free vibration and forced-released vibration. A humidity measurement was performed on all 54 specimens.

Free-vibration tests

The BING device (http://www.xylo-metry.org/fr/bing.html) was used. The test piece rests on two rigid supports (nylon threads 17 cm long and 0.35 mm in diameter) or on elastic supports (Fig. 1). Whenever possible, the supports are placed on the vibration nodes of the fundamental frequency. The specimen is impacted at one end with a 13-mm-diameter steel ball weighing 9 g (bending or compression vibration depending on the orientation of the impact). A microphone is placed at a distance of 2 cm from the other end of the specimen.

The microphone is unidirectional, type EMU4535 (Lem Industries). The analog-to-digital converter is a Picoscope 3224 (Pico Technology). It possesses 12-bit resolution. The anti-aliasing filter was set to the Nyquist-Shannon frequency. The acquisition parameters used are detailed in Table 2. Recordings were not performed in an anechoic room and are of much lower quality than for our previous studies (Brancheriau et al.[17,18]; Aramaki et al.[19]).

In this study, only the acoustic parameters resulting from the fundamental frequency were taken into account. The acoustic parameters measured were the fundamental frequency f_1 and temporal damping α_1 (Aramaki et al.[19]). Each test was conducted in triplicate. The test results were the mean values of the measured parameters.

Forced-released vibration test

The test piece was supported by silk threads located at the position of the vibration nodes of the fundamental frequency. It was subjected to forced bending vibration using an electromagnet facing a thin iron plate of negligible mass glued to the end of the specimen (Fig. 2). A computer-driven frequency generator applied frequency scans and a laser displacement sensor measured the amplitude of the oscillation on the vibration surface (central area of the test specimen). An initial frequency scan was performed to determine the fundamental frequency, and then a second scan centered on this frequency allowed determining the quality factor (Q) through the half-power bandwidth. Then

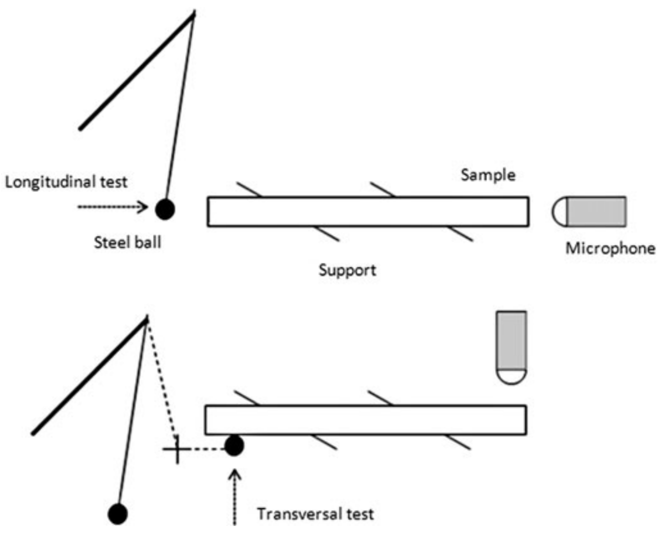

Fig. 1. Experimental setup of bending (transversal) and compression (longitudinal) free-vibration device

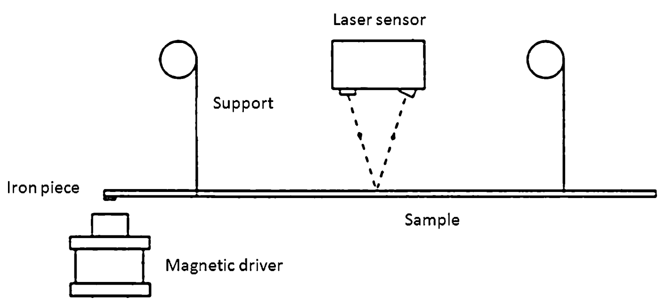

Fig. 2. Experimental setup of forced-released bending vibration device

Table 2. Free vibration acquisition parameters

	Vibration test	Sampling frequency (kHz)	Frequency resolution (Hz)	Acquisition duration (ms)
All 54 specimens	Transversal (bending)	19.5	0.6	1680
All 54 specimens	Longitudinal (compression)	156.5	19.1	52
Dalbergia sp.	Transversal (bending)	4.9–19.5	0.2–2.4	420–6687

the test specimen was excited at its resonance frequency; the applied stress was then abruptly interrupted and the logarithmic decrement (λ) of the specimen's oscillations was recorded.

The laser displacement sensor used was a model LD1607-4 from Micro-Epsilon. It possesses a resolution of 1 μm. The analog-to-digital converter used was a PCI-6221 (National Instruments) with 16-bit resolution. Sampling frequency was 100 kHz and acquisition duration was 10 s for bandwidth measurement and 400 ms for logarithmic decrement measurement.

This device was originally designed to test specimens 100–200 mm long, 10–20 mm wide, and 1.5–2.5 mm thick. The acoustic parameters measured were the fundamental frequency f_1, internal friction by logarithmic decrement analysis ($\tan\delta = \lambda/\pi$), and the inverse of the quality factor $Q^{-1} = \Delta f/f_1$ (Brémaud[15]). Each test was conducted in triplicate. The test results were the mean values of the measured parameters.

Results and discussion

Sample moisture content

The moisture content of the 54 specimens was determined as per the instructions of the NF EN 13183-1 standard.[20] Mean moisture content distribution was 11.1%, with a standard deviation of 1.0%, a minimum of 8.2%, and a maximum of 13.9%. The observed mean was similar to the theoretical moisture content of 12%. This theoretical value falls within the confidence interval of the distribution with a statistical risk of 5%.

Measurement uncertainties

Measurement uncertainties were estimated by repeating at least 30 times a test on specimen no. 19038 (*Entandrophragma cylindricum* Sprague). This specimen was selected due to its density of 634 kg/m^3, which is close to the group's mean density (711 kg/m^3). The tests were conducted using nylon thread supports. The estimated measurement uncertainty was calculated as follows:

$$\varepsilon_y = \frac{1.96\, s(y)}{\bar{y}} \tag{1}$$

where $s(y)$ is the standard deviation of variable y, and $\bar{y}$ is the mean of variable y.

Whatever type of test was conducted, the uncertainty concerning the fundamental frequency was less than 1%. Uncertainty for variable α_1/f_1 was 6.8% during bending free vibration and 9.9% during compression vibration. Concerning the forced-released bending vibration test, the uncertainty for variable $\Delta f/f_1$ ($= Q^{-1}$) was 4.5% and that for λ/π ($= \tan\delta$) was estimated at 26%.

The uncertainty of 6.8% obtained for variable α_1/f_1 was higher than during previous studies, e.g., 4.4% reported by Brancheriau et al.[17] This may be explained by the resolution of the converter used and by the absence of an anechoic chamber. The uncertainty of 26% obtained for variable λ/π is very high in our particular case because this test was not designed for the test specimen thickness – and thus rigidity – used (insufficiently strong electromagnet excitation for correct λ estimation). These test specimen dimensions were chosen for being usable on both types of test.

Effect of the supports

Study of the influence of the support was conducted on sample no. 19038. The test was repeated at least 30 times for bending-free and compression vibration using nylon threads and elastic rubber bands.

A comparative test of the two means (dependent *t*-test for paired samples) was used, with a statistical risk of 5%. This test shows that there was no significant difference in fundamental frequency. Significant differences did appear, however, between bending free vibration and compression vibration for variable α_1/f_1 depending on the support used. During bending, the mean value obtained with the elastic rubber bands was 15% lower than that with the nylon thread (α_1/f_1 for elastic band / nylon was 0.85). During compression, the mean value obtained with the elastic bands was 10% higher than that with the nylon thread (α_1/f_1 for elastic band/nylon was 1.11).

The observed differences for variable α_1/f_1 were of opposite sign depending on the type of stress applied. Vibration damping should be greater for very flexible rubber bands than for nylon threads, except in the event of disturbances induced by resonance coupling between the structure and the specimen. Indeed, one of the frame's resonance frequencies was identified at 260 Hz. This frequency is close to the bending fundamental frequency (about 230–360 Hz, mean 303 Hz; during compression: 6610 Hz). It may interfere with the vibrational response of those specimens with natural frequencies within the lower part of the observed range. In our case, the elastic bands tended to limit coupling with the frame, whereas the more rigid nylon threads enhanced this coupling.

Comparison with the results of previous studies

The results obtained with bending vibration were first compared to the data of previous studies (Brancheriau et al.[17,18]; Aramaki et al.[19]). The specimen dimensions in these studies were 20 × 45 × 350 mm (T, R, L axes). The adjusted coefficient of determination is significantly different from zero at the 5% risk level ($R^2a = 0.46$, $n = 54$, Fig. 3). The resulting adjustment equation is $\alpha_1/f_{1\text{Studies}} = 0.77\alpha_1/f_{1\text{Flex}} + 0.007$. The constant is significant and the direction coefficient is statistically different from unity: the 95% confidence interval of the direction coefficient was [0.54; 0.99]. This result is partly related to the use of different supports: elastic supports for the previous study and nylon supports in the present case. The systematic bias might be related to the difference in

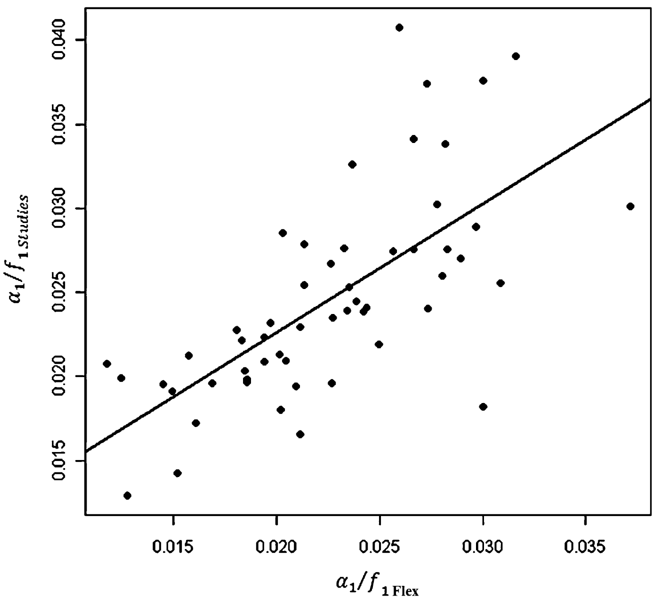

Fig. 3. Comparison of results obtained with bending free vibration (temporal damping-to-frequency ratio for the fundamental frequency, $\alpha_1/f_{1\mathrm{Flex}}$) compared to previous studies $\alpha_1/f_{1\mathrm{Studies}}$ (Brancheriau et al.[17,18]; Aramaki et al.[19]; $n = 54$)

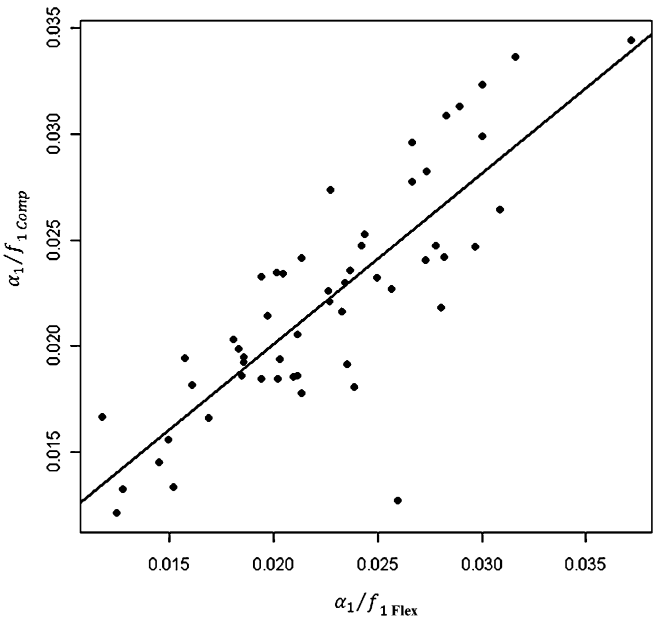

Fig. 4. Comparison of results obtained during bending free vibration $\alpha_1/f_{1\mathrm{Flex}}$ and compression free vibration $\alpha_1/f_{1\mathrm{Comp}}$ ($n = 54$)

microphone positioning for the two studies. However, most of the observed differences primarily reflect the intraspecific variability, as test specimens were different from previous studies.

Comparison of results obtained during bending and compression

The comparison of results obtained between the dynamic bending and compression tests is shown in Fig. 4 (using nylon threads). The adjusted coefficient of determination is significant ($R^2a = 0.67, n = 54$). The adjustment equation may be written as $\alpha_1/f_{1\mathrm{Comp}} = 0.81\ \alpha_1/f_{1\mathrm{Flex}} + 0.004$. However, the constant is not significant, so it can safely be ignored. The adjusted relationship can then be written as $\alpha_1/f_{1\mathrm{Comp}} = 0.97\ \alpha_1/f_{1\mathrm{Flex}}$ (adjusted coefficient of determination $R^2a = 0.65$). The values obtained during compression (frequency of 6500 Hz) and during bending (frequency of 300 Hz) were very similar, although those for compression are slightly lower. We expected to observe the opposite phenomenon, as internal friction, and hence the α_1/f_1 ratio, should increase with frequency.[6] This may be explained by the fact that, during bending, resonance coupling with the frame can occur for specimens with a natural frequency close to 260 Hz.

Comparison of results obtained through free- and forced-bending vibration

Figure 5 shows the comparison of results obtained during bending free vibration and forced-released vibration. For the latter method, only variable $\Delta f/f_1$, i.e., Q^{-1} obtained in forced vibration, was taken into account as the uncertainty

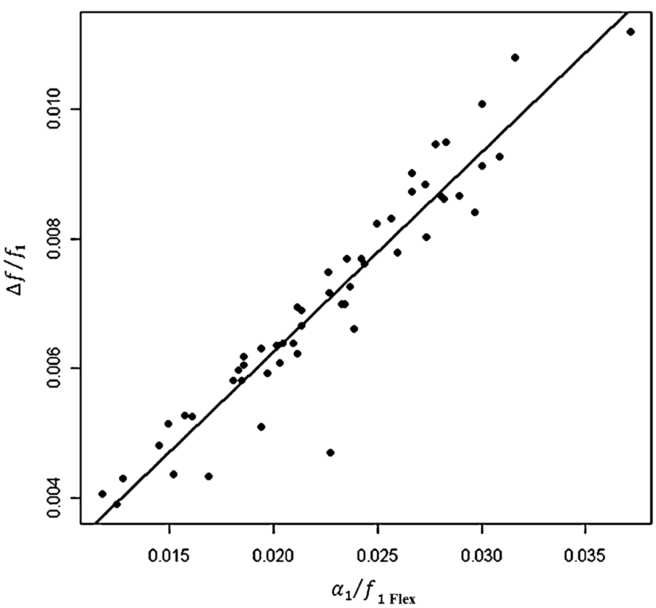

Fig. 5. Comparison of results obtained through free vibration $\alpha_1/f_{1\mathrm{Flex}}$ and forced vibration $\Delta f/f_1 (= Q^{-1})$, both in bending ($n = 54$)

relative to λ/π was too high. The adjusted coefficient of determination is significant ($R^2a = 0.90$, $n = 54$). The adjustment equation can be written as $\Delta f/f_1 = 0.31\alpha_1/f_{1\mathrm{Flex}} + 8.\ 10^{-5}$. The constant is not significant. The direction coefficient differs significantly from unity, with a 95% confidence interval of [0.28; 0.34]. The value of the direction coefficient suggests a relationship of the $\Delta f/f_1 = \alpha_1/(\pi f_1)$ type.

The relationship between internal friction and temporal damping of vibrations is demonstrated theoretically. Internal friction is measured by studying the phase shift between the stress applied and the resulting deformation (viscoelastic behavior), or by studying energy loss during an oscillation period (hysteretic behavior).[1,21,22] The dissipation factor associated with hysteretic behavior is independent of excitation frequency, but proportional to the square of vibration amplitude and to the stiffness of the structure (Eq. 2, according to Venizelos[21] and Chaigne and Kergomard[22]):

$$|\Delta W| = \pi \eta_H k X^2 \tag{2}$$

where ΔW is the energy dissipated per cycle, η_H is the hysteretic dissipation factor, k is the structure stiffness with one degree of freedom, and X is the vibration amplitude. A system with hysteretic damping that dissipates the same amount of energy per cycle as a system with viscoelastic damping possesses a hysteretic dissipation factor equal to the loss angle η_V (Venizelos[21]).

Subsequently, we shall study the case of viscoelastic behavior, assuming that $\eta_H = \Delta f/f_1 = Q^{-1}$. The equation describing the movement of a sufficiently slender beam during longitudinal vibration can be written as follows (the Poisson effect is ignored):

$$\frac{E}{\rho}\frac{\partial^2 u}{\partial x^2} - \frac{\partial^2 u}{\partial t^2} = 0 \tag{3}$$

where E is Young's modulus, u is displacement, and ρ is density. To take into account the viscoelastic phenomenon, the modulus is considered to be a complex value (Liu and Ödeen[23]): $E'' = E_d \exp[j\eta_V]$ with $\eta_V \ll 1$. The solution to Eq. 3 is selected in the form of a stationary plane wave: $u(x,t) = \varphi(x)\exp[j\gamma t]$ where φ is spatial dependence and the damping coefficient α is included in the temporal term $\gamma = 2\pi f + j\alpha$. Using Eq. 3 and its stationary planar solution, the dispersion relationship can be written:

$$\frac{\gamma}{k} = \sqrt{\frac{E_d}{\rho}}\ \exp\left[j\frac{\eta_V}{2}\right] \Leftrightarrow \frac{2\pi f}{k}\left(1 + j\frac{\alpha}{2\pi f}\right) \approx \sqrt{\frac{E_d}{\rho}}\ \left(1 + j\frac{\eta_V}{2}\right) \tag{4}$$

Finally, we obtain the relationship between temporal damping during longitudinal vibration α and internal friction η_V:

$$\eta_V = \frac{\alpha}{\pi f} \tag{5}$$

If the solution to Eq. 3 is selected in the form of a progressive plane wave, then $u(x,t) = \exp[j(2\pi ft - k''x)]$. During its propagation, the wave attenuates and the damping coefficient is a spatial term ($k'' = k - jk'$). Using Eq. 3 and its progressive planar solution, the dispersion relationship can be written:

$$\begin{aligned} k'' &= 2\pi f\sqrt{\frac{\rho}{E_d}}\ \exp\left[-j\frac{\eta_V}{2}\right] \Leftrightarrow k\left(1 - j\frac{k'}{k}\right) \\ &\approx 2\pi f\sqrt{\frac{\rho}{E_d}}\ \left(1 - j\frac{\eta_V}{2}\right) \text{ and } \frac{k'}{k} = \frac{\eta_V}{2} \end{aligned} \tag{6}$$

By positioning oneself at one end of the beam, the value of the attenuation term of the progressive wave must be equal to that of the stationary wave: $\alpha L/C = k'L$ where C is celerity. This leads to $\alpha = 2\pi f k'/k$. By using this last equation with Eq. 6, we obtain the same relationship as Eq. 5. The results should be identical, whatever type of wave is considered.

The equation of the movement of a sufficiently slender beam during transverse vibration can be written as follows (section rotation inertia, shear, and Poisson effect ignored):

$$\frac{EI}{\rho A}\frac{\partial^4 u}{\partial x^4} + \frac{\partial^2 u}{\partial t^2} = 0 \tag{7}$$

where I is moment of inertia. The solution to Eq. 7 is selected in the form of a stationary plane wave. The dispersion equation is written:

$$\frac{\gamma}{k^2} = \sqrt{\frac{E_d I}{\rho\ A}}\ \exp\left[j\frac{\eta_V}{2}\right] \tag{8}$$

We thus obtain a relationship between temporal damping during transverse vibration α and internal friction η_V identical to that obtained for longitudinal vibration (Eq. 5). If the chosen solution is of the form $u(x,t) = \exp[j(2\pi ft - k''x)]$, however, the relationship between α and η_V becomes $\eta_V = 2\alpha/(\pi f)$ if phase velocity is used, which would be a mistake (unfortunately made by Brancheriau et al.[17]). If the group velocity is used, the relationship between α and k' becomes $\alpha L/C_g = \alpha Lk/(4\pi f) = k'L$ and we obtain $\alpha = 4\pi fk'/k$. This last equation, used with Eq. 8, leads to a relationship between temporal damping during transverse vibration α and internal friction η_V identical to that obtained for longitudinal vibration (Eq. 5).

Some of the values of α_1/f_1 are, however, overestimated in the present case due to the resonance coupling with the frame. Perhaps, the thickness of the air film between specimen and microphone might also generate a slight measurement bias. The slope coefficient of the adjustment equation should be less than 0.31. Another contributing factor is that the measurement of $Q^{-1} = \Delta f/f_1$ is also slightly overestimated (by 1.1% on average[15]) as the excitation response spectrum is convoluted by the observation window spectrum (generally a sine cardinal function).

Damping changes according to frequency

The resonance frequencies of the Madagascar rosewood sample were rendered variable by progressively decreasing the specimen's length. The free-vibration test serves to simultaneously measure internal friction at several resonance frequencies in bending. In this case, the first three vibration frequencies were analyzed over a 41–5761 Hz range. In the 400–1000 Hz frequency range, internal friction was on average 3.8×10^{-3}, and increased by about 1.4×10^{-3} towards the highest studied frequencies. In bending vibration, the contribution of shear and rotary inertia is known to affect the apparent frequency dependence.[7–9] However, in our case, the slenderness of the specimen was important (length/thickness ratio from 16 to 125). Also, rosewood species have a much reduced anisotropy as compared to previously studied species such as spruce. So, anisotropic effects should remain moderate.

The changes in temporal damping (α) according to frequency are shown in Fig. 6 (two frequency values were not

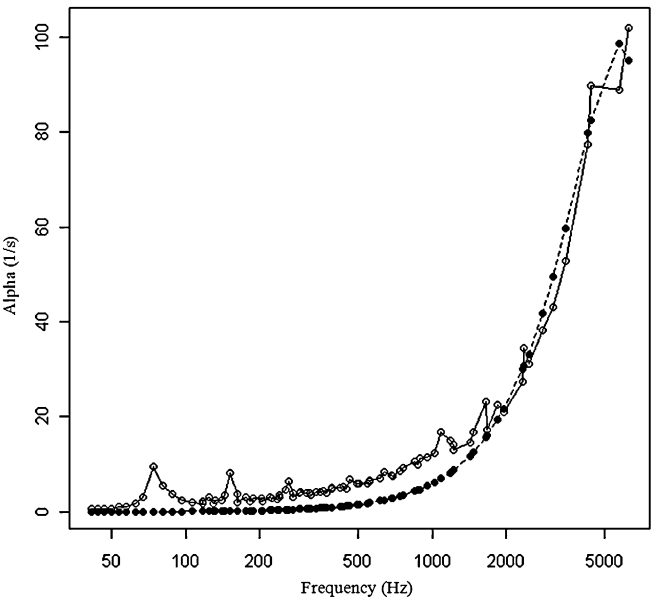

Fig. 6. Changes in temporal damping α according to frequency f for the Madagascar rosewood specimen (*open circles*, experimental points; *solid circles*, adjustment, $n = 88$)

assessed and these frequencies belong to the third natural frequency). Peaks are visible in this figure at 74 Hz, 151 Hz, and 263 Hz. These are the result of resonance coupling between the frame and the test specimen (the nylon threads have natural frequencies of less than 1 Hertz). This phenomenon biases the measurements, although all points are kept to make an adjustment of the form $\alpha = \beta_1 f^2 - \beta_2 f^4$ (β_1 and β_2 are positive constants, Fig. 6). This form is the theoretical first-order form obtained according to the following development.

The general differential equation constitutive of linear viscoelasticity can be written as:[22,23]

$$\sigma + \sum_{p=1}^{\infty} a_p \frac{\partial^p \sigma}{\partial t^p} = E_0 \left(\varepsilon + \sum_{q=1}^{\infty} b_q \frac{\partial^q \varepsilon}{\partial t^q} \right) \tag{9}$$

In the case of cyclical stress ($\sigma = \sigma_0 \exp[j2\pi ft]$ and $\varepsilon = \varepsilon'' \exp[j2\pi ft]$), the complex modulus is written as follows:

$$E'' = E_0 \frac{1 + \sum_{q=1}^{\infty} b_q (j2\pi f)^q}{1 + \sum_{p=1}^{\infty} a_p (j2\pi f)^p} \tag{10}$$

The simplest generalization is given by the first-order model (or Zener model). In this case, and by identification with the expression $E'' = E_d \exp[j\eta_V]$ with $\eta_V \ll 1$, we obtain:

$$\begin{aligned} & E_0 \frac{1 + b_1 a_1 (2\pi f)^2}{1 + a_1^2 (2\pi f)^2} \left(1 + j \frac{(b_1 - a_1) 2\pi f}{1 + b_1 a_1 (2\pi f)^2} \right) \\ & \approx E_d (1 + j\eta_V) \Rightarrow \begin{cases} E_d = E_0 \dfrac{1 + b_1 a_1 (2\pi f)^2}{1 + a_1^2 (2\pi f)^2} \\ \eta_V = \dfrac{(b_1 - a_1) 2\pi f}{1 + b_1 a_1 (2\pi f)^2} \end{cases} \end{aligned} \tag{11}$$

Improved relationships were proposed by Ouis.[24] Equation 11 shows that E_d and η_V are a function of frequency. The temporal damping parameter α can thus be written (Eqs. 5 and 11):

$$\begin{aligned} \alpha = \pi f \eta_V &= \frac{1}{2}(b_1 - a_1)(2\pi f)^2 \frac{1}{1 + b_1 a_1 (2\pi f)^2} \\ &= \frac{1}{2}(b_1 - a_1)(2\pi f)^2 \sum_{p=0}^{\infty} \left[-b_1 a_1 (2\pi f)^2 \right]^p \end{aligned} \tag{12}$$

By using the first-order full series development of Eq. 12, temporal damping can be expressed in the following form (assuming $b_1 a_1 (2\pi f)^2 \ll 1$:

$$\alpha \approx \frac{1}{2}(b_1 - a_1)(2\pi f)^2 \left[1 - b_1 a_1 (2\pi f)^2 \right] \tag{13}$$

Based on the experimental data obtained, the determination of coefficients for Eq. 13 leads to $\alpha = 6 \times 10^{-6} f^2 - 9 \times 10^{-14} f^4$ (Fig. 6, $n = 88$ points). The calculated coefficients are significant at the 5% risk level. The creep time of the Zener model is thus equal to $b_1 = 1.96 \times 10^{-5}$ s. The creep time minus the relaxation time is equal to $b_1 - a_1 = 3 \times 10^{-7}$ s. According to the properties of the Zener model, changes in internal friction η_V according to frequency are characterized by a peak at the frequency $f_z = 1/\left(2\pi\sqrt{b_1 a_1}\right)$, i.e., 8165 Hz for the calculated values. This model, however, constitutes a first approximation of dynamic behavior and translates the mean behavior only within the 40–5500 Hz interval.

Conclusion

A series of bending and compression free-vibration tests were conducted using nylon or elastic threads as supports. Forced-released bending vibration tests (silk threads) were also conducted on a batch of 54 tropical species of varying density. Mean sample moisture content was 11.1%. The purpose of the tests was to compare temporal damping and internal friction measurements obtained by various experimental methodologies. The bending free-vibration tests were disrupted by resonance coupling with the frame. We were nevertheless able to demonstrate that:

- The type of support (nylon threads or highly elastic threads) has a significant influence on the measurement of the temporal damping-to-frequency ratio α/f during free vibration, even when the supports are positioned at the theoretical vibration nodes of the specimen's fundamental frequency.
- The α/f ratio measurements obtained during bending free vibration are linearly linked to those obtained during compression vibration. The same applies between measurements obtained during bending free vibration and during forced bending vibration. This last observation suggests a relationship of the type $\eta_V = \alpha/(\pi f)$.
- A theoretical study using the motion equations demonstrated that the expression of internal friction η_V according to temporal damping α was identical during compression and bending free vibration: $\eta_V = \alpha/(\pi f)$. This

study took into consideration stationary or propagation type waves.
– Changes in temporal damping α according to frequency f were observed on a sample of rosewood (*Dalbergia* sp., Madagascar) during bending free vibration. The frequency range was 41–5761 Hz, achieved by progressively decreasing the specimen length. An adjustment of form $\alpha = \beta_1 f^2 - \beta_2 f^4$ is theoretically justified as the first-order form obtained from the generalized differential equation of linear viscoelasticity.

Comments

In the article referenced Brancheriau et al.,[17] Eq. 3 should read $\tan\delta = \alpha_1/(\pi f_1)$. Consequently, the internal friction values (parameter with no measurement unit) given in Table 2 in Brancheriau et al.[17] should be divided by 2. In the article referenced Brancheriau et al.,[18] Eq. 8 should read $\alpha_i = \pi f_i \tan\delta$. The results and conclusions of these two articles remain valid, however.

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