Characterisation and categorisation of the diversity in viscoelastic vibrational properties between 98 wood types

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Characterisation and categorisation of the diversity in viscoelastic vibrational properties between 98 wood types

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Abstract:

• ***Context*** Increased knowledge on diversity in wood properties would have implications both for fundamental research and for promoting a diversification of uses as material.

• ***Aims*** The objective is to contribute to overcoming the critical lack of data on the diversity of wood dynamic mechanical/viscoelastic vibrational properties, by testing lesser-known species and categorizing sources of variability.

• ***Methods*** Air-dry axial specific dynamic modulus of elasticity (E'/γ) and damping coefficient ($\tan\delta$) were measured on a wide sampling (1792 specimens) of 98 wood types from 79 species. An experimental device and protocol was designed for conducting systematic (i.e. rapid and reproducible) characterizations.

• ***Results*** Diversity at the specimens' level corroborates the "standard" relationship between $\tan\delta$ and E'/γ, which is discussed in terms of orientation of wood elements and of chemical composition. Diversity at the species level is expressed on the basis of results for normal heartwood, with specific gravity (γ) ranging from 0.2 to 1.3. Axial E'/γ ranges from 9 to 32 GPa and $\tan\delta$ from 4×10^{-3} to 19×10^{-3}. Properties distribution follows a continuum, but with group characteristics. The lowest values of $\tan\delta$ are only found in certain tropical hardwoods. Results can also suggest alternative species for musical instruments making.

• ***Conclusion*** The variations in specific gravity, in stiffness or in "viscosity" appear to be predominantly linked to different levels of diversity: between species, or between wood types (reaction wood or taxonomy-related differences in heartwood extractives).

Keywords:
damping coefficient /dynamic mechanical properties / specific dynamic modulus of elasticity / specific gravity / viscoelastic vibrational properties / wood diversity

1. Introduction

Exploring the diversity of wood properties has long been a goal of foresters and wood technologists, and more recently has found implications in research into functional ecology and biomechanics (e.g. Chave *et al.* 2009). Large databases of physico-mechanical properties can also contribute to a physical understanding of traditional preferences for specific woods in various cultural uses (Brémaud 2012). They are also the pre-requisite for applying material selection methods (e.g. Wegst 2006), which could allow more efficient, diversified and potentially sustainable utilisation of wood materials. Amongst the 50000+ wood-producing species, data are available for a proportionally moderate, yet quite important number of species for some properties: at least 8000 species for specific gravity or density (e.g., Détienne and Chanson 1996; Chave *et al.* 2009), a minimum of 1000-2000 species for the longitudinal modulus of elasticity (unpublished database at CIRAD; many other wood technology resources). Unfortunately, there is still a critical lack of knowledge on the diversity of some other relevant properties, notably concerning anisotropy and viscoelasticity. An up-to-date census on most published data on viscoelastic vibrational properties reveals that ≤400 species have been characterized, even partially (Brémaud *et al.* 2009; Brémaud 2012).

The diversity in wood properties expresses variations in structure (cellular and sub-cellular) and chemical composition (constitutive polymers and secondary metabolites). For wood along the grain, cellular anatomy mostly intervenes in the sense of "porosity", i.e. it determines specific gravity (γ) and thus affects Young's modulus (E). On the contrary, vibrational properties (specific dynamic modulus of elasticity = E'/γ and damping coefficient = $\tan\delta$) are primarily governed at the cell-wall level, with E'/γ

decreasing, and tanδ increasing, with increasing microfibril angle (Obataya *et al.* 2000). As a result, a strong relationship generally exists between tanδ and E'/γ (Ono and Norimoto 1983, 1984). Variations in grain angle have similar impacts on both properties and result in a comparable tanδ-E'/γ relationship (Brémaud *et al.* 2010a, 2011b). Furthermore, the composition of the "matrix" of hemicelluloses and lignin determines the viscous behaviour (Obataya *et al.* 2000, Olsson and Salmén 1992, 1997). Some extractive compounds can also play a key role in modifying tanδ, by as much as a factor 2, with only minor effects on E'/γ (Yano 1994; Matsunaga *et al.* 1996; Obataya *et al.* 1999; Minato *et al.* 2010; Brémaud *et al.* 2010b, 2011a).

Anatomical and chemical features can be related to or even be characteristic of various levels of diversity, from plant order to species, but also be related to biogeography. Softwoods generally have a simpler anatomy, and a higher content of lignin which also has a more condensed chemical structure (Olsson and Salmén 1992, 1997). Amongst hardwoods, tropical ones show more diversity and often some typical features such as interlocked grain or high extractives content (*EC*) (e.g. Hernandez 2007; Brémaud *et al.* 2010a, b). Cellular anatomy and secondary metabolites can be particularly characteristic of a genus or even a species. In addition to species diversity, there is a wide within-species variability, between or within trees, between different wood types, e.g. "normal" vs. reaction wood (variations in both anatomy and polymers), or heartwood vs. sapwood (variations in extractives but similar anatomy and constitutive polymers).

The exploration and analysis of the diversity in wood properties requires obtaining very large datasets. A few long-term studies using the same methodology exist (e.g. Détienne and Chanson 1996; unpublished CIRAD database and other research institutes resources). In order to compare a maximum of species, however, results from different sources have to be compiled (e.g. Chave *et al.* 2009; Brémaud *et al.* 2009). This efficient approach has nevertheless drawbacks: even in the case of "simple" properties such as specific gravity or density, comparison of data obtained by different methodologies can be misleading (Williamson and Wiemann 2010). For viscoelastic vibrational properties, many sources (mainly Japanese) have employed non-contact forced vibrations of free-free (i.e., freely supported) beams (e.g. Fukada 1950; Obataya *et al.* 2000). Comparison of results on well-known or "reference" species across several sources supports the reproducibility potential of this method (e.g. analyses of the database described in Brémaud *et al.* 2009; Brémaud 2012).

The general objective of this work is to increase knowledge on the diversity of wood dynamic mechanical / viscoelastic vibrational properties. In a previous article, physico-chemical indicators were proposed for estimating variations in damping coefficient (Brémaud *et al.* 2010b). The present paper aims at producing new and reliable data on lesser-known species and at categorizing sources of variations. An attempt is also made at confronting species diversity and within-species variability. 98 contrasting wood types, of which 65 had never been tested previously, are characterized. Potential sources of experimental errors are briefly reviewed, and a device and protocol are described for conducting systematic and rapid "routine" tests. Results are analysed at the specimen, wood type and species level. Repartition of properties between wood types is discussed in connexion to their origin and to actual or potential acoustical end-uses.

2. Material and methods

2.1 Wood material

Material was chosen in order to cover: (i) a wide range in botanical origins, specific gravity and extractives content; (ii) both "reference" species for which data are available, and species for which vibrational properties had never been studied; (iii) a range of actual or potential acoustical end-uses. 79 species were studied in total. In order to confront species diversity and within-species variability, different wood types (WT) were collected for some species (e.g. heartwood vs. sapwood or reaction vs. normal wood). The sampling covered 98 WT: 19 (from 12 species) for softwoods, 14 (12 spp.) for temperate-zone hardwoods and 65 (55 spp.) for tropical hardwoods. It comprised of 264 stocks of wood, e.g. different trees and/or different "qualities". Part of the wood material was obtained from the well-identified stocks from the CIRAD wood workshop. Another part was provided by several French instrument makers and, when needed, botanical species were subsequently identified.

2.2 Sampling, scaling and preparation of test specimens

Specimens were cut to dimensions of 150×12×2 mm^3 (longitudinal × radial × tangential), using a circular saw with a quality finishing blade and a specific machining guide and fixture. This procedure ensured smooth surfaces that did not require further processing (such as hand sanding which would be detrimental to the parallelism of the specimens). Thickness variations were ≤0.05mm. The total number of specimens was 1792.

The quality of the specimens' machining is of utmost importance. The accuracy of the thickness is the main source of experimental uncertainty on the specific modulus of elasticity (E'/γ). Damage in the surface layers, such as those resulting from machine planing, belt sanding or milling, must be avoided, as they reduce the modulus of elasticity and increase the damping (Sali and Kopac 1998).

The sampling and scaling of specimens was carefully planned regarding local variations in wood. The width of specimens included at least one full growth ring – when these were distinct. Systematic grain angle deviations often cannot be avoided, especially so in tropical hardwoods, but they were carefully recorded, given their important effect on vibrational properties (Brémaud *et al.* 2010a, 2011b).

The slenderness (length/height ratio) of specimens is very important. In bending vibration, the total deflection includes a contribution of shear properties, which increases with reducing slenderness, with increasing anisotropy, and with increasing order of vibration modes and frequency (Ono and Kataoka 1979; Obataya *et al.* 2000). This effect can be calculated (Nakao *et al.* 1985; Brancheriau and

Baillères 2002; Kubojima *et al.* 2004), taking into account the range in axial-to-shear anisotropy of vibrational properties between very different woods (Brémaud *et al.* 2011b). For *E'* not to be under-evaluated by more than 2% (by Euler-Bernouilli eq.1, at the first bending mode), the minimum *l/h* ratio is of order 25 to 40 for woods within the low to high range of anisotropy respectively. For tanδ (at the 1st bending mode), the contribution of shear remains under 2% for *l/h* ratios >20 and can be neglected for *l/h* ratios >35. With the usual geometry (*l/h* = 75) of specimens under study, the contribution of shear should be negligible at the 1st bending mode, whatever the wood type. Slenderness should also be designed so that specimen stiffness is not excessive, to allow precise displacement measurements.

2.3 Physical conditions

Before being tested, all specimens were conditioned for at least 3 weeks in standard "air-dry" regulated conditions (20±1°C and 60-65% relative humidity RH). Equilibrium moisture content (EMC, calculated from measured "air-dry" weight and after oven-drying) ranged between 6% and 12% depending on species. Differences in EMC were primarily related to those in extractives content (Brémaud *et al.* 2010b). According to Obataya *et al.* (1998), a variation in EMC from 6 to 12% in a given wood (spruce) conditioned at different RH would result in a decrease in E'/γ of approximately -6% and an increase in tanδ of approximately 24%. However, woods with various chemical contents can exhibit different moisture content dependence of vibrational properties (Obataya and Norimoto 1995; Obataya *et al.* 2001).

For practical reasons, part of the tests could not be run in the climate chamber but with an uncontrolled RH of 55 to 65%. Variations in MC during the time of the tests were however quite small (≤3% relative variation, corresponding to ≤0.3% absolute change) and we could not detect significant short-term (~30min) variation in E'/γ nor in tanδ. A sub-sample of 55 specimens, covering a wide range of properties, was tested in both conditions (inside and outside a climatic room) and measured values were identical on average. This, however, should not hold true if bigger differences in RH were considered.

2.4 Non-contact forced-released flexural vibrations of free-free beams

2.4.1 Basic principle

Slender wooden beams are hung by thin threads located at the nodes of vibration of the mode under study (here, the 1st mode). The specimen is made to vibrate through an electro-magnet facing a thin steel piece glued to one end of the sample. A frequency sweep detects the resonance frequency, from which the specific dynamic modulus of elasticity is determined according to the Euler-Bernouilli equation:

$$\frac{E'}{\rho} = \frac{48\pi^2 l^4}{m_n^4 h^2} f_{Rn}^2 \qquad (1)$$

Where *l* is the length of the specimen and *h* its thickness, f_{Rn} is the resonance frequency of the mode *n*, and m_n is a constant depending on the mode order (m_1 = 4.730). The specific modulus is expressed as E'/ρ in MPa.m^3.kg^{-1} (or m^2.s^{-2}) when using density (ρ, i.e. specific mass in kg.m^{-3}) or as E'/γ in GPa when using specific gravity (γ, without unit).

The damping coefficient (or loss factor, tanδ) is determined, in the time-domain, through the logarithmic decrement (λ=πtanδ, Fig. 1b) of amplitudes, after stopping the excitation which is fixed at f_R. In the frequency-domain, tanδ is determined by a frequency scan, through the bandwidth (Δf) at half power (or at -3dB) of the resonance curve (Fig. 1a), often called the quality factor ($Q^{-1}=\Delta f/f_R$). Both measurements should be equivalent (tan$\delta \approx Q^{-1} \approx \lambda/\pi$) for values <<0.1 (Jones 2001).

2.4.2 Experimental devices and development of a semi-automated interface

The first used device employed an eddy-current displacement sensor (5µm resolution, distance of detection 2±0.2mm), facing a thin aluminium plate glued on one end of the specimen (Fig. 2). The frequency scan was imposed manually from a function generator. The resonance frequency (f_R) and the decrement of amplitude after stopping the excitation were recorded with a fast Fourier transform (FFT) analyser and the data files were later analysed in MS-Excel. The logarithmic decrement (λ, Fig. 1b) was determined by a regression on the peak amplitudes versus time. One triplicate test required ≥15 minutes.

A more automated device was then designed in order to minimise the time required for a test, and all manual steps (Brémaud 2006). Displacement was measured by a laser-triangulation sensor (Fig. 2), which simplifies positioning of specimens (10µm resolution, distance of detection 40±4mm). Tests were fully computer-driven through a control/acquisition card (National Instruments, Austin, USA, NI PCI 6221, A/D conversion 16bits) and a program that we specifically developed in Labview®, with the following steps (Fig. 3). A wide (150-750Hz by default, adjustable) scan detected the 1st resonance frequency f_R. Then a narrower (0.98×f_R – 1.02×f_R by default, adjustable) frequency sweep was run for measuring precisely (±0.05Hz) f_R and the bandwidth at half-power (Δf). The sampling rate was of 100 kS/s and the acquisition time, by default, 10s. The signal (convoluted by a sine cardinal function as a "natural" window is used in order not to modify the bandwidth) was smoothed by a moving average (on 5 points), on which f_R and Δf were determined. Vibration was then set at f_R until the vibration was stable, and stopped. The logarithmic decrement (λ) after stopping the excitation was calculated by a regression on the peak amplitudes versus time on the steadiest part of the decay. The time required for measuring f_R, tanδ= Q^{-1}, and tanδ=λ/π of a specimen, with 3 repetitions, was ≤5min.

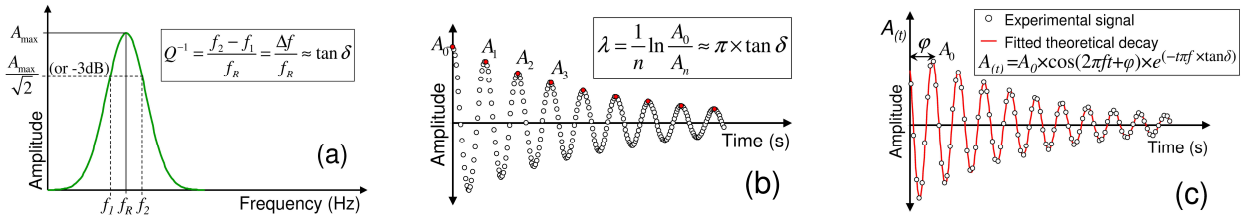

Fig.1 Determination of tanδ in the frequency (a) or temporal (b, c) domains. (a) bandwidth method; (b) logarithmic decrement method; (c) "inverse" method

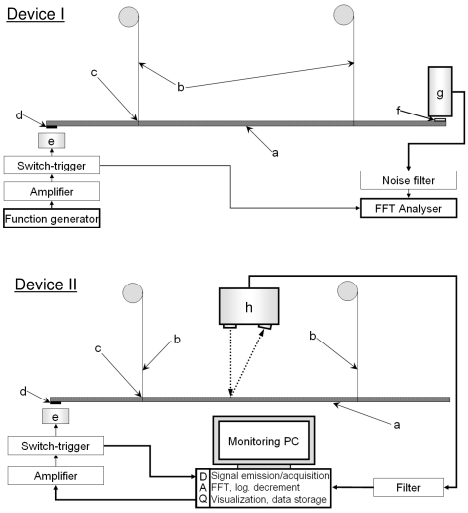

Fig.2 Experimental devices: a = wooden specimen; b = supporting silk threads; c = vibration node location; d = thin steel plate; e = electro-magnet. Device I: g = eddy-current sensor facing a thin aluminium plate = f. Device II: h = laser sensor

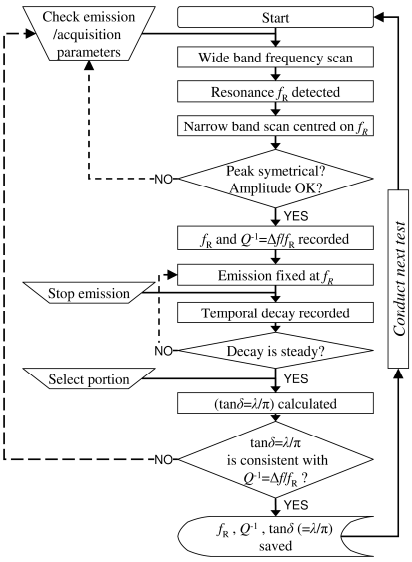

Fig.3 Flow-chart of the computer-driven vibration method developed (device II)

2.5 Validation of the experimental method

2.5.1 Calculated uncertainty and observed repeatability

The theoretical uncertainty on E'/γ is 5.9% (due to machining precision on thickness), and variations between repetitions were <1%.

For the determination of damping by bandwidth (Q^{-1}), the calculated uncertainty is governed by the frequency resolution, that is, by the sampling rate and duration of acquisition. Uncertainty will be between 2.5% and 5% at 100 kS/s over 10s (or twice higher values if using a sampling rate of 50 kS/s), for realistic ranges of Q^{-1} values for wood. For tanδ determined by logarithmic decrement, the theoretical uncertainty depends on the initial amplitude of vibration and on the spatial resolution of the displacement sensor. In our experimental conditions, it ranges from 1% to 15% (resolutions of 5µm and 10µm). Measurements by bandwidth (tan$\delta=Q^{-1}$) have a lower relative uncertainty for woods with higher tanδ, whereas those by logarithmic decrement (tan$\delta=\lambda/\pi$) have a lower relative uncertainty for woods with lower tanδ.

These calculated errors were closely matched by observed variations between repetitions (Fig. 4). Average experimental error was 3% for the bandwidth method and 5% (sensor resolution of 10µm) or 2% (5µm) by the logarithmic decrement method. For the latter, however, out-of-range values were observed for specimens with excessive stiffness and/or irregular surfaces. Nevertheless, the precision of tanδ determination in the temporal domain could be greatly improved by using a simple "inverse" method (Fig. 1c). In this case, tanδ was identified over the whole signal (not only peak amplitudes), by fitting the parameters of the equation of decay (Fig. 1c) to the experimental signal by optimization (using the solver in MS Excel) so as to minimize the difference between the calculation and observations. Error was then normally ≤ 2%, and did not exceed 5% even for "odd" specimens (Fig. 4).

Globally, the experimental error on tanδ ranged from 0 to 15.2% (mean = 3.2%) and was ≤ 5% for 80% of all tested specimens.

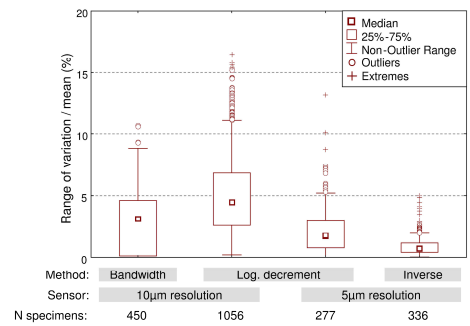

Fig.4 Range of variation ([max-min]/mean values) of tanδ between 3 to 6 repetitions per specimen, with different sensors and methods of determination

2.5.2 Comparison of measurements obtained by different methods

The values of tanδ determined in both the temporal and frequency domains (with the developed semi-automated device) were very consistent (Fig. 5). This is in agreement with the theory of viscoelastic damping (Jones, 2001) and confirms its validity over the expectable range of axial tanδ for "air-dry" wood. Measurements by bandwidth were on average slightly higher (≈ +0.4%), due to the modulation of the resonance peak by the observation window.

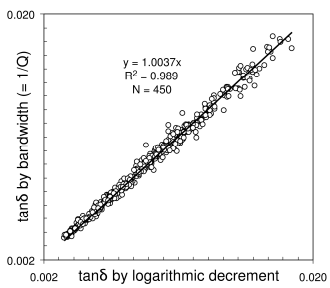

Fig.5 Comparison of tanδ determined in the temporal (logarithmic decrement method) and frequency (bandwidth method) domains. Each point: average of 3 repetitions

In bending vibration tests, the specific dynamic modulus of elasticity can be derived according to either Euler-Bernouilli (in which the influence of shear is neglected) or to the Timoshenko theory (which takes into account the influence of shear) (e.g., Brancheriau and Baillères 2002). In order to compare the respective values obtained for E'/γ,

tests were conducted with a natural vibration method which allows both calculations (without inputting hypothetical values for shear) (Bordonné 1989). A reduced sampling of 130 beams, with dimensions 360×20×20 mm^3 (L×R×T), were put into bending vibrations by percussion and their response (resonance frequencies of the 3 fist bending modes) was recorded with a microphone. Beams were then cut into small specimens (2-6 per bar) which were tested by the forced vibration method.

For the same "bulk" specimens (20×20mm section, *l/h* ratio of 18), E'/γ calculated according to Bernouilli was on average 6% lower than according to Timoshenko (Fig. 6). For specimens tested by forced vibrations, E'/γ was equivalent according to both theories, as was expected given their high slenderness (*l/h*=75) (Nakao *et al.* 1985; Kubojima *et al.* 2004). These, however, displayed more variability (R^2=95% vs. 99%), due to local variations.

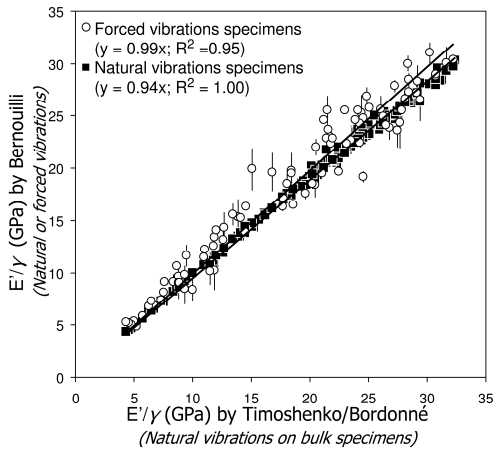

Fig.6 Comparison of E'/γ calculated according to Euler-Bernouilli (for small slender specimens in forced vibrations and bulk specimens in natural vibration) and to Timoshenko (for bulk specimens in natural vibration). Vertical error bars: standard deviation between 2-6 small specimens prepared from a bulk one

2.5.3 Additional parameters to consider

The added mass of the thin steel piece fixed to the wooden test specimen has a negligible effect on tanδ, but decreases the resonance frequency (Kataoka and Ono 1975). Kubojima *et al.* (2005) calculated the change in the constant m_n in the Euler-Bernouilli equation (eq. 1) due to the ratio (μ=*M*/*m*) of the added mass (*M*) to the mass of the wooden beam (*m*). For values of $\mu \leq 5\%$ (approximately 0.7% in our experiments), this can be approached by linear relations. The resulting decrease in apparent E'/γ is of ≈ -3.437×μ and was around -2.4% on average over all tested specimens. This effect could be neglected for dense woods, but it has to be corrected for very light ones, and subsequently must be taken into account when comparing in very different wood materials.

Supporting threads, when they are loose and flexible, have almost no influence on f_R (Brancheriau and Baillères 2002) nor on tanδ measurements, even if they are not strictly located at the position of the 1st mode's node: an inaccuracy of ±5% of the total length should remain acceptable (Kataoka and Ono 1975). Tight or stiff supporting threads, however, may interfere with the specimen vibration and/or result in a coupling with the device's frame (Brancheriau *et al.* 2010). Tanδ and f_R are stable when the distance between the exciting electro-magnet and the steel piece is ≥2mm, but measurements are affected when this distance is <1mm (Kataoka and Ono 1975).

The fluid friction with air does not affect damping under the usual test conditions (Kataoka and Ono 1975; David 1999). In the low-frequency range (<100Hz), however, its contribution would not be negligible for thin wooden beams (Kitahara and Matsumoto 1973).

2.6 Data sorting and statistical analysis

Data were analyzed at the specimen, wood type, and species levels. First, all tested specimens (N=1792) were used for analyzing the relationship between tanδ and E'/γ, by comparing present results with the "standard" trend from Ono and Norimoto (1983, 1984):

$$\tan\delta_S = 10^{-A} \times (E'/\rho)^{-B} \qquad (2)$$

Where tanδ_S is "standard" damping coefficient and coefficients A and B are 1.23 and 0.68 over a wide range of softwoods (further detailed below in the results and discussion).

Then, analyses of this relationship were detailed for 3 broad groups of normal wood: softwoods, and hardwoods with low or high extractives content (*EC*). Classification into low (<5%) or high (>7%) EC was based on available database (e.g. Brémaud *et al.* 2010b) and/or literature values. Sapwood was usually considered as low *EC* unless contradictory data were known. Species with "medium" (5-7% EC) and those for which no information on *EC* could be obtained were excluded from this analysis, as were some samples with atypical heartwood. Specimens with important grain deviations were included in analyses of the tanδ-E'/γ relationship. But these specimens were excluded from basic statistics on the different wood types, for which 1317 specimens were kept as representative (see Tab. I). Data were first averaged between different specimens from a given stock, then between the means of different stocks (when applicable).

The "deviation from standard damping" = DSδ (Brémaud 2006; Brémaud *et al.* 2009; 2010b) was used for expressing the "intrinsic viscosity" (i.e., de-correlated from specific modulus of elasticity) of the different wood types:

$$DS\delta = 100 \times \frac{\tan\delta_i - \tan\delta_S}{\tan\delta_S} \quad (3)$$

Where tanδ_i is the damping coefficient of a given wood, and tanδ_S is the standard damping from equation 2.

In order to compare all wood types according to various properties, Principal Components Analysis (PCA) was performed, using XLstat® (Addinsoft SARL) in MS-Excel. Active variables represented the three main aspects of specific gravity, elasticity and viscosity, and were selected to be as far as possible de-correlated from each other. That is, "elasticity" was represented by E'/γ (instead of Young's modulus E' which is quite strongly correlated to specific gravity) and "viscosity" by DSδ (equation 3 above). The broad categories "softwoods", "temperate hardwoods" and "tropical hardwoods" were added as inactive qualitative variables.

3. Results

3.1 Total diversity at the specimens' level

Over all individual specimens, measured properties covered a continuous and broad range: 0.21 to 1.38 for specific gravity; 4.6 to 34.1 GPa for E'/γ; 3.3×10^{-3} to 20.6×10^{-3} for tanδ (Tab. I). Damping coefficient had the highest coefficient of variation (>40%), but the three properties covered a similar span (ratio between maximum and minimum values of 6-7).

Table I Basic statistics of total diversity in specific gravity (γ), specific modulus of elasticity (E'/γ) and damping coefficient (tanδ), between specimens and between wood types

		γ			E'/γ (GPa)			tanδ (10^{-3})		
	N	range	mean	cv	range	mean	cv	range	mean	cv
Specimen level										
All specimens	1792	0.21-1.38	0.84	26%	4.6-34.1	18.5	33%	3.3-20.6	7.1	41%
Representative of wood types	1317	0.21-1.38	0.86	28%	4.6-34.1	19.7	30%	3.3-20.6	6.9	44%
Wood type level										
All wood types	98	0.22-1.31	0.81	31%	6.3-32.7	20.0	32%	3.9-18.7	7.7	42%
Normal heartwood	78	0.22-1.31	0.83	30%	9.0-32.2	20.0	29%	3.9-18.7	7.4	43%

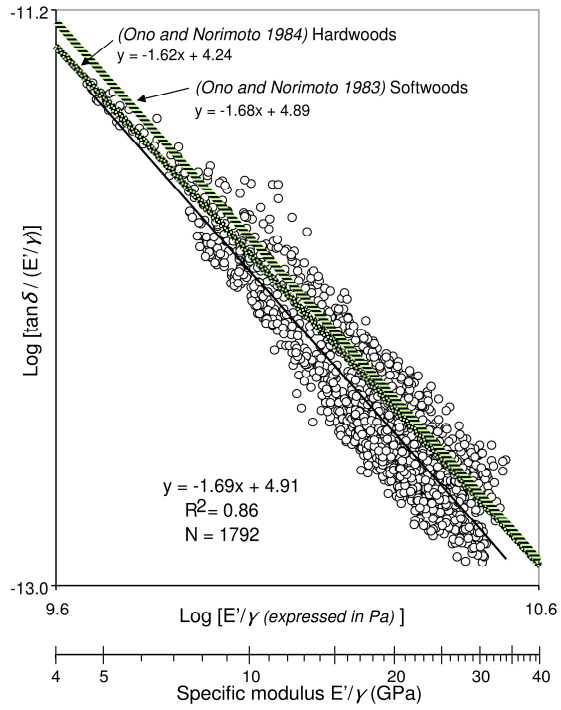

Fig.7 Relationship between damping coefficient and specific dynamic modulus of elasticity: comparison of our global sampling with trends reported by Ono and Norimoto (1983, 1984) by plotting tanδ/(E'/γ) versus E'/γ on double logarithmic scale

Damping coefficient and specific modulus of elasticity followed a relationship very similar to the "standard" one (eq. 2). This "standard" relationship was reported by Ono and Norimoto (1983, 1984) in the logarithmic representation shown in Fig. 7, by plotting tanδ/(E'/γ) (which is supposed to be proportional to the energy dissipated per vibration cycle) versus E'/γ. This representation, however, reduces the apparent dispersion. When plotting directly tanδ versus E'/γ (as in Fig. 8), the relationship has the form of a power law: $\tan\delta=10^{-A}\times(E'/\gamma)^{-B}$ (i.e., linear regressions can be performed in a log-log scale, shown in the inset of Fig. 8) . On all studied specimens of very different wood types, the relationship was highly significant (at a level < 0.1%: Pearson's coefficient of correlation R=0.71, N=1792), but explained only half of the variations in tanδ (R^2=0.5). This strength of association is of the same order as above references, when comparing the coefficients of determination (R^2) obtained in the two different representations (i.e., by plotting tanδ directly, or tanδ/(E'/γ), versus E'/γ) (Tab. II). Distinct categories – softwoods, hardwoods with low or high extractives content – showed lower dispersion (R^2=0.76, 0.73 and 0.57 respectively) and nearly parallel trends, but shifted towards higher or lower tanδ values (Fig. 8).

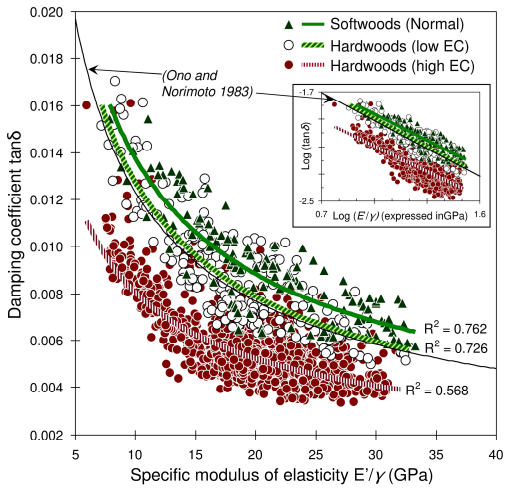

Fig.8 Relationships between tanδ and E'/γ for normal wood of softwoods and of hardwoods with low (<5%) or high (>7%) extractives content. The inset shows the logarithmic representation which allows calculation of linear regressions

Table II Parameters of the relationship $\tan\delta=10^{-A}\times(E'/\gamma)^{-B}$ as obtained by regressions on different samples

	N specimens	A	B	R^2_{direct} tanδ = $f(E'/\gamma)$	$R^2_{combined}$ tanδ/(E'/γ) = $f(E'/\gamma)$
All samples	1792	1.322	0.692	0.50	0.86
Softwoods (normal wood = NW)	140	1.222	0.639	0.76	0.95
Hardwoods (NW) with high extractives content	1153	1.474	0.620	0.57	0.90
Hardwoods (NW) with low extractives content	221	1.231	0.677	0.73	0.94
25 softwood species (a)	1227	1.23	0.68		0.91
30 hardwood species (b)	118	1.34	0.62		0.83

Constants are derived from regressions based on E'/γ expressed in GPa. R^2_{direct} and $R^2_{combined}$ = coefficient of determination obtained from plotting tanδ directly versus E'/γ, or tanδ/(E'/γ) versus E'/γ, respectively.
(a) Ono and Norimoto (1983) (b) Ono and Norimoto (1984)

3.2. Species diversity in vibrational properties

Considering the mean properties of normal heartwood from the different species (Tab. III), the specific gravity (γ) ranged from 0.22 (*Ceiba pentandra*) to 1.31 (snakewood = *Brosimum guianense*); the specific storage modulus (E'/γ) from 9.0 GPa (*Pinus caribeae*) to 32.2 GPa (*Picea sitchensis*); and the damping coefficient (tanδ) from 3.9×10^{-3} (*Aniba canellila*) to 18.7×10^{-3} (*Arbutus unedo*). However, the widest range in E'/γ was observed when including reaction woods: from 6.3 GPa (compression wood of *Pinus pinaster*) to 32.7 GPa (tension wood from *Populus sp.*). The span in properties (ratio of maximum to minimum values) was 6.0 for γ, 4.8 for tanδ and 3.6 for E'/γ (5.2 when including reaction wood). As previously observed at the specimen level, tanδ had the highest coefficient of variation between species (normal heartwood) and between all wood types (Fig. 9; Tab. I). On the contrary, within a given wood type, tanδ was a little less variable than E'/γ (mean coefficient of variation of 9% and 11% respectively).

Table III Mean (m) values and coefficient of variation (cv = standard deviation/mean) of specific gravity (γ), specific storage modulus (E'/γ) and damping coefficient (tanδ) for normal heartwood of all studied species. Botanical families are abbreviated by their 4 first letters. Category: S = Softwoods; Te.H = Temperate hardwoods; Tr.H = Tropical hardwoods

Family	Category	Species	Code	N specimens	N stocks	γ m	γ cv (%)	E'/γ (GPa) m	E'/γ (GPa) cv (%)	tanδ (10^{-3}) m	tanδ (10^{-3}) cv (%)
PINA	S	*Abies alba* Mill.	Abi.al	4	1	0.54	4	30.0	5	6.7	4
ACER	Te.H	*Acer pseudoplatanus* L.	Ace.ps	1	1	0.64		10.6		16.1	
ACER	Te.H	*Acer sp.* (American)	Ace.sp	1	1	0.72		10.5		11.5	
CAES	Tr.H	*Afzelia bipindensis* Harms.	Afz.bi	13	5	0.82	5	23.5	10	4.2	7
CAES	Tr.H	*Afzelia quanzensis* Welw.	Afz.qu	5	1	0.85	7	12.7	5	11.1	16
LAUR	Tr.H	*Aniba canelilla* (Kunth) Mez	Ani.ca	9	1	1.20	2	29.1	4	3.9	5
ERIC	Te.H	*Arbutus unedo* L.	Arb.un	5	1	0.94	2	12.0	7	18.7	9
SAPO	Tr.H	*Baillonella toxisperma* Pierre	Bai.to	6	1	0.83	1	21.2	3	7.2	4
PAPI	Tr.H	*Bobgunnia fistuloides* (Harms) Kirkbr. & Wiersema	Bob.fi	19	2	0.96	5	17.3	10	4.8	8
PAPI	Tr.H	*Bocoa prouacensis* Aubl.	Boc.pr	35	5	1.26	2	26.0	10	4.2	12
MORA	Tr.H	*Brosimum guianense* (Aubl.) Huber	Bro.gu	41	11	1.31	2	22.5	7	5.4	10
MORA	Tr.H	*Brosimum rubescens* Taub.	Bro.ru	39	7	0.99	6	23.3	11	4.5	8
MORA	Tr.H	*Brosimum utile* Pitt.	Bro.ut	5	1	0.47	3	21.7	8	8.6	15
BUXA	Te.H	*Buxus sempervirens* L.	Bux.se	6	2	0.93	0	9.6	12	15.3	9
CAES	Tr.H	*Caesalpinia echinata* Lam.	Cae.ec	55	15	1.01	9	21.5	11	4.4	14
BETU	Te.H	*Carpinus betulus* L.	Car.be	9	2	0.74	0	20.8	2	9.5	1
MELI	Tr.H	*Cedrela odorata* L.	Ced.od	1	1	0.48		21.8		7.8	
BOMB	Tr.H	*Ceiba pentandra* Gaertn.	Cei.pe	5	1	0.22	10	10.1	13	14.0	12
CUPR	S	*Chamaecyparis sp.* (Hinoki)	Cha.sp	14	1	0.39	3	27.0	7	6.3	6
LAUR	Tr.H	*Chlorocardium rodiei* (Schomb.) Rohwer	Chl.ro	4	1	1.05	1	27.8	2	4.3	4
CORN	Te.H	*Cornus mas* L.	Cor.ma	4	1	1.11	0	15.6	2	8.3	7
CUPR	S	*Cupressus sempervirens* L.	Cup.se	11	3	0.49	13	17.1	17	8.9	19
PAPI	Tr.H	*Dalbergia baronii* Baker	Dal.ba	14	1	0.75	3	19.4	8	5.2	7
PAPI	Tr.H	*Dalbergia latifolia* Roxb.	Dal.la	1	1	0.75		18.5		7.3	
PAPI	Tr.H	*Dalbergia maritimensis* or *D. louvelli*	Dal.ma	5	2	1.07	10	21.0	2	4.0	17
PAPI	Tr.H	*Dalbergia melanoxylon* Guill. et Perr.	Dal.me	10	2	1.31	1	15.7	12	5.8	14
PAPI	Tr.H	*Dalbergia nigra* (Vell.) Allemão ex Benth.	Dal.ni	1	1	0.81		20.5		7.0	
PAPI	Tr.H	*Dalbergia retusa* Hemsley	Dal.re	1	1	0.95		11.8		8.6	
PAPI	Tr.H	*Dalbergia sp.* (Bahia)	Dal.sB	3	1	1.15	2	13.0	4	4.7	7
PAPI	Tr.H	*Dalbergia sp.* (Madagascar)	Dal.sM	53	9	0.96	11	20.1	10	4.6	8
PAPI	Tr.H	*Dalbergia sp.* (Jacaranda do Para)	Dal.sP	1	1	0.88		18.4		5.6	
CAES	Tr.H	*Dialium cochinchinense* Pierre	Dia.co	4	1	1.10	2	24.0	5	6.4	13
CAES	Tr.H	*Dialium pachyphyllum* Harms	Dia.pa	12	2	1.01	13	26.3	6	6.2	8
EBEN	Tr.H	*Diospyros sp.* (Madagascar)	Dio.sp	3	1	1.18	0	16.8	1	9.1	5
PAPI	Tr.H	*Dipteryx odorata* (Aubl.) Willd.	Dip.od	9	1	0.99	3	16.4	2	5.9	3
CAES	Tr.H	*Guibourtia arnoldiana* J.Leon.	Gui.ar	4	1	0.84	1	25.8	1	5.6	4
CAES	Tr.H	*Guibourtia conjugata* (Bolle) J. Léonard	Gui.co	2	1	1.02	1	17.0	1	7.5	5

Family	Category	Species	Code	N specimens	*N stocks*	γ m	γ *cv (%)*	E'/γ (GPa) m	E'/γ *cv (%)*	tanδ (10^{-3}) m	tanδ *cv (%)*
CAES	Tr.H	*Guibourtia sp.*	Gui.sp	7	*2*	0.89	*8*	16.6	*29*	10.7	*8*
CAES	Tr.H	*Hymenaea courbaril* L.	Hym.co	8	*1*	0.77	*4*	28.4	*5*	5.3	*2*
CAES	Tr.H	*Hymenaea parvifolia* Huber	Hym.pa	9	*1*	1.11	*2*	23.4	*5*	5.0	*1*
JUGL	Te.H	*Juglans nigra* L.	Jug.ni	1	*1*	0.58		12.7		8.0	
MELI	Tr.H	*Khaya senegalensis* (Desr.) A. Juss.	Kha.se	4	*1*	0.85	*0*	9.2	*4*	12.0	*6*
PAPI	Te.H	*Laburnum anagyroides* Medik.	Lab.al	12	*3*	0.90	*6*	13.4	*8*	9.2	*6*
LAUR	Tr.H	*Licaria cannella* (Meisn.) Kosterm.	Lic.ca	16	*7*	1.01	*5*	26.1	*9*	5.6	*8*
STER	Tr.H	*Mansonia altissima* (A. Chev.) A. Chev	Man.al	4	*1*	0.62	*4*	21.4	*9*	5.7	*5*
MYRI	Tr.H	*Mauloutchia sp.*	Mau.sp	5	*1*	0.71	*1*	26.6	*8*	7.7	*7*
PAPI	Tr.H	*Millettia laurentii* De Wild.	Mil.la	9	*1*	0.93	*2*	23.3	*3*	4.8	*6*
CLUS	Tr.H	*Moronobea coccinea* Aubl.	Mor.co	8	*1*	0.92	*1*	25.1	*2*	4.7	*3*
MORA	Tr.H	*Morus mesozygia* Stapf.	Mor.me	3	*1*	0.87	*2*	19.3	*7*	5.1	*1*
PAPI	Tr.H	*Ormosia flava* (Ducke) Rudd	Orm.fl	9	*1*	0.84	*1*	29.9	*4*	4.5	*9*
CAES	Tr.H	*Peltogyne venosa* (Vahl) Benth.	Pel.ve	8	*2*	0.80	*0*	26.8	*7*	5.6	*7*
PINA	S	*Picea abies* Karst.	Pic.ab	40	*14*	0.50	*10*	24.4	*18*	8.4	*8*
PINA	S	*Picea sitchensis* (Bong.) Carr.	Pic.si	5	*1*	0.47	*1*	32.2	*2*	5.9	*2*
PINA	S	*Pinus caribaea* Morelet	Pin.ca	3	*1*	0.36	*4*	9.0	*2*	13.2	*3*
PINA	S	*Pinus nigra* subsp. *laricio* Maire	Pin.ni	5	*1*	0.51	*4*	19.2	*6*	8.8	*6*
PINA	S	*Pinus patula* Schiede ex. Schlecht. et Cham.	Pin.pa	4	*1*	0.54	*9*	31.1	*3*	6.6	*5*
PINA	S	*Pinus pinaster* Aiton	Pin.pi	18	*7*	0.42	*6*	14.2	*12*	12.0	*10*
PINA	S	*Pinus sylvestris* L.	Pin.sy	14	*5*	0.48	*12*	17.9	*14*	10.6	*13*
PAPI	Tr.H	*Platymiscium sp.*	Pla.sp	4	*1*	1.02	*1*	25.5	*5*	4.8	*2*
PAPI	Tr.H	*Platymiscium ulei* Harms	Pla.ul	19	*3*	0.73	*9*	20.4	*7*	4.8	*11*
ROSA	Te.H	*Prunus avium* L.	Pru.av	1	*1*	0.62		17.4		10.0	
PAPI	Tr.H	*Pterocarpus erinaceus* Poir.	Pte.er	86	*4*	0.83	*3*	19.3	*4*	5.6	*6*
PAPI	Tr.H	*Pterocarpus macrocarpus* Kurz	Pte.ma	22	*1*	0.75	*1*	12.9	*4*	6.8	*4*
PAPI	Tr.H	*Pterocarpus soyauxii* Taub.	Pte.so	170	*16*	0.77	*9*	18.3	*15*	5.2	*14*
PAPI	Tr.H	*Pterocarpus tinctorius* Welw.	Pte.ti	6	*1*	0.93	*2*	14.0	*7*	6.8	*9*
ROSA	Te.H	*Pyrus communis* L.	Pyr.co	4	*1*	0.69	*3*	9.9	*9*	16.7	*11*
RHIZ	Tr.H	*Rhizophora mangle* L.	Rhi.ma	5	*1*	1.13	*1*	28.8	*4*	7.3	*4*
CAES	Tr.H	*Scorodophloeus zenkeri* Harms.	Sco.ze	14	*2*	0.88	*8*	23.0	*15*	6.8	*1*
ROSA	Te.H	*Sorbus domestica* L.	Sor.do	24	*5*	0.81	*7*	19.3	*17*	9.9	*16*
PAPI	Tr.H	*Swartzia panacoco* (Aubl.) Cowan	Swa.pa	8	*2*	1.16	*8*	26.0	*8*	4.4	*16*
PAPI	Tr.H	*Swartzia sp.*	Swa.sp	46	*9*	1.21	*6*	26.3	*10*	4.3	*7*
MELI	Tr.H	*Swietenia macrophylla* King	Swi.ma	1	*1*	0.48		20.7		6.4	
BIGN	Tr.H	*Tabebuia sp.*	Tab.sp	4	*1*	0.85	*1*	23.2	*4*	5.0	*2*
TAXA	S	*Taxus baccata* L.	Tax.ba	25	*5*	0.64	*6*	11.1	*17*	10.0	*8*
CUPR	S	*Thuja plicata* D.Don	Thu.pl	1	*1*	0.39		19.5		7.2	
RUTA	Tr.H	*Zanthoxylum tsihanimposa* H.Perr.	Zan.ts	5	*1*	0.57	*9*	18.4	*6*	6.2	*6*
PAPI	Tr.H	*Zollernia ilicifolia* (Brongn.) Vogel (or *Swartzia sp*)	Zol.il	6	*1*	1.06	*4*	21.4	*6*	5.1	*10*
PAPI	Tr.H	*Zollernia paraensis* Huber	Zol.pa	14	*1*	1.16	*4*	21.1	*7*	5.8	*7*

3.3. Principal components analysis (PCA) on wood types

Principal components analysis allows representation of the diversity of wood types according to several properties. As active variables should be as independent as possible, the analysis was conducted on γ, E'/γ, and the deviation of damping from the standard $\tan\delta - E'/\gamma$ trend (DSδ, eq.3). The Young's modulus (E'), specific loss modulus ($E''/\gamma = \tan\delta \times E'/\gamma$) and damping coefficient ($\tan\delta$) were projected as inactive variables (Fig. 10a) in order to better understand the repartition of the individuals. Schematically, axis 1 mainly denotes "solidity" (high γ and E', reflecting porosity of the cellular material), vertical axis 2 is principally governed by E'/γ (related to microfibril and/or grain angle), and the upper-left to lower-right diagonal expresses a decreasing viscous behaviour (DSδ and E''/γ), which is mostly related to chemical composition (Brémaud *et al.* 2010b, 2013).

4. Discussion

4.1. Interpretation of the tan*δ* – *E'/γ* relationship in terms of sources of variability between wood types

For hardwood specimens with low extractives content (*EC*), the relationship between tan*δ* and *E'/γ* had a R^2 of 73% and constants *A* and *B* (Tab. II) nearly equal to the values of the "standard" relationship on softwoods (Ono and Norimoto 1983). The results in Ono and Norimoto (1983) are based on 25 species, which represent quite well different gymnosperm families, whereas the present study had only 12 softwood species, which were mostly Pinaceae for which damping is usually higher than average (Brémaud *et al.* 2009). Accordingly, the "softwood" trend here had slightly higher tan*δ* values than the "standard", but was also slightly less dispersed (Tab. II). Conversely, the hardwood relationship from Ono and Norimoto (1984) is much more dispersed (Tab. II) and has slightly lower (≈ -6%) tan*δ* than the "softwood standard", probably because it includes several tropical species with high extractives content. The trend observed here on hardwood specimens with high *EC* (>7%) shows they clearly had a lower tan*δ* (-33% in average) at a given *E'/γ*, and a higher dispersion (R^2=57%), than both "standard softwoods" and hardwoods with low *EC*.

The relationship between tan*δ* and *E'/γ* is governed by the orientation of wood elements and can be reconstructed by models taking into account either the microfibril angle (Obataya *et al.* 2000) or the grain angle (Brémaud *et al.* 2011b). Vertical shifts of curves can reflect differences in chemical composition (Obataya *et al.* 2000, Brémaud *et al.* 2010a, 2011a, c) and/or in wood moisture content (Obataya *et al.* 1998, Sasaki *et al.* 1988), both of which affect tan*δ* more than *E'/γ*. A shift in tan*δ* of approximately 30% was observed between the trend for normal wood and that for compression wood (species: spruce and pines), due to variations in lignin composition and structure (Brémaud *et al.* 2013). Extractives, on the other hand, can either be neutral, or decrease (or sometimes increase) tan*δ* by as much as a factor 2, while affecting only marginally the axial *E'/γ* (Brémaud *et al.* 2010ab, 2011a; Matsunaga et al. 1996; Minato et al. 1997, 2010; Obataya et al. 1999; Sakai et al. 1999; Yano 1994; Yano et al. 1995). This appears consistent with the important shift between the trends for hardwoods with low and high EC, and with the high dispersion for the later. Extractives can also modify wood equilibrium moisture content (e.g. Hernandez 2007) in a range of circa 6 to 12% EMC at 20°C and 65%RH (Brémaud *et al.* 2010b), but moisture-related shifts in the tan*δ*-*E'/γ* trends mostly take place at higher wood MC (Sasaki *et al.* 1988).

Thus, the "standard" relationship from Ono and Norimoto (1983) was confirmed by present results, both qualitatively (general form) and quantitatively (values of the constants *A* and *B* in eq. 2, Table II), and concerns, statistically, both representative softwoods and hardwoods with low extractive content. Deviations of damping coefficient of a given wood from this standard trend can be considered as a "normalized damping" (*DSδ*, eq. 3), relatively de-correlated from the effect of orientation, and mostly related to chemical variations.

4.2. Distribution of vibrational properties between broad categories

Globally, wood types were rather broadly distributed along the range of *γ* and *E'/γ* (Fig. 9a,d). Tropical hardwoods covered the whole range of specific gravity but with a predominance of high values. Some of the studied softwoods and temperate hardwoods, however, were also denser than usual (normal wood of yew and compression woods of spruce and pines, secondary species of hardwoods with *γ*≥0.9). Softwoods (which included both compression wood, and the so-called "resonance wood" selected for string instruments soundboards) had the most scattered values of *E'/γ*. Tempered and tropical hardwoods were more distributed towards, respectively, lower and higher ranges of *E'/γ*. Consequently, together with their often high *γ*, Young's modulus (*E'*, Fig. 9b) higher than 20GPa could only be found for tropical hardwoods. These were also the only category with very low ($<6\times10^{-3}$) tan*δ* (Fig. 9e). This confirms that tropical hardwoods could not be replaced by temperate-zone species for applications requiring very low damping (e.g. xylophones) and/or high Young's modulus (e.g. violin bows) (Holz 1996; Brémaud and Poidevin 2009; Brémaud 2012; Bucur 2006; Wegst 2006). The predominance of low tan*δ* for tropical hardwoods partly results from their often high values of *E'/γ* (as both properties are still correlated at the wood type level), and also from a lower intrinsic damping (DS*δ*, Fig. 9f), which is mostly due to their often higher content of "mechanically active" extractive components (Brémaud *et al.* 2010b).

4.3. Classification of wood types in relation to their origins and potential uses

In the PCA on all wood types, globally, a "continuum" of behaviour was observed, although the different wood categories cover preferential areas (Fig. 10b). The right-hand part of the "individuals" graph was characteristic of tropical hardwoods, in which some sub-groups may be defined. From a botanical point of view, the lower-right corner (i.e. exceptionally low loss parameters and moderate *E'/γ*) was dominated by heartwood of species from certain genera (*Dalbergia*, *Pterocarpus*, *Platymiscium*) belonging to the Dalbergieae tribe (= dalbergioid clade, Leguminosae-Papilionoideae). This is probably due to the characteristic nature of their extractives,

which strongly decrease tanδ in several genera of this tribe (Yano *et al.* 1995; Brémaud *et al.* 2009, 2010b, 2011a; Traoré *et al.* 2010). It also probably explains the predominance of Dalbergieae in the xylophone-making traditions of several continents (Brémaud 2012; Holz 1996; Traoré *et al.* 2010; Wegst 2006). Still from the point of view of utilisations, woods currently used for making Baroque to Modern violin bows are grouped at the far end of axis 1, i.e. they are mainly described by their high specific gravity and Young's modulus, along with a low tanδ (Brémaud and Poidevin 2009; Wegst 2006). Other wood types in their vicinity could consequently be considered for this application: we have proposed several promising alternative species to bow makers for conducting practical trials (to be published).

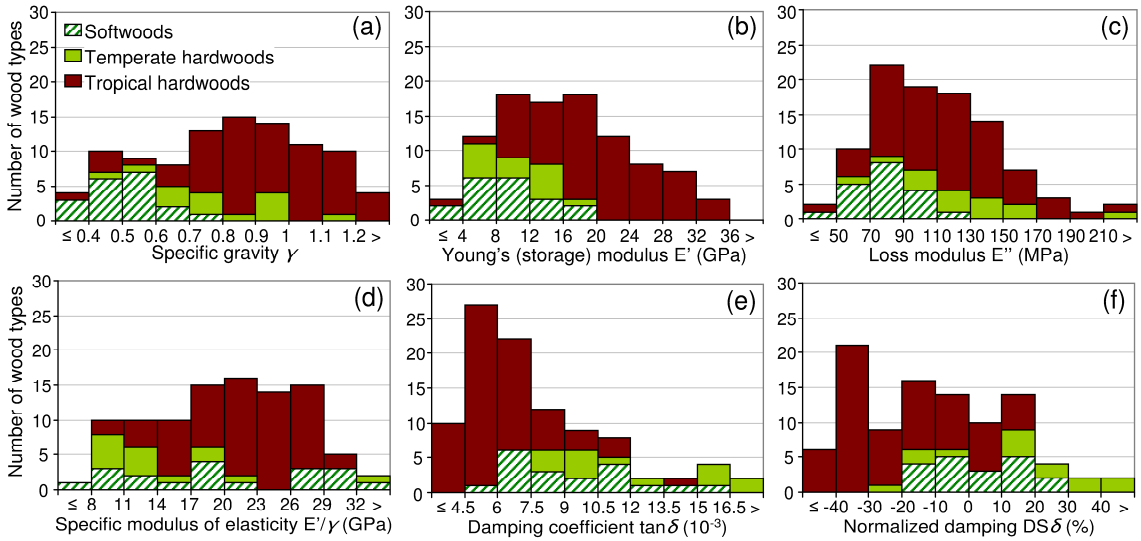

Fig.9 Distributions of specific gravity (a), dynamic mechanical properties (b, c, d, e) and "normalized damping" (f) for the 98 wood types

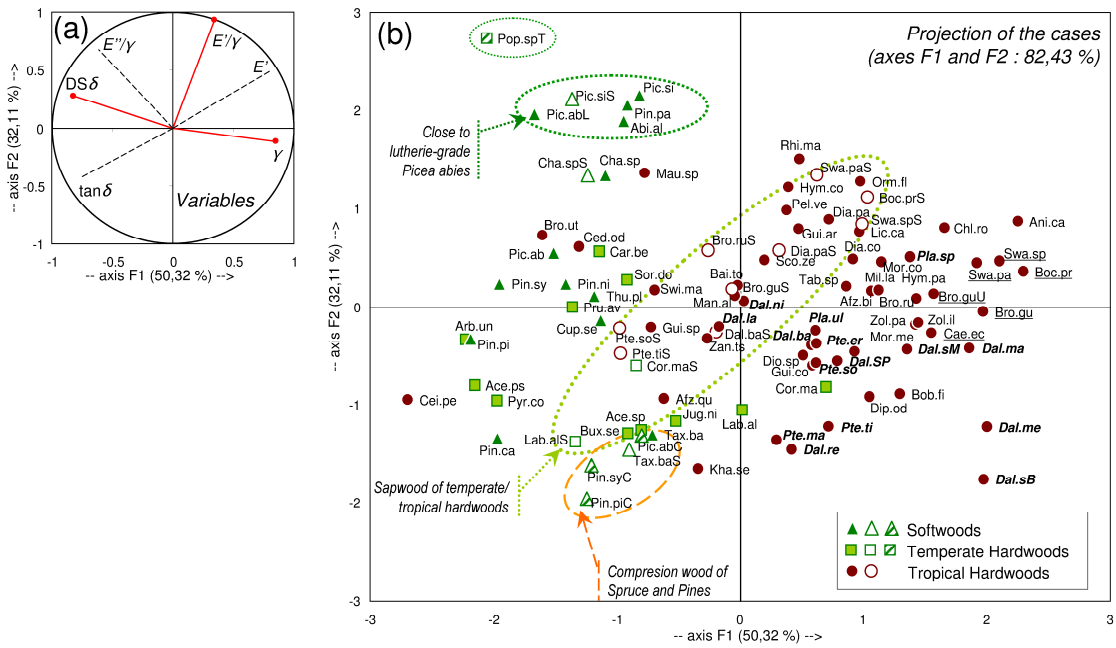

Fig.10 Principal components analysis. (a) Projection of variables / correlation circle. Solid lines: active variables (γ, E'/γ and DSδ); dashed lines: inactive additional variables. (b) Projection of individuals. Filled symbols = normal heartwood; open symbols = normal sapwood; hatched symbols = reaction wood. Labels: see Tab. III; italics = Dalbergieae; underscored = woods used for violin bows

Temperate hardwoods were generally rather distinct from tropical ones, and dominated the lower-left portion of the plane, i.e. woods characterized by their low modulus and high tanδ. Despite quite a wide range in specific gravity, no clear multi-variable distinction appeared within this category, which might however simply reflect the moderate number (12) of species under study.

The only characteristic shared by all softwoods was their lower than average specific gravity. Their ordinary wood types were poorly differentiated according to vibrational properties. Nevertheless, a distinct sub-group including "lutherie-grade" *Picea abies* was primarily governed by high specific

modulus of elasticity combined to proportionally high loss properties (DSδ and E''/γ). This group also comprised other species of Pinaceae, suggesting that "resonance" Norway spruce may not be unique in its vibrational properties. Old growth Sitka spruce is often used as "alternative resonance wood" (e.g. Ono and Norimoto 1983; Bucur 2006), but the anatomical and chemical features of other woods of the same genus or even family could also lead to comparable properties (e.g. Brémaud 2012).

When confronting species diversity with intra-specific variability, the sapwoods of hardwood species (both temperate and tropical) covered a wide range of porosity and of E'/γ. But they were distributed orthogonally to the "viscosity" direction, which meant they were "neutral" regarding DSδ and E''/γ. Regarding reaction wood, compression woods formed a small group with very low E'/γ (as expected), but also slightly negative DSδ (Brémaud *et al.* 2013). This group was not exceptional however: it was close to normal wood of yew but also to some temperate hardwoods. The only tension wood under study (poplar) was completely the reverse, with a very high E'/γ and also exceptionally high normalized damping.

The multi-variate confrontation of all wood types suggests that: (i) species diversity is the biggest source of variation in specific gravity and Young's modulus (with reaction wood and heartwood formation as secondary effects); (ii) reaction (compression or tension) wood formation is responsible for the most extreme differences in air-dry specific modulus of elasticity, ahead of the (nevertheless very large) inter-specific diversity; (iii) taxonomy-related content in heartwood secondary metabolites appears to be the prominent source of diversity in normalized damping, although extreme variations in constitutive polymers (such as between normal and reaction woods) also play a significant role. These property-dependent responses to different sources of variability might have implications from a biomechanical point of view. Although present results concern air-dry wood properties, some tests on 6 tropical species suggest that little dispersed (but non-linear for damping) relationships can relate air-dry and green wood vibrational properties (Dlouhá 2009, Dlouhá *et al.* 2011).

From the viewpoint of acoustical end-uses, the present results allow better definition of the group characteristics of several preferred species for a given use in musical instruments making, and to propose mechanically realistic alternative species. They also confirm that the traditional avoidance of sapwood in hardwoods and of compression wood in softwoods is justified, not only because of dimensional stability, aesthetical aspect or biological durability, but mostly so because of vibrational characteristics. The very wide range of wood material studied also allowed identification of secondary, little-known species with high potential interest in selected acoustical end-uses. However, it should be kept in mind that, in order to compare very different wood types in a rigorous way, a well-defined and generalized methodology is required, as demonstrated in this paper.

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