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ACOUSTICS OF WOOD

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Abstract

This article presents several acoustic methods effective for examining physical properties of wood , as a living material . Three main aspects are commented :

- "Environmental acoustics " associated with the propagation of acoustic waves in urban forest
- "Material characterization " related to anisotropy, global and local mechanical properties of solid wood and wood based composites
- "Wood quality" related to the development of nondestructive methods for the characterization of wood products and defect detection.

For efficient use of wood in the future three major areas need to be addressed : the development of efficient nondestructive techniques, the improvement of natural qualities of wood through the modification of its properties with different treatments, and the development of new products corresponding to the requirements of modern society.

INTRODUCTION

Wood is a biological renewable substance and one of the most fascinating material by its very complex structure and by its wide and intensive uses. In the "Concise encyclopedia of wood and wood-based materials" wood is defined as " the hard, fibrous tissue that comprises the major part of stems, branches and roots of trees, belonging to the plant groups known as the gymnosperms and the dicotyledonous angiosperms". Wood can be considered as a biological composite that is produced by the living organisms of trees. Its organization can be observed on discrete scale levels. A comprehensive understanding of wood behavior necessitates an interdisciplinary approach.

The present article is devoted to those aspects related to the development of acoustic methods as an effective means for examining physical properties of wood, as a living material. In the first part "Environmental acoustics" a discussion of the physical phenomena associated with the propagation of acoustic waves in urban forests is presented. The second part "Material characterization" responds to practical considerations about wood uses. The third part "Wood quality" is related to wood quality assessment.

ENVIRONMENTAL ACOUSTICS

Trees are accepted presence in the urban landscape as individuals in streets, parks and gardens or as components of woodlands as “relic” surviving from forest before urbanization, or as planted and spontaneous regenerated blocks on derelict sites. These trees are labeled *urban trees* in contrast with *forest trees*. The concept of urban forestry has been developed firstly in Canada, during the years 1960, and was defined as a practice proposing a global approach of tree management in view of integration of urban activity and population. (Bucur 2006)

In planning housing development in urban and suburban areas, a major challenge is to manage the native forest trees as well as exotic trees. Because of urban environment, trees could decline, changing their size and silhouette and in the same time, being from the pathological point of view, sound trees. Good selection criteria should be used when retaining trees on a specific site, determined by urban morphology (Muir 1984). Having in mind that trees are very long lived individuals (300, 900 or 2000 years) if air, water, minerals from the soil and sunlight are supplied, criteria used for urban trees selection and plantation are growth requirements of each species as described by the sylvicultural practice and specific features evaluated for individual trees and stands.

The politics of the Green Areas and Environment Departments in many cities in the world is to preserve and develop the green heritages which have an important social, aesthetic, cultural, educational or climatic role. The need to inform and instruct people about various aspects of environmental protection is generally accepted today. The management of green urban areas requires a wider political, administrative and technical approach (European Commission 1996).

The rapid urbanization after the First World War and after the Second World War alliterated the micro-climate in urban areas, by gradual replacement of original forest by man-made buildings and structures which increased the heat storage capacity of cities. The interest of acousticians for noise abatement in urban areas with vegetation, shrubs or belt of trees is quite old (Aylor 1972a,b, Herrington 1974, Herrington and Brock 1977, Aylor 1977, Carlson et al. 1977, Bullen and Fricke 1982, Schaudinischky et al. 1982, Price et al 1988, Rogers and Lee 1989,). Street trees as well as parks, gardens and green spaces are natural air conditioners and in limited range noise attenuators. Mecklenberk et al.(1972) noted that noise attenuation capacity of trees is directly related to the dense and wide planting zones. The efficiency of noise attenuation is 0.36 dB/m for mixed species zones and only 0.17 dB/m for zones planted with only one type of species.

The existing information in the literature on noise reduction in urban environment is disseminated in publications related to forest and agricultural studies quite abundant during the period 1970-1990 and very scarce later. On the other hand we note publications related to the development of modeling techniques for noise reduction in urban areas (Embelton 1996, Barrière and Gabillet (1998), Marquis-Favre et al. 2005)

The design of comfortable environment must pay attention to the "*soundscape*" as defined by the Canadian musician Murray Schafre, at the end of 1960's, which should complete the "*landscape*" design, and which refers to visual scenario of the environment. The meanings of soundscape are social, historical, cultural and environmental and were promoted by international organizations and congresses (Inter-Noise) and has been applied to practice (sound maps) for urban planning, environmental, architectural and equipment design. A positive impression on urban soundscape is produced by large vegetation areas, belt of trees, public gardens and parks.

In urban residential areas, the disposition of trees around the houses should be made for the maximum noise reduction, tied together with aesthetics and air-quality improvement. In residential suburban areas, the discomfort is produced by highway systems. In this case, the noise reduction can be achieved by creating trees belts and noise barriers. Outdoors, the description of the noise environment in audible range, is provided by the A-frequency weighted day and night average sound level. The environmental noise impact depends on the total energy received at the observation point, the rate of occurrence of noise events and the magnitude of noisier single event. The reduction of noise level requires the following three main steps:

- the evaluation of noise environment under existing conditions,
- the determination of the acceptable noise level,
- the determination of the difference between the two previous steps.

In urban communities the sources of noise are numerous and may include noise produced by highways, rail and aircraft transportation (Attenborough 1982, Andersonn and Kruze 1992, Attenborough et al. 1992, Tanaka et al. 1979, Watts et al. 1999,). The techniques for noise control are related to the control at the source, at the receiver and at the transmission path. (Beranek and Vèr 1992)

Models of different complexity were used for traffic noise prediction since 1950. Tendency to unify noise calculation algorithms in Europe was realised with the standard ISO 9613-2. The propagation of highway noise over a forest stand expressed by the variation of the sound pressure level versus the distance has clearly shown the important attenuation produced by the forest stand. In urban areas, trees can be used as noise buffers, able to reduce noise with 5 to 10 dB, if some general recommendations are respected (plant trees near the noise source, plant trees/shrubs with dense foliage as close as possible, plant belt trees of 7 to 17 m wide, etc…).

Rail transportation is one of the most used systems through the world for passengers and freight within urban and suburban areas. The noise is produced by the propulsion system of the railcars and locomotives, by the interaction between the wheels and rail, and by the aerodynamic connected phenomena. Rail systems generate ground borne vibrations which are important and depend on the resonance frequencies of the train suspension systems and of the smoothness of the wheels and rails (Gautier et al. 2004). The attenuation effect of belt vegetation is combined with the terrain configuration.

The aircrafts and helicopters generate annoying noise in urban, suburban and natural recreational environment which interferes with the aesthetic quality of the landscape (Gierke et al 1998). The noise radiated from the aircraft propagates through the atmosphere and interacts with the forest stand and the ground. Forest stands planted near the airports can be a good solution for the reduction of noise annoyance produced by the continuously growth of aviation traffic.

WOOD MECHANICAL CHARACTERIZATION

Global and local characterization

Global mechanical characterization of wood as an elastic anisotropic (orthotropic) material is based on the assumption that its properties can be represented by an equivalent homogeneous anisotropic continuum. The anisotropic elastic behavior of a medium must be associated to a scale of observation. The anisotropy and heterogeneity are not absolute characteristics of a material, but are relative to a given physical property and to the scale length of the corresponding physical phenomenon , for instance the wavelength for propagation phenomena. Most commonly wood symmetry is orthotropic, corresponding to three main axes noted L (longitudinal), R (radial) and T tangential) and are related to the tree growth direction and to the annual rings.

For the determination of wood elastic constants with ultrasonic techniques, two typical situations can be observed (Bucur 2005). Firstly, when the symmetry axes are well defined and easy to recognize on the specimens. This situation is the most common one, and, the determination of the terms of the stiffness tensor is straightforward. Secondly, when the anisotropic directions are unknown. This situation is typical when the specimens are sphere type or polyhedral type. In this case the determination of the terms of the stiffness tensor is much more complicated. It is perhaps useful to mention here that as for wood, for artificial composite materials of orthotropic or transverse isotropic symmetry, the properties are strongly dependent on the orientation of reference coordinates. Optimization procedures were developed for the determination of off-diagonal terms of stiffness matrix and for the calculation of technical constants of wood, using bulk waves and surface waves.

The evaluation of the viscoelastic behavior of wood is associated with the measurement of attenuation coefficients. The numerical significance of attenuation depends on the specific measurements conditions. The main factors affecting the attenuation measurements in wood are : the geometry of the radiation field and implicitly the geometry of the specimen, the materials characteristics of scattering and absorption - dependent on species, anisotropic direction, frequency, scale of observation, etc.

For global characterization, the specific aspects related to the measurement of ultrasonic velocities in wood are related to the fact that wood material to be sensed and probed with ultrasonic waves might be divided in three main groups : tress and logs, small clear specimens and wood - based engineering products. The practical success of ultrasonic methods is determined by the utilization of appropriate transducers, which must have good sensitivity and resolution, controlled beam pattern, reproducible performance under various testing conditions and high signal to noise ratio.

Local elastic characterization of structural elements at microscopic and submicroscopic scales can be performed with acoustic microscopy, for which the resolution is at the millimeter or micron scale, for ultrasonic frequencies in the hundred of MHz or GHz range. The staining technique which is necessary in optical microscopy is not needed in acoustic microscopy. The very fact that an acoustic microscope can visualize directly the structure and measure the acoustic and elastic properties of woos specimens may be a chief attribute in the development of a new nondestructive procedure for very fine quantitative anatomical studies. We refer here to the possibility of elastic constants measurements of all anatomic elements. This is an important field to be developed in the future.

Anisotropy

The origin of fibrous solids anisotropy, perceived as the variation of material response with direction of applied stress, lies in the preferred organization of the internal structure of the material (the orientation of “fibers “ in solid wood or of layers in laminated wood-based composites).

For wood which is a biological material the anisotropy results from the non-random distribution and orientation of the structural components. Most biological materials are heterogeneous. However a non-random organization of structural elements enables us to consider these materials as homogeneous anisotropic media at macroscopic level for overall mechanical behavior investigation. This means that the material response to the applied stress is characterized by a set of linear relationships between stress and strain components, or in other words, the material elastic behavior is fully defined by its stiffness tensor.

An accurate estimation of wood mechanical behavior requires simultaneous views on its structure and on ultrasonic wave propagation phenomena. Propagation phenomena expressed by ultrasonic velocities are affected by wood structure which acts as a filter. This interaction reveals sharply the anisotropy of this material, resulting from the specific disposition of anatomical elements during the life of the tree.

Of particular interest in the orthotropic anisotropy estimation are the relationships between the bulk velocities observed on the "velocity surface" which is composed from three sheets corresponding to the quasi-longitudinal, quasi-shear and pure transversal waves. Anisotropy can expressed as ratios of these velocities and as invariants of the elastical tensors deduced with ultrasonic measurements.. The stability of calculated invariants versus different angles of wave propagation confirms the validity of the orthotropic model choose for the tested material.

The acoustic invariants have been deduced from Christoffel equations, and were related to bulk velocities measured in principal directions of elastic symmetry and out of them Because of the tensorial nature of the voluminous experimental data, averaging was possible by defining a global parameter (ratio of invariant on transversal plane TR to the average invariants in LR and LT planes) representative of the overall acoustical parameters of a wood species. It was observed that wood species having high density and complex anatomic structure in RT plane at millimeter scale exhibit high values for the ratios of invariants (0.61 for pernambuco of 935 kg/m^3 density) compared with species with simple anatomic structure (0.355 for spruce of 400 kg/m^3 density). The acoustic invariants provide useful physical insight into acoustical parameters and could serve in nondestructive research of wood properties. (Bucur 1988).

As for crystals, a rather more sophisticated way of anisotropy estimation needs the computation of Voigt and Reuss moduli. Henceforth this approach was considered for the assignment of elastic invariants, deduced from all nine stiffnesses and compliances and ultrasonic velocities. The anisotropy ratio derived from simultaneous analysis of the Voigt and Reuss moduli is a useful complement to the anisotropy ratio deduced with acoustic invariants for the studies of structural organization of wood (Bucur 1989). The exceptionally strong elastic anisotropy of wood is due to the strict alignment of its constituents, that is to say to the preferential orientation of the anatomical elements for “textural anisotropy” and to the cell wall organization for “microstructural anisotropy”.

Nonlinearity in wood acoustical behavior can be observed in two situations : when the waves are not perturbative, but have finite amplitude (field of nonlinear acoustics) (Solodov 2003) and when a small wave perturbation is superimposed on a static pre-deformation due to the presence of a static pre-stress (Sasaki et Ando 1998).

It was observed that wood exhibits exceptionally large anisotropy but weak nonlinear response (Bucur and Rasolofosaon 1998).

Certainly, the understanding of nonlinear elasticity in wood has an academic interest (Solodov et al. 2004) mainly related to the measurements of third-order elastic constants and residual stress. As for other anisotropic materials, practical aspects are related to the development of "non-classical" nonlinear nondestructive evaluation techniques using subharmonic and self-modulation modes. (Solodov 2003 a, b, Solodov et al. 2003, 2004, Johnson 2001)

Moisture content and temperature

Mechanical properties of solid wood and wood-based composites are strongly affected by the fluctuation of relative humidity and temperature. In addition, micro-organisms activity which attack wood is controlled by the same parameters. The effects of these parameters are not always easily separated. In order to understand the interaction of wood material with environmental conditions, it is necessary to consider different levels of temperature (below freezing, from freezing to the temperature at which the thermal decomposition begins and up to the temperature combustion) and relative humidity that induces moisture content fluctuation below or up to the fiber saturation point. The dependency of ultrasonic velocities and related mechanical parameters on moisture content of wood and ambient temperature was demonstrated.

The study of the effect of pressure at constant temperature and moisture content on acoustical properties of two species, spruce and cherry shown that the modification of the acoustical properties are directly related to the ruin of the anatomic structure of wood (Bucur 2000). The ruin of wood structure produced by ionizing radiation was detected with the decreasing of measured ultrasonic velocity (Suchorski 1999). Biological deterioration of wood by bacterial, fungal attack, boring agents or ionizing radiations can be well put in evidence through the variation of ultrasonic velocities. The calculation of acoustic invariants allowed the synthetic treatment of the big amount of experimental data.

WOOD QUALITY AND ASSESSMENT

Methods

The challenge to the scientist or engineer interested in the development of acoustic nondestructive techniques, for wood quality assessment is:
- to know what information is needed to fully characterization of each wood product,
- how to use this information to explain its behavior,
- to develop new wood improved properties,
- to reduce costs

The nondestructive acoustic methods (ultrasonic, stress wave or resonance methods, acoustic emission or acousto-ultrasonics) has been developed to evaluate the quality of trees, logs, lumber and wood-based composites, to detect the bio-deterioration of wood structural members, the adhesive curing, the reliability of adhesively-bonded structures, the survey of old historic timber structures, the estimation of residual mechanical performances of structural elements, in situ, etc.(Bucur 2005)

The ultrasonic technique is based on the measured parameter is the time of propagation of the acoustic wave. Various stages are usually taken into consideration during acoustic inspection such as : detection, localization, characterization and decision to act on it, if the defect is important enough. The success of the acoustic nondestructive methods is related primarily to the understanding of wave propagation phenomena in testing material and ultimately to the defining how to use the results of the basic research to improve the technology. Defects such as the slope of grain, the presence of reaction wood, the curly figures, the sylvicultural treatment –pruning or thinning can be detected with ultrasonic velocity method. The genetic selection of clones having high stifnesses can be performed by mass screening of plantation wood. The grading of logs, lumber, veneer etc. is based on the correlations established between the modulus of elasticity and the modulus of rupture. Ultrasonic velocity method and stress wave method are powerful tools for grading structural lumber, round wood and logs in industry, where elements of large size are handled. The major problem of grading lumber or veneer with contact ultrasonic technique is the very high rate of production, which is about 2 - 3 m/s. Attenuation measurements combined with velocity measurements can improve the detection of discontinuities in wood-based composites. With advances in transducers technology and with a multi parameter technique such as mode conversion technique inspection of large areas of wood products can be performed.

The success of acoustic nondestructive methods is related primarily to the understanding of the ultrasonic waves propagation phenomena in testing material and ultimately to the defining how to use the results of the basic research to improve the technology.

Wood species for musical instruments

It is an understatement to say that wood is a unique material used in the art of musical instruments craftsmanship. After a long period of evolution in the history of mankind, the skill and devotion of "luthiers" established the most appropriate wood species for typical instruments. If we confine our discussion to the classic symphonic orchestra, having four main standard groups: the strings, the woodwinds, the brasses and the percussion, it must be borne in mind that wood is used for strings, woodwind and percussion instruments. Undoubtedly, among all instruments the violin is the most fascinating one. It is therefore natural to consider the resonance wood selection, analyzing knowledge related to structural organization or to acoustical and mechanical properties of this material. Wood used for musical instruments is considered to have the most remarkable quality, with unique acoustic properties.

Spruce resonance wood (*Picea abies*) is extremely anisotropic from acoustical point of view, and is characterized by high values of sound velocity in longitudinal direction (6000 m/s) and relatively low density (400 kg/m^3) (Bucur 1987) . In the same time shear velocities in transversal plane are very low (300 m/s). The most important characteristics of spruce for musical instruments is the high acoustic and elastic anisotropy, produced by a very regular macroscopic structure.

Strong relationships were established between elastical properties and the typical structural characteristics such as : the grown ring pattern and the corresponding microdensitometric pattern, the microfibril angle, or the mineral constituents in the cell wall. The factors affecting the acoustical properties of woods for musical instruments are : the natural aging, the environmental conditions – temperature and moisture content), the long term loading and the varnishing.

Defects detection in wood

In contrast with wood for musical instruments, free of defects, we consider the common wood in which defects are always present. The techniques developed for defect detection are : the ultrasonic velocity method, the acoustic emission method and the acousto-ultrasonic method.

The ultrasonic velocity method is employed for the detection of natural defects of wood like knots, slope of grain, etc., and to assess the deterioration or modification of wood structure by different parameters such as moisture content, temperature and biological agents, to detect biodeterioration of wood structural members. Other aspects are related to the detection of adhesive curing, to the reliability of adhesively - bonded structures, to the survey of old historic timber structures, to the estimation of residual mechanical performances in situ of structural elements, etc..

The use of acoustic emission technique has been reported for the detection of different defects in trees induced by cavitation phenomena or by biological agents (fungi and termites) the monitoring of different technological processes like curing, drying, strength prediction of large structural elements and wood machining. It must be noted that in "wood science" firstly the acoustic emission technique has been used for the study of fracture mechanics on solid wood.

The parameters that characterize an acoustic emission signal are : mode of emission (continuous or burst), rate of emission, acoustic event, accumulated activity, the threshold set at a selected discriminatory level, the duration of the event, the ring-down count, the amplitude of the highest peak, the rise time, frequencies within the emitted wave, energy as the area under the envelope of the amplitude-time curve, cumulative energy recorded progressively since the beginning of the test, energy rate, “take off” point, mean square voltage , root mean square voltage, or, signal level . The main requirements of an acoustic emission system are : to distinguish between signals from pertinent and insignificant sources, to exclude mechanical and electrical interference from the field, to reduce records suitable for comparison with past and future records.

The acousto- ultrasonic technique has been also developed for the defect detection in wood, for decay detection and detection of delaminations in adhesive bond in wood-based composites, as well as the detection of integrity of joints in structural elements.

An acoustic emission system includes transducers, preamplifiers, mean amplifier, signal processors, transient recorders, spectrum analyzer, microprocessor and data storage system. In order to reliably assess the experimental data, it is assumed that each acoustic event is counted only once, all damaging events will produce acoustic emission signals of sufficient amplitude to be counted and said signals are equally damaging to the structure. The selection of a particular parameters of acoustic emission signal (level of acoustic activity, background noise, signal attenuation, etc) is prescribed by its specific application. Capacitive piezoelectric transducers are recommended for quantitative analysis because of their uniform sensitivity over a wide frequency band. Stress was put on termite detection (Mankin et al. 2002). Polyvinylidene fluoride film was used to detect the termite attack. Film sensitivity could be increased by using multiple sheets (Weissling and Thomas 2000)

When comparing ultrasonics, acoustic emission and acousto-ultrasonic techniques for defect sensing in wood and wood-based composites, confirmation of the complementary nature of the utilization of acousto-ultrasonic technique is evident. All these techniques involves the characterization of the inspected structure on the basis of the information contained in the detected signal which is governed by several parameters, such as material properties (density, ultrasonic velocities, attenuation coefficients, stiffnesses), geometrical characteristics of the sample (dimensions, defects, microstructural size), environmental conditions (temperature, humidity, moisture content, history of loading), and experimental conditions (transducer characteristics, coupling media, electronic equipment, filters, amplifiers, cables, etc).

The mean advantages of acoustic methods over other nondestructive testings are:

- the wide material volume surveyed,
- the real time nature of the techniques
- the capability of continuously monitoring structures.

The most important disadvantage of these methods is the necessity to put the probes in direct contact with the specimens. This inconvenient can be avoid through the development of non contact transducers.

High power ultrasound

High power ultrasound (macrosonics) is a relatively new branch of ultrasonics and is related to the high – intensity (1 W/cm ^{2}) applications which produce permanent changes in the treated medium. Successfully application of high – power ultrasound is very much related to the transducers and to the uniform distribution of acoustic field into the processed medium. (Gallego - Juarez 1990)

The propagation of high – intensity ultrasonic waves in media produces nonlinear effects associated to the finite high amplitudes. The nonlinear effects are : wave distortion, radiation pressure, cavitation , dislocations, etc. which can induce mechanical rupture, chemical effects, interfaces instabilities, friction, etc. (Gallego - Juarez 2002). All these physical effects can be employed to enhance processes that depends on the ultrasonic field irradiated into the medium.

In wood technology, for the moment, the applications are very scarce and could be related to wood processing such as drying, defibering, cutting, plasticizing, extraction improvement, regeneration effect on aged glue resins and wood preservation. A very big step towards the improvement of wood drying was achieved with the combined utilization of high-power ultrasound and infrared radiation. The ultrasonic cutting of wood has several advantages over the conventional methods such as : improvement of the smoothness quality of the machined surface, producing small kerf and sawdust, no deformation due to cutting forces and no burned surfaces, as well as small tool wear.

Ultrasonic technique for regeneration of aged glue resin is quite currently used today. The improvement of wood preservation with high-power ultrasound is a good achievement of this technique.

CONCLUDING REMARKS

Wood is a biological composite produced by the living organisms of trees. To promote the efficient use of wood-based materials in the future, the major areas which need to be studied are :

- the development of new nondestructive techniques for the evaluation of physical, and mechanical properties of wood-based products,
- the improvement of natural qualities of wood through the modification of its properties with different treatments, creating new wood-based products corresponding to the requirements of the modern society.

REFERENCES

Anderson GS, Kruze UJ (1992) Outdoor sound propagation . In Beranek L, Ver IL (eds) *"Noise and vibration control engineering. Principles and applications".* Wiley, New York, pp 113 -144

Attenborough K (1982) Predicted ground effect for highway noise. J Sound Vibration 81 : 413 - 424

Attenborough K, Taharzadeh S, Bass HE et Al (1995) Benchmarks cases for outdoor sound propagation models. JASA 97 : 173 - 191

Aylor D (1972 a) Noise reduction by vegetation and ground . JASA 51 : 197 - 205

Aylor D (1972 b) Sound transmission through vegetation in relation to leaf area density, leaf width and breath of canopy. JASA 51 : 411 - 414

Barrière N, Gabillet Y (1998) Traffic noise control by forests. The meteorological screening effect. Proc Euro Noise 98 : 1117 - 1122

Beranekk L, Vèrrr IL (1992) *Noise and vibration control engineering. Principles and applications.* Wiley, New York.

Bullen R, Fricke F (1982) Sound propagation through vegetation. J Sound Vibration 80 : 11 -23

Bucur V (1987) Varieties of resonance wood and their elastic constants. J Catgut Acoust Soc 47 : 42 - 48 ; also in "Research Papers in Violin Acoustics 1975 - 1993" CM Hutchins, V Benade (eds) Acoustical Soc of America : 787 - 794

Bucur V (1988) Wood structural anisotropy estimated by invariants. Int. Assoc. Wood Anatomists Bull. 9, 1 : 67 - 74

Bucur V (1989) Bulk and surface waves for wood anisotropy characterizatioon. Mat. Sci. Eng. A 122: 83 - 85

Bucur V (2006) *Urban Forest Acoustics*. Springer Verlag, Heidelber

Bucur V (2005) *Acoustics of Wood.* Second edition. Springer Verlag, Heidelberg

Bucur V (2003) *Nondestructive characterization and imaging of wood*. Springer Verlag, Heidelberg

Bucur V, Rasolofosaon P (1998) Dynamic elastic anisotropy and nonlinearity in wood and rock. Ultrasonics 36 : 813 - 824

Bucur V, Barlow CY, Garros S (2000) The effect of hydrostatic pressure on physical properties and microstructure of spruce and cherry. Holzforschung 54 : 83 - 92

Carlson DE, McDaniel OH, Reethof G (1977) Noise control by forests. Proc. Inter Noise 77 : B576 - B586

Embelton TFW (1996) Tutorial on sound propagation outdoors. JASA 110 : 31 -48

European Commission (1996) Future noise policy. Green paper, Directorate general for environment, nuclear safety and civil protection. Brussells

Gallego - Juarez J A (1990) Transducers needs for macrosonics. In "*Power transducers for sonics and ultrasonics*" Eds Hamonic B, Decarpigny JN, Springer, Berlin : 35 - 47

Gallego - Juarez JA (2002) New industrial applications of high power ultrasound. Proc 6^{e} Congres Français d'Acoustique, Lille 8 - 11 April : 19 - 26

Gautier PE, Poisson F, Foy F (2004) Les enjeux actuels des recherches en acoustiqueeeeee et vibrations dans le domaine ferroviaire. Acoust. Techn 37 : 6 - 11

Gierke HE von, Eldred KM, Break RK (1998) Environmental impact statements . In *" Handbook of acoustical measurementsd and noise control*" CM Harris ed. , Acoustical Soc America , Melville : 54.1 - 54-22

Herrington LP (1974) Trees and acoustics in urban area. J. Forestry 72 : 462 - 465

Herrington LP, Brock C (1977) Propagation of noise over and through a forest stand. Proc of the Conference on Metropolitan physical Environment. Northeastern Forest Experiment Station, USADA Forest Service, Gen. Techn. Rep NE - 25 : 226 - 228

Johnson PA (2001) Application of dynamic nonlinear elasticity ti damage interrogation. Proc. Ultrasonics Int 2001, 2-5 July, Delft. Tutorial - Ultrasonics Applications.

Mankin RW, Osbrink WL, Oi FM, Anderson JB (2002) Acoustic detection of termites infestation in urban trees . J. Econ. Entomol 95 : 981 - 988

Marquis - Favre C, Premat E, Aubée D (2005) Noise and its effects - a review on quantitative aspects of sound Acta Acustica 91 : 613 - 642

Mecklenberg RA, Ritelman WF, Schumaier DR, DenBrink CV, Flores L (1972) The effect of plants on microclimate and noise reduction in urban environment. Hort. Sci. 95 : 61 - 64 []

Muir J (1984) Silvicultural information to help select and manage trees in urban or suburban developments. Arboricultural J 8 : 13 -17

Price MA, Attenborough K, Heap NW (1988) Sound attenuation through tress : measurements and models. JASA 84 : 1836 - 1844

Rogers JC, Lee SM (1989) Sound scattering from forests : considerations and initial measurements . Proc Int. Conf. Acoustics UK 14 : 277 - 281

Sasaki Y, Ando K (1998) Acoustoelastic phenomena of wood. Proc 5th World Conference on Timber Eng. Montreux, August 17 - 20 Suisse : 296 - 303

Schaudinischky LH, Schiller G, Keller Y (1982) Acoustic properties of individual trees and forest strips. Forstarchiv 53 : 52 - 57
Solodov I (2003a) Nonlinear ultrasound in solids : from classical fundamentals to non - classical NDE applications. Proc Ultrasonics Int '03, Granada , Invited paper

Solodov I (2003b) Ultrasonics of nonlinear interfaces in solids : new physical aspects and NDE applications. Proc World Conference on Ultrasonics, Paris , Invited paper: 555 - 564

Solodov I, Korshak B, Pfleiderer K, Wacklerl J, Busse G (2003) Nonlinear ultrasonic inspection and NDE using subharmonic and self modulation modes. Proc World Conference on Ultrasonics 2003, Paris, September 7-10 : 1335 - 1338

Solodov I, Pfleiderer K, Busse G (2004) Nondestructive characterization of wood by monitoring of local elastic anisotropy and dynamic nonlinearity. Holzforschung 58 : 504 - 510

Suchorski P (1999) Velocity of ultrasonic waves in wood as an indicator of its deterioration rate under gamma radiation. In " Mechanical performance of wood and wood products" Cost Action E 8. Eds : P. Morlier, G. Valentin, University of Bordeaux : 111- 119

Tanaka K, Ikeda S, Kimura R, Simazawa K (1979) The function of forests in soundproofing. Bul. Tottori Univ. For 11 : 77 - 102

Watts G, Chinn L, Godfrey N (1999) The effects of vegetation on the perception of traffic noise. Appl. Acoustics 56 : 39 - 56

Weissling TJ, Thomas EM (2000) Use of an acoustic emission detector for locating Formosan subterranean termite feeding activity when installing and inspecting aboveground termite bait stations. Fla. Entomol 82 : 60 - 71