

PIEZOELECTRIC PROPERTIES OF WOOD

by
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Authorized translation from the Russian



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Пьезоэлектрические свойства древесины

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TRANSLATOR'S PREFACE

Anyone who has dealt with the classification of trees is aware of the vexing problems and arguments encountered in distinguishing the finer details of the various species and subspecies. This is but one dimension of the problem, however, for another is added when geographic boundaries are transcended. There seem to be disparities in the classification of trees in a given stand or forest from one part of the world to another. Now add the further complexity of translation from one language to another and the three-dimensional picture is complete.

In view of all this, when referring to the various kinds of wood tested and discussed in the present work the translator has chosen to use the term "species" throughout in order to emphasize the fact that although the common names – birch, oak, pine, etc. – are used almost exclusively by the author and are generic rather than specific in general character, we cannot be sure to what extent the woods named correspond in their properties to similarly named woods in the U.S., Canada, and other countries. This is due in part to an overlapping of generic groupings in Russian and English, in part to distinctions made in one language and not in the other. The same situation, incidentally, exists even in American and British (in England, for example, certain species of mahogany and red pine are sometimes called redwood, but are quite dissimilar from the giant trees of California).

As the most pronounced example of this disparity, in Russian the spruces and firs are grouped under a single common name. Certain hemlocks and spruces are grouped with the pines. Fortunately, in these and a few other instances the Latin scientific names are given. It is rather inopportune that the author has not given the scientific names in every case. One must remember, however, that even specification of the exact scientific names does not guarantee constancy in properties of the wood from forest to forest, country to country. Geographic-environmental differences constitute a major influence on a single species.

The following criteria, referring to a few of the woods discussed in the present book, may prove useful:

Spruce (*Picea excelsa* L.) – known also as white fir or white deal if imported in sawn form; corresponds to American spruce and is properly known as "Baltic spruce." Although spruce in general is harder to work owing to its tough knots, the Baltic variety is milder and easier to plane and saw.

Pine (*Pinus silvestris* L.) – known also as Danzig pine, Danzig fir, redwood, yellow deal (in sawn form), properly as red Baltic pine. The Baltic variety is more workable than some others. In Russian this is sometimes called "normal" or "true" pine to distinguish it from others which are grouped under the same name but which are actually hemlocks or spruces.

Oak (*Quercus pedunculata*) – properly known as Austrian oak; prominent in the Slavonian and Croatian forests, similar to but slightly inferior to British oak. The trees are much taller, the wood straighter-grained than the familiar oak in America, which usually represents the derivation of several species. This is one of the strongest, most compact, and most durable of oaks.

Ash (*Fraxinus excelsior*). The Russian variety of European ash is whiter and stronger, has black heartwood, and is very elastic; it is difficult to compare with American ash because the latter is derived from so many species and there seems to be a lack of standardization. The European ash generally has finer pores and wood rays. The closest resemblance will be found in Canadian ash.

Birch (*Betula verrucosa* L.)—apparently similar to the *B. pendula* and *B. lenta*, or black birch so common in Russian forests and so often the subject of Russian folk literature and song.

Aspen (*Populus tremula* L.)—a larger tree in Europe, soft, light, elastic, easily split, with little warping or cracking; used for the whitest and highest quality paper pulp. This tree is probably most similar to the American trembling aspen.

Beech (*Fagus silvatica*)—known as common or European beech. It is redder, silkier-grained, and much less strong and durable than North American beech.

The reader who is interested in further comparison of North American and European woods is directed to the definitive work on this subject by A. L. Howard, *A Manual of the Timbers of the World* (third edition, MacMillan and Co. Ltd., London, 1948). This book, however, being intended for readers in Great Britain, is somewhat deficient in its coverage of American trees (but it is rather comprehensive on Canadian varieties) and should be supplemented with the works by Gregus (1945) and Tiemann (1944), cited at the end of the present book, as well as Brown, Panshin, and Forsaith, *Textbook of Wood Technology* (McGraw-Hill Book Co., New York, 1949).

The book is interesting from several points of view. In it the author takes as his starting point the structural aspects of wood, the tenets of crystallography and crystal symmetry. Already the primary twofold significance for wood technologists and solid state scientists begins to be apparent. The greater part of the book is devoted to the results of an extensive and thorough experimental program conducted by the author over a period of years on the piezoelectric and physical-mechanical properties of wood and wood materials and their mutual correlation, with frequent reference to and comparison with the work of his predecessors and contemporaries, Russian and non-Russian. In the concluding chapter the vast experimental material is collated and generalized into a primitive formulation of the physical and chemical laws governing the behavior of the effects involved.

Here, then, is a textbook on the piezoelectric properties of wood and its derivatives, but, more than a textbook, it is the first authoritative full-length work on the fascinating new field of noncrystalline anisotropic substances exhibiting properties thought heretofore—until discovered by Russian scientists—to be the exclusive attribute of crystals. As such, this field represents a new interdisciplinary involving several branches of science and technology, from biology at the one extreme to solid state physics at the other, organic chemistry bridging the gap.

FOREWORD

The piezoelectric effects in wood were discovered by Academician A. V. Shubnikov.

The problem of piezoelectricity in wood arose in connection with the more general problem of the piezoelectric effect in noncrystalline substances.* "Experiments with wood," wrote A. V. Shubnikov, "are of great significance in crystallography, for they can be used to establish an entirely new method for assigning at least some of the constituent parts, if not the wood fibers themselves, to one of the twenty piezoelectric groups of crystallographic symmetry" (Shubnikov, 1946, p. 94).

The possibility of piezoelectricity occurring not only in monocrystalline materials, but in the so-called piezoelectric textures as well was physically substantiated and experimentally verified in papers by A. V. Shubnikov. Shubnikov determined the symmetry groups of the piezoelectric textures, extended the general theory of piezoelectricity to the piezoelectric textures, studied the basic texture tensors, obtained piezoelectric textures with artificial orientations, and discovered new piezoelectric textures with natural orientation.

The discovery of piezoelectricity in wood and the first attempts at making a quantitative study of it brought the problem to the attention of specialists working in various, often widely divergent fields of scientific endeavor. Wood processors expressed a great interest in piezoelectricity, a property of wood entirely new to them. Those working in crystallography and crystal physics recognized the refutation of the popular notion that piezoelectricity was to be found only in monocrystals and at most in piezoelectric textures with crystalline grains.

In the very earliest papers on the piezoelectricity of wood it was reported that the guilty party was cellulose. This stimulated the interest of chemists in conjunction with the age old disputation as to the crystalline or amorphous structure of cellulose. There arose many questions regarding the possible applications of wood as a piezoelectric for engineering purposes. Biologists too were interested in the piezoelectricity of wood and cellulose in connection with the possible biological significance of the piezoelectric effect in plants in general.

Out of all this stems the far-reaching scientific importance of an extensive research program on the piezoelectric properties of wood. The scientific and practical application of the piezoelectric effect in wood, as well as any conclusions resulting from the very fact that it exists cannot be realized without careful study of the piezoelectric properties of wood and their relationship to the structure of wood and other relevant characteristics of the latter.

In studying the piezoelectric effect in wood, we should adhere to the fundamental method of crystallography, i.e., successive application of the symmetry principle, for this principle underlies the physics of crystals, of which the theory of piezoelectricity is one branch.

* A. V. Shubnikov, "On the tensor piezoelectric moduli of noncrystalline anisotropic media," Report in the Division of Physical-Mathematical Sciences of the Academy of Sciences of the USSR, April 26, 1940.

In the present book the elements of tensor calculus are applied. It must be realized that herein we could not begin to approach the exposition of the tensor calculus as given in the literature devoted especially to that subject (Kochin, 1951; Dubnov, 1950, 1952; Rashevskii, 1953). We remark in particular that what we are considering is piezoelectric material of a biological origin. Despite the fact that we have not made a special study of the biological role of piezoelectricity in plants, to deny it altogether would in the present state of the art be premature.

We began our preliminary experiments at the Crystallography Institute of the Academy of Sciences of the USSR, with the head scientist of this institute, V. P. Konstantinova, taking part, and all of the systematic experimental work from 1948 on was conducted in the Wood Products Laboratory of the Forestry Institute of the Academy of Sciences of the USSR with the participation of the head laboratory technician, F. F. Sadovskii, who performed a tremendous service in setting up the equipment and conducting the tests.

During the course of the research the author received time and again invaluable counsel from Academician A. V. Shubnikov, Candidate of Physical Mathematical Sciences I. S. Zheludev, and Prof. Yu. M. Ivanov, head of the Forestry Institute's Wood Products Laboratory. To all of these the author conveys his deepest appreciation.

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CHAPTER I

PRINCIPLES OF INVESTIGATION OF THE PHYSICAL PROPERTIES OF ANISOTROPIC SUBSTANCES

§ 1. Anisotropy in the Structure and Properties of Crystalline and Certain Noncrystalline Materials

By anisotropy we mean nonuniformity in the properties of a body with respect to different directions in that body. In studying the physical properties of anisotropic materials it is necessary not only to determine the quantities that characterize the corresponding properties, but also to indicate the directions in which these properties were determined.

Examples of anisotropic materials are all monocrystals and certain noncrystalline substances, although the nature of the anisotropy in crystals and noncrystals proves to be notable different in each case. The principles of investigating the physical properties of anisotropic materials are set out most clearly in the case of crystals. The question arises, to what extent are we justified in extending these principles to noncrystalline anisotropic substances? Naturally, we are primarily concerned with mathematical principles. The study of the physical properties of monocrystals as anisotropic bodies is based on the successive application of the principle of symmetry. In crystallography it is always stressed that anisotropy and symmetry are the most important properties of crystals, but at the same time it is pointed out that these properties are also exhibited in noncrystalline materials.

The investigation of the causes of anisotropy and its relationship with symmetry logically begins with a consideration of crystals.

"Crystals are bodies with a regular structure such that the particles composing them (atoms, ions, molecules) are distributed according to the law of space lattices" (Ansheles, 1952). In studying crystals we can turn our attention to the individual properties depending on chemical composition, or, expressing the substance of the definition just given, depending on the type of particles that make up the lattice; such is the approach in chemistry. It is not, however, the fundamental approach in crystallography, which is concerned not with the study of individual properties, but of the so-called general properties of crystals that evolve from the laws governing the lattice structure. In the study of the general properties of crystals we stand aloof from the separate properties of the particles that constitute individual crystals and instead consider the latter as geometric points distributed in space according to definite laws relative to one another. The investigation of the set of such points leads to the concept of the space lattice. The structure of space lattices is mathematically described by means of the laws of symmetry. In view of this, the knowledge and understanding of symmetry is extremely valuable in crystallography. Crystal symmetry is contained first and foremost in the symmetry of the space lattice, i.e., in the symmetry of distribution of the material particles making up the monocrystalline substance.

Crystals must by their very nature have symmetry, limiting the variety of their structure by the laws of crystallographic symmetry. This fact has made it possible to apply symmetry as the basis for crystal classification and, by examination of the laws of crystal symmetry, to predict the number of different kinds of crystals.

"We have seen that in the given instance nature is extremely restricted by her own intrinsic laws and cannot realize more than thirty-two kinds of crystals differing in their symmetry. This ability to sort out all cases of crystal symmetry ahead of time is the crowning achievement of the study of symmetry and demonstrates just how far we have penetrated into the nature of symmetry and into the laws of crystal formation in particular" (Vul'f, 1952).

Every medium that has a regular and discrete structure is characterized by the fact that moving along different paths within it an unequal number of material particles is encountered. The simplest illustration of this may be found in a plane matrix of points (sites) Fig. 1), where the directions b , c , r , k turn out to be non-equivalent, since the lines corresponding to these directions pass through a different

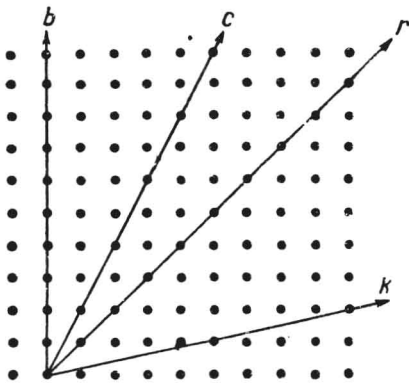


Fig. 1. A medium having a regular and discrete anisotropic structure. Unequal numbers of material points are encountered along the lines b , c , r , k , whereupon the directions are non-equivalent (after E. E. Flint, 1952).

number of points on the matrix, which is used here to characterize a regular and discrete medium. In view of this, a body having a regular and discrete internal structure cannot have like (isotropic) properties in all directions, i.e., it is anisotropic. If the properties of such a body are expressed by vectors and are drawn from one point representing the origin, the ends of the vectors will not lie on the surface of a sphere, but on the surface of some other geometric contour, the symmetry of which will depend on the symmetry of the space lattice of the given regular and discrete crystalline medium.

Consequently, crystal anisotropy, like crystal symmetry, is an outcome of the internal structure of the crystal.

Anisotropy and symmetry, however, despite their tremendous importance in crystallography and crystal physics, are not exclusively properties of crystals, since they can be manifested in noncrystalline materials as well.

In the literature on symmetry, especially in the recent edition of a book by Vul'f (1952), in A. V. Shubnikov's book (1940), and in others, numerous examples of its appearance in the animal and plant world, in technology and practice are cited, testifying to the fact that symmetry is indeed not solely a property of crystals.

Hardly anyone would contest the assumption that symmetry in the structure and properties of noncrystalline substances also must be governed by a regular and discrete allocation of some kind of structural element: cells, fibers, grains, molecules, etc. Such a distribution, although considerably less systematic in comparison with the crystal lattice, is the cause of anisotropy in materials.

It is interesting to note that many crystallographers and physicists actually consider wood as an exemplary case of an anisotropic noncrystalline substance.

Crystalline materials are very often set off in contrast with amorphous materials. Amorphous materials, as one would expect from the name itself, are those consisting of disordered fine particles, and on this basis they are frequently endowed with only "spherical" symmetry (uniformity of the corresponding properties in all direction drawn inside the isotropic body). In this connection we need emphasize that not all amorphous substances are isotropic, far from it. This is all too frequently forgotten, unfortunately, which is the reason for various misconceptions. One such false notion is the denial of the possibility of piezoelectric effects in noncrystalline substances (Cady, 1949).

The facts presented, it seems to us, leave no doubt that the well developed crystallographic method of successive application of the symmetry principle can be used in studying the physical properties of noncrystalline anisotropic materials, including wood.

§ 2. Crystallographic Symmetry

The study of symmetry is presented with varying degrees of comprehensiveness in every course in crystallography. Of all the papers on symmetry, where the explanation of the problems of symmetry is not limited solely to the demands of crystallography, the most well-known are the monography by A. V. Shubnikov (1940) and the recent re-edition of the book by A. V. Shubnikov (1952). Modern problems in symmetry are developed in a book by A. V. Shubnikov (1951). In 1949 the principal papers of the prolific Russian crystallographer E. S. Fedorov were revised and published in the collection *Symmetry and Structure of Crystals* [in Russian].

We quote the definition given by E. S. Fedorov (1949) for a symmetric figure: "A symmetric figure is one which can be exactly superposed on itself in various positions, or superposition can be effected in various positions when we replace the object by its own mirror image" (p. 60). The superposition, or congruency, of a symmetric figure is determined by the presence of so-called symmetry elements, which may be points, lines, or planes. The more ways that congruency can be attained for a given figure, the higher is the degree of symmetry of that figure. The number of superpositions was adopted by E. S. Fedorov as the magnitude of the symmetry. If the value of the symmetry is equal to unity, there is no symmetry in the figure, and the latter is called asymmetric (Fedorov, 1949). Crystallographic symmetry is characterized by symmetry equations, which include an enumeration of all the elements of symmetry of the given group with some indication of the number and order of elements.

The presence of several group criteria and the complexity and intricacy of the symmetry equations necessitates the use of a simplified notation for the symmetry groups, in other words, the symbolic language.

The symbolic language, as opposed to the symmetry equations, does not include all the elements of symmetry, but is instead limited to the use of only the so-called generating elements of symmetry. In the symbolic language of Shubnikov, which we have adopted here, the following notation is employed: 1, 2, 3, 4, and 6 are the first-, second-, third-, fourth-, and sixth-order symmetry axes; $\bar{2}$, $\bar{4}$, and $\bar{6}$ are the second-, fourth-, and sixth-order reflected axes; the colon (:) represents perpendicularity; a dot

($\cdot$) represents parallellicity; the solidus ($/$) is used to separate two axes, shown as the numerator and denominator of the resulting fraction, that do not intersect at right angles.

CHAPTER II

CERTAIN ASPECTS OF THE STRUCTURE AND PROPERTIES OF WOOD AS AN ANISOTROPIC INHOMOGENEOUS MATERIAL

§ 1. Anisotropy of Wood and Its Irregularity

Wood is a typical anisotropic material. Its anisotropy is manifested in its structure and in its physical-mechanical properties. The principal directions of anisotropy, as we know, are longitudinal (along the trunk), radial, and tangential (with respect to the circumference of the trunk or the annual growth layers). Sometimes in studying the anisotropy of mechanical properties, the difference between the radial and tangential directions is neglected, and both of these, along with all the other intermediate directions, are considered as equivalent transverse directions, set off in distinction to the longitudinal direction, parallel to the trunk (Mitinskii, 1911; Pavlov, 1947). Such a notion is justified when applied to the trunk as a whole or to a cylindrical wood sample whose geometric axis coincides with the core of the tree. But there is little justification, and at times none at all, in applying this notion to structural elements or samples whose form is other than cylindrical. It is more proper, therefore, to account for the anisotropy in the generally accepted manner required by experiment, by distinguishing in wood the three directions specified above and, correspondingly, three planes coinciding with transverse, longitudinal radial, and longitudinal tangential cuts of the trunk.

Therefore, granting that anisotropy does exist in wood, the problem of a suitable method to take this anisotropy into account by a choice of practicable symmetry forms can be solved in several ways. The essential factors here are the form and dimensions of the specimens cut from the tree.

By analogy with crystalline materials, which, as already mentioned, are always anisotropic (in this sense we are speaking here also by analogy), we are correct in expecting that in wood the symmetry in structure need not coincide with the symmetry of its various properties. In the present instance, however, we cannot reasonably expect to find as definite a connection between these forms of symmetry as in crystals, where the principle of maximum and minimum symmetry always holds.

We see in crystals one cause of anisotropy, the structure of the crystal lattice. In wood the anisotropy is also defined by structure, but now the structure is in turn influenced by the entire complex of structural factors, to wit: the macroscopic and microscopic structure, structure of the cell wall, structure of the basic constituent of wood — cellulose — and so on. Because of this, at the present time the symmetry in properties is most conveniently determined empirically and by generalization of the data already in existence, an approach successfully applied by A. N. Mitinskii (1948) in the study of the elastic anisotropy of wood. Valuable experimental material on the resistance of wood to compression at various angles with respect to the direction

of the fiber and annual rings is contained in papers by Baumann (1922), A. I. Flakserman (1931), and Yu. M. Ivanov (1953).

The investigation of the anisotropy of various properties of wood, including its elastic properties, is greatly encumbered by the distinctly pronounced inhomogeneity of the structure and properties of wood. For evaluating the degree of irregularity in the anisotropy of wood, the investigation of the variations in its physical-mechanical properties along the height and radius of the trunk is of utmost value.

The changes in physical-mechanical properties of wood along the height of the trunk are insignificant. The physical-mechanical properties of wood over the radius of the trunk vary to an extremely greater extent. These variations are manifested in very different ways in coniferous, deciduous ring-porous, and deciduous diffuse-porous trees.

Regarding coniferous trees, with increasing maturity (pine, cedar, larch), as noted by L. M. Perehygin (1949), "the properties of wood at first increase in magnitude away from the pith toward the cortex (later the bark), reach a maximum at about $2/3$ of the radius, after which they again diminish" (p. 208).

Characteristic of the deciduous ring-porous group is a diminution in the physical-mechanical properties from the pith to the bark.

For the deciduous diffuse-porous trees, judging from data on birch, aspen, and linden (American: basswood), L. M. Perehygin (1949) notes one regularity in common—enhancement of the physical-mechanical qualities outward toward the bark.

The reasons for the indicated regularities can be determined on the basis of a consideration of the connections between the structure of the wood and its physical-mechanical properties.

The structure of wood is characterized by several of the most common criteria that appear in the various structural elements (trunk, cells, cell wall, fibrils), to wit: 1) elongation in the longitudinal direction, which is typical of the trunk, annual rings, cells, cellulose molecules; 2) lamellar structure, which occurs in the trunk, annual rings, cells, fibrils; 3) all kinds of radial growths, formed in the various elements of the tree during its multiphase growth (knots, wood rays, bordered pits).

Wood structure is conventionally classified on the basis of visual criteria in its corresponding elements. A breakdown is made into the macroscopic structure (visible to the naked eye), microscopic structure (observable in the compound microscope), and submicroscopic structure (the size of whose elements falls below that which can be resolved by the compound microscope). The submicroscopic structure is made up of the molecular structure of the individual wood components.

The wood structure reflects not only the growth and development of the tree at various times, but also the diverse influences of the external medium, which may be regulated to a certain extent by forestry techniques. External factors can greatly distort the main growth line in the formation of the annual rings. In light of this, the annual rings represent an authentic year-by-year record of such events as drought, heavy frost, cutting of branches, and even the periodicity of sun spot appearances (Vavilov, 1950). These are all factors causing the variation in structure of wood along the radius of the trunk and the consequent variation in its physical-mechanical properties.