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(54) METHOD OF WOOD STRENGTH AND STIFFNESS PREDICTION

VERFAHREN ZUM VOHERSAGEN VON HOLZTRAGFÄHIGKEIT UND -STEIFIGKEIT

PROCEDE DE PREDICTION DE RESISTANCE ET DE RIGIDITE DE BOIS

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(56) References cited:
EP-A- 0 403 020
WO-A-01/65253
US-A- 4 926 350
US-A- 5 804 728
US-A1- 2002 025 061
WO-A-00/11467
US-A- 4 500 835
US-A- 4 941 357
US-A- 5 960 104

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Description

Field of the Invention

[0001] The present invention relates generally to wood strength and stiffness prediction.

Background of the Invention

[0002] It can be appreciated that wood strength grading has been in use for many years. This has traditionally been accomplished by using visual grading rules to predict strength. Other technologies such as mechanical bending and X-ray, to sense density, have been used to estimate the strength of wood.

[0003] The main problem with conventional visual wood grading is that is does not predict strength or stiffness accurately. The use of the mechanical bending improved the ability to predict stiffness of the lumber but the correlation to strength is poor. X-ray based systems predict strength and stiffness based on density only.

[0004] While these devices have been suitable for the particular purpose to which they addressed, they are not as suitable for highly accurate strength and stiffness prediction of today's variable and often low-quality wood resource.

[0005] US Patent 4,926,350 (Bechtel et al) teaches a non-destructive testing system for lumber which involves measurement of grain angle about a board and transformation of the measured grain angle values to extract features indicative of knot identification, grain angle perturbations or strength of the board.

Summary of the Invention

[0006] The present invention provides a new prediction method of wood strength and stiffness.

[0007] The general purpose of the present invention, which will be described subsequently in greater detail, is to provide a new prediction method that has many of the advantages of the board strength prediction methods mentioned above and in addition, novel features that result in a greater prediction accuracy.

[0008] To attain this, the present invention includes generally the use of streams of sensor information integrating into a physical model providing for strength and stiffness prediction. It is to be understood however that the invention is not limited in its application to the details of the method and to any arrangements of the components set forth in the following description or illustrated in the drawings, or to the details of the algorithm employed. The invention is capable of other embodiments and of being practiced and carried out in various ways.

[0009] One object of the present invention is to provide a prediction of wood strength that will predict the strength and stiffness in the lumber based on a physical model using several sensing technologies. Physical model, in this context, refers generally to an algorithm that utilizes the material mechanical behavior and impact of various wood characteristics on strength and stiffness.

[0010] Another object is to provide a prediction of wood strength and stiffness that can integrate many technologies into a single model thereby providing differing accuracy prediction based on the sensors used.

[0011] Another object is to provide a prediction of wood strength and stiffness that with sensor technologies added together improves the ability of any one sensor to predict strength and stiffness.

[0012] To the accomplishment of the above and related objects, this invention is embodied in the form illustrated in the accompanying drawings, attention being called to the fact, however, that the drawings are illustrative only, and that changes may be made in the specific construction illustrated.

[0013] In one aspect, the method of the present invention may be characterized as a method of, accomplishing, non-destructive testing of a wood piece using a multiplicity of sensors. The method includes the steps of causing the controlling and processing of, the following:

a) sensing the wood piece,
b) collecting information from the sensors, and
c) integrating the information into a physical model providing for strength and stiffness prediction.

[0014] The step of collecting information may include collecting information relating to material characteristics of the wood piece and relating to fiber quality characteristics of the wood piece. The material characteristics may include one or more of the following material characteristics of the wood piece: growth ring thickness; grain angle deviation; clear wood density; knot location; knot density; knot type; knot size; location in the tree from which the wood piece was cut. The fiber quality characteristics may include one or more of the following fiber quality characteristics: microfibril angle, juvenile wood, biodeterioration; reaction wood species; and manufacturing or drying defects including one or more of the following defects: sawcuts, checks, shake; size of actual cross-section, and species.

[0015] In one embodiment the method further includes the steps of providing one or more of the following sensor types: X-ray, microwave, camera vision, laser triangulation three-dimensional geometry, material vibration measurements, laser based tracheid effect measurement.

[0016] The invention provides a method continue as per claim 1. Clear wood equivalent (CWE) will hereinafter also be referred to as clear wood density equivalent/clear wood equivalent density.

[0017] The further step of constructing clear wood density equivalent as a first step in strength and stiffness prediction may also include; comprising:

a) Measuring of material density in a plurality of dimensions, for example using x-ray sensors,
b) Estimating other wood volume characteristics, including grain angle, growth ring angle, location in the tree from which the wood piece was cut, fiber quality including microfibril angle, and 3D geometry of the scanned piece,
c) Reducing clear wood equivalent density by the effect of the wood volume characteristics using relationships of these characteristics on mechanical behavior of wood.
d) Detecting size, location and classification of wood defects, including but not limited to, knots, biodeterioration, reaction wood, juvenile wood, manufacturing and drying defects, pith, pitch, wet pockets,
e) Further reducing clear wood equivalent density by the effect of wood defects in respective locations of occurrence and effect these characteristics on mechanical behavior of wood; and
f) Constructing strength and stiffness models using clear wood density equivalent.

[0018] The further step of constructing clear zero grain angle wood equivalent as a first step in strength and stiffness prediction may also be included, comprising:

a) Measuring of material grain angle in a plurality of dimensions,
b) Constructing clear wood zero grain angle equivalent by assigning a nominal density value which is an average for a wood species whenever grain angle relative to a longitudinal axis of the piece is zero, and less wherever the grain angle deviates from zero and accordingly to grain angle effect on mechanical behavior of the wood piece,
c) Reducing clear wood equivalent density by the effect of the wood volume characteristics using theoretical and empirical relationships of these characteristics on mechanical behavior of wood,
d) Further reducing clear wood equivalent density by the effect of wood defects in their respective locations of occurrence and the effect on mechanical behavior of the wood piece, and
e) Constructing strength and stiffness models using clear wood density equivalent.

[0019] The further step may be included of estimating clear wood equivalent in an area of the wood piece occupied by a knot by virtually removing density occupied by a knot and replacing it by a density of clear wood, mechanically equivalent to the removed knot.

[0020] The sensors may include a sensor collecting pixel values from a corresponding matrix of pixels in the sensor, and wherein for every pixel density, d_{ij}, the method and software includes the step of computing clear wood equivalent, e_{ij}, using adaptive threshold clear wood density, a_{ij}, in the equation:

$$e_{ij} = \text{RemaingClearWood} + \text{KnotEquivalent}$$

wherein:

$$\text{RemaingClearWood} = a_{ij} - k_{ij} * K$$

i is virtual pixel index along the length of the wood piece
j is virtual pixel index traversely across the wood piece
K is knot density ratio, defined as a ratio of clear wood density to density of knot
knot density is difference between wood density d_{ij} and clear wood density

$$k_{ij} = d_{ij} - a_{ij}$$

[0021] KnotEquivalent is defined as clear wood density equivalent residing in knot volume,

$$\text{KnotEquivalent} = k_{ij} * K * M$$

wherein M is the material knot property ratio:

$$M = \text{Knot Property} / \text{Clear Wood Property}.$$

[0022] The step of computing e_{ij} may include substituting:

$$e_{ij} = a_{ij} + (d_{ij} - a_{ij})*K*(M-1).$$

[0023] The step of predicting strength and stiffness may include the step of estimating effect of the grain angle by decomposing the grain angle into running average and local deviation components, wherein the running average component is a function (g_{ave} (GA)) of running average grain angle along a length of the wood piece excluding grain deviations around knots, and wherein the local deviation component is a function (g_{dev} (GA)) of the grain angle defined as a difference between a local measured grain angle and the running average grain angle. The method further includes the step of computing grain angle effect functions g_{ave} (GA) and g_{dev} (GA) for determining the effect of grain angle on a material property wherein both g_{ave} (GA) and g_{dev} (GA) are computed according to the following equation:

$$g(GA) = \frac{1}{R \cdot \sin^n(GA) + \cos^m(GA)}$$

[0024] n and m are empirical constants, R is the ratio between the material property measured parallel to the grain versus the material property measured perpendicular to the grain. Optimizing constants R, n, and m are specific to the wood species corresponding to the wood piece.

a) The method further include the steps of:

applying the running average modification function (g_{avg}(GA)) to the clear wood equivalent density by multiplication according to:

$$e'_{ij} = e_{ij} * g_{avg}(GA_{ij})$$

b) modifying the grain deviation function (g_{dev}(GA)) to derive a further grain angle deviation modification function to avoid multiple density reduction due to knot detected in density according to:

$$g'_{dev}(GA_{ij}, k_{ij}) = g_{dev}(GA_{ij}) + (1 - g_{dev}(GA_{ij}))\ k_{ij}/T$$

wherein T is a constant threshold value density, and

c) applying the grain angle deviation modification function $g'_{dev}(GA_{ij},K_{ij})$ to clear wood equivalent density by multiplication

$$e'_{ij} = e_{ij} * g'_{dev}(GA_{ij}, k_{ij}).$$

[0025] The method may further include the step of estimating a moisture content effect function, m(MC), in the clear

wood density equivalent by computing m(MC) with a reference to 12% moisture content wherein
m(MC) = either A - B * MC for MC < MC_{sat}, or
m(MC) = m_{sat} for MC ≥ MC_{sat}
Where

$$B = (P - 1)/(0.12 - MC_{sat} - 0.12 * P)$$

$$A = 1 + 0.12 * B$$

$$m_{sat} = A - B * MC_{sat}$$

[0026] P is the ratio of a material property of interest when the wood piece is saturated with moisture to the same material property when the wood piece is oven-dray

$$P = S_{sat}/S_0$$

[0027] MC_{sat} is fiber saturation point moisture content within the percentage range 25 to 30%.

[0028] The method may further include the step of estimating a modulus of elasticity (MOE) profile of a section of the wood piece using estimation of modulus inertia computed from a clear wood density equivalent by:

(a)computing an inertia profile along a longitudinal axis of the wood piece according to:

$$I_i = \Delta x^3 \sum_{j=1}^{K} (c_i - j)^2 \cdot e_{ij}$$

wherein the longitudinal axis is in an x-axis direction, and wherein Δx is a pixel increment in the x-axis direction, and wherein center of gravity is computed according to:

$$c_i = \frac{\sum e_{ij} \cdot j}{\sum e_{ij}}$$

and wherein e_{ij} is clear wood equivalent density;
(b) computing MOE within a longitudinal window on the wood piece, wherein $MOE_k = f(I_i, k)$,
and wherein $f(I_i,k)$ is a function that estimates the MOE in location k, using the inertia profile I_i, whereby MOE_k provides an estimate of the MOE along the board main axis, to provide an MOE profile. The function $f(I_i,k)$ may be estimated using weights W_j according to:

$$f(I_i,k) = \sum_{j=1}^{M} W_j \cdot I_{k+i-M/2}$$

[0029] The function $f(I_i,k)$ may also be calculated as a close-form solution modulus of inertia profile according to:

$$E_{Est} = D\frac{1}{K}$$

wherein

$$K = \Delta x^2 \left(\sum_{N/2} \sum_{N/2} y_i - \frac{1}{2} \sum_N \sum_N y_i \right)$$

Δx is a discrete increment in the direction of the x axis,

$$y_i = \frac{w_i}{J_i}$$

w_i is discrete representation of w(x), and
J_i is I_i

[0030] The step of estimating modulus of elasticity from the MOE profile may use a low point or an average of the MOE profile.

[0031] The method may include the step of constructing clear wood density equivalent of a limited section of the wood piece, wherein the limited section is translated along the grain direction axis of the wood piece. The step of constructing clear wood density equivalent may include:

(a) computing minimum clear wood equivalent density profile in a window of the wood piece and running the window along the grain direction axis of the wood piece such that the window combines adjacent weak areas

$$e_j^{MIN} = Min_{i=0}^{i=W-1}(e_{ij})$$

wherein i is pixel index within window, i = 0 ... W-1, along the grain direction axis, wherein the grain direction axis is in the nominal grain direction of the wood piece
j is index perpendicular to the grain direction axis,
(b) computing weighted clear wood equivalent density for the entire section

$$e = \sum_{j=1}^{N} w_j \cdot e_j^{MIN}$$

wherein w_j is a cross-sectional weight which is greater at edges of the wood piece and reduced in the middle of the wood piece between the edges,
(c) computing tension strength (UTS) and bending strength (MOR) from e

$$UTS = f^{UTS}(e)$$

$$MOR = f^{MOR}(e)$$

[0032] Where f^{UTS} and f^{MOR} are empirical relationships between clear wood density and strength.

[0033] The strength functions f^{UTS} and f^{MOR} may be determined according to

$$\mathrm{UTS} = f^{UTS}(e) = \mathrm{A}\ \mathrm{e}^{\mathrm{p}}$$

and

$$\mathrm{MOR} = f^{MOR}(e) = \mathrm{B}\ \mathrm{e}^{\mathrm{r}}$$

wherein A, p, B, r are empirical constants.

[0034] The method may also include the further step of estimating bending and tension strength of at least a portion of the length of the wood piece by determining a minimum of a lengthwise strength profile of the wood piece.

[0035] The method may further include the step of refining the model by optimization of model parameters to minimize prediction error. For example, the model may be optimized for a particular wood species for particular commercial dimension lumber size.

[0036] In the method the step of collecting information relating to fiber quality may include the step of estimating fiber quality by measuring a vibration frequency of the wood piece, wherein the vibration frequency is a result of vibration induced only by feeding of the wood piece in an infeed feeding the wood piece, for example between a plurality of infeed rolls, to the sensors and without any explicit vibration-inducing impact means.

[0037] The method may further include the step of estimating bending and tension strength of the wood piece by measuring a vibration frequency of the wood piece wherein the vibration frequency is a result of vibration induced only by feeding of the wood piece in an infeed feeding the wood piece to the sensors and without any explicit vibration-inducing impact means.

[0038] At least two pairs of infeed rolls and two pairs of outfeed rolls, respectively upstream and downstream of the sensors, may be employed. A non-contact optical scanner may be employed to measure the vibration frequency, which may be measured by dividing the vibration signal into different sections corresponding to the support and constraint conditions of the wood piece on the infeed or the outfeed rolls. The support conditions may be unconstrained, semi-constrained, or fully-constrained.

[0039] In the method a parameter E may be calculated according to:

$$\mathrm{E} = \mathrm{K\ f2\ m/\ I}$$

wherein E is estimated MOE, K is a constant than contains the effect of the type of constraint, whether unconstrained, semi-constrained or fully constrained, as well as board span effect, I is a constant for a particular board cross-sectional size and m is distributed mass. m may be assumed constant, or measured, for example by a scanner using a radiation source.

[0040] In the method, the moisture content may be estimated using microwave measurement, or using microwave measurement and density estimation, and density characteristics may be measured by a scanner using a radiation source. The moisture content (mc) may be computed according to:

$$mc = K\,a^{n}$$

where K and n are empirical constants, and a is microwave amplitude. The microwave amplitude may be measured when an applied microwave radiation is polarized in a direction transverse to a longitudinal axis of the wood piece. The moisture content (mc) may also be computed according to:

$$mc = K\,a^{n}\,d^{m}$$

where K, m, and n are empirical constants,
a is microwave amplitude, and d is density, which may be measured by a scanner using a radiation source. Moisture content and microwave amplitude may be corrected for temperature.

[0041] The lumber value of the lumber may be maximized by cutting lumber or end trimming lumber based on estimated modulus of elasticity profile, wherein increased lumber value of the lumber is achieved by trimming off a part of the lumber board having a grade reducing property.

[0042] A computer program product which can be used in the method according to the present invention includes computer readable program code means for causing refining the physical prediction model of the workpiece by computer readable program code means for causing optimization of model parameters to minimize prediction error. Input variables in the property (strength or stiffness) physical prediction model include collected board data and model parameters. The Predicted Property = f*(Model Parameters, Board Data),* where, *Model Parameters =* (p_1, p_2, p_3,..., p_N,) and *Board Data* is the sensor information gathered about the wood piece as set out above. The error to be optimized is a measure of the difference between predicted property and observed property, for example absolute value of the difference, that is Error = AbsoluteValue (Predicted Property - Observed Property). The optimization of model parameters is achieved by minimizing combined error of a large sample of boards. For example, combined error for a sample of boards is a sum of the errors, as defined above, that is SumOfErrors = Sum(Error_i). Combined error could be quantified in various ways, including R-square, root-mean-squared error, etc. Optimization is implemented by varying values of *Model Parameters* so the combined measure of the error for a sample in minimized. Various optimization algorithms may be employed, for example genetic algorithm, random walk, direction set (Powell's) method, etc as would be known to one skilled in the art.

Brief Description of the Drawings

[0043] In the accompanying drawings, in which like reference characters designate the same or similar parts throughout the several views:

FIGURE 1 is a diagrammatic view of multiple sensors measuring attributes and properties of a board for physical modeling by a processor algorithm to predict strength and stiffness of the board as algorithm outputs.

FIGURE 1A illustrates board coordinates, showing the main axis (X) along the nominal grain angle direction.

FIGURE 1B illustrates a board divided into a 3-dimentional grid of discrete elements, showing index notation for different directions.

FIGURE 1C illustrates a board divided into a 2-dimentional grid of discrete elements, showing notation of clear wood equivalent elements e_{ij} and a section of length W taken from it to estimate strength assigned a location in the center of the section.

FIGURE 1D shows an example of a density and clear wood equivalent profile for a virtual detector (pixels of the same index j) along the board main axis X. The upper-most graph (with peaks pointing upwards) show actual density profile with its reference density profile below. The density peaks correspond to knots. The lower-most profile (with peaks pointing downwards) shows clear wood equivalent density.

FIGURE 1E shows an example of predicted tension and bending profiles along the board main axis X, showing the lowest point (minimum) computed from a moving section along the board main axis.

FIGURE 1F shows an example of moment of inertia profile with a section of a board used to compute modulus of elasticity (MOE) for a given location where prediction of modulus of elasticity (MOE) is computed using moment of inertia within a section of length s that moves along the board main axis.

FIGURE 1G illustrates loading conditions assumed for computation of predicted modulus of elasticity (MOE) using moment of inertia within a section of length s.

FIGURE 2A illustrates steps involved in clear wood density computing for a density cross-section showing original density d_{ij} and adaptive threshold a_{ij}.

FIGURE 2B illustrates steps involved in clear wood density computing for a density cross-section, showing clear wood equivalent density e_{ij}.

FIGURE 3 are linear and nonlinear models of a function reflecting effect of moisture content m (MC).

FIGURE 3A is a moisture content prediction model showing predicted vs. oven-dry moisture content for southern yellow pine (SYP).

FIGURE 4 illustrates a linear grading machine geometry, showing infeed wheel sets #1 and #2, outfeed wheel sets #1 and #2, and 3D-profile sensor.

FIGURE 5 illustrates board behavior as the board passes through the linear grading machine. Characteristic points A, B, C, and D define different sections in the linear profile sensor profile corresponding to different support conditions of the board, wherein:

a) in FIGURE 5A the board leading end is at point A
b) in FIGURE 5B the board leading end is at point B
c) in FIGURE 5C the board leading end is at point C
d) in FIGURE 5D the board leading end is at point D.

FIGURE 6 is continued board behavior as it passes through the linear grading machine having characteristic points E, F, and G and a board adjustment before and after the characteristic point F, wherein:

a) in FIGURE 6A the board trailing end is at point E
b) in FIGURE 6B the board trailing end is at point F
c) in FIGURE 6C the board trailing end has passed point F
d) in FIGURE 6D the board trailing end is at point G.

FIGURE 7 is 3D-profile sensor profile segmented into different sections using characteristic points of FIGURES 5A-D and 6A-D.

Detailed Description of Embodiments of the Invention

[0044] We have developed a machine to predict the strength and stiffness of wood based on a physical model using several sensing technologies. A physical model is an algorithm that relates the sensor information to the strength/stiffness of the material based on physical properties of the material and other characteristics, such as defects. The machine can integrate many sensing technologies into a single model and provides differing accuracy prediction based on the types and number of sensors used. In one embodiment, this technology builds on an X-ray based strength-grading machine, such as sold by Coe Newnes/McGehee ULC under the trademark XLG (X-ray Lumber Gauge).

[0045] The following physical aspects of wood effect strength and stiffness of wood directly: wane, moisture content, Modulus of Elasticity including whether measured flatwise or edgewise, growth ring thickness or density (rings/inch), grain angle deviation, density, knots (location, density, type and size), location in the tree from which the wood was cut, fiber quality, such as mirofibril angle, juvenile wood, biodeterioration, etc., reaction wood species, manufacturing and drying defects, such as sawcuts, checks, shake, etc. and, size of actual cross-section.

[0046] These wood aspects are measured or predicted with various sensing technologies and the data is used to predict the wood strength and stiffness. The reason to chose a physical model over other techniques such as a neural network, regression, or functional approximation model, is the stability and low training requirements. The model is based on the physical characteristics of the wood and how they affect the strength and stiffness directly rather than a statistical model. The sensor technologies added together improve the ability of any one sensor to predict strength and stiffness.

[0047] The object is to have the predicted wood characteristics match the observed characteristics. The sensor technologies that can be used include but are not limited to the following: density map, moisture content, slope of grain map, growth ring measurements, dynamic wood bending for stiffness measurement, dynamic oscillation to determine stiffness, wood fiber quality determination (color vision, gray scale, infra-red, etc), determination of species, profile measurement, location wood is cut from in the tree, and mechanical wane propagation measurement.

[0048] Combining some or all of these physical measurements, for example as combined according to the detailed methodology described below, leads to a better-predicted wood strength and stiffness accuracy.

[0049] With respect to the following description then, it is to be realized that the optimum relationship between the components and steps of the invention, to include variations in method, components, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

Clear Wood Equivalent

[0050] Clear wood equivalent (CWE) is used as an input to specific strength and stiffness models. Various prediction models may be used or developed based on this concept, such as prediction of ultimate tensile strength, modulus of rupture, etc. The CWE method approximates equivalent properties of a section of material in terms of density.

[0051] Wood, in a coordinate system such as seen in FIGURE 1A, is divided into a grid of virtual pixels (rectangular section) in the face plane or 3-dimensionally, as illustrated in FIGURE 1B. The size of the virtual pixels is configurable so as to be optimized. Initially a reference density from calibrated X-ray measurement is assigned to a pixel. Reference density is taken from density adaptive threshold. Following this, the initial density is modified by various wood characteristics, among which the most important is knot modification. The resulting density is equivalent to clear wood. In this context clear wood is defined as straight grained, defect-free, with a reference moisture content of 12%. FIGURE 1D shows an example of an actual density profile (ADP) along with its corresponding reference density profile (RDP) and corresponding clear wood equivalent (CWE) density profile along the main axis X. The equivalent to clear wood is then used directly for strength and stiffness using various algorithms, known relationships; etc.

[0052] Some of the following steps may be in used in clear wood equivalent density approximating of a virtual pixel:

a) Start with reference density (adaptive threshold) at a virtual pixel.
b) modify initial density for knots by considering presence of a knot in a location if the difference between the reference and actual density of the knot is non-zero.
c) segment into regions so that a region contains a knot, use the segmented regions to recognize the knots region or regions.

[0053] Different modification functions are used for the following knot types: sound through knot, sound edge knot, sound intermediate knot, loose through knot, loose edge knot, loose intermediate knot.

[0054] Knot modification uses a concept of replacing a knot by its equivalent in terms of fiber strength or stiffness. This involves virtually removing the knot, computing remaining clear fiber volume, computing volume of the removed knot and adding the strength/stiffness equivalent of the knot to clear fibers. For every pixel density, d_{ij}, clear wood equivalent, e_{ij}, is computed using adaptive threshold a_{ij} (see Figures 2a and 2b)

$$e_{ij} = \mathrm{RemainClearWood} + \mathrm{KnotEquivalent} \qquad (1)$$

[0055] Where,

$$\mathrm{RemainClearWood} = a_{ij} - k_{ij} * K \qquad (2)$$

i is virtual pixel index along wood length (virtual line index)
j is virtual pixel index across wood length (virtual detector index)
K is knot density ratio, defined as a ratio of Clear Wood Density to Knot Density and knot density is

$$k_{ij} = d_{ij} - a_{ij} \qquad (3)$$

KnotEquivalent is defined as clear wood density equivalent residing in knot volume,

$$\mathrm{KnotEquivalent} = k_{ij} * K * M \qquad (4)$$

[0056] Where M is property (stiffness or strength) knot ratio

$$M = \mathrm{Knot\ Property} / \mathrm{Clear\ Wood\ Property} \qquad (5)$$

[0057] The above relationships may be simplified to

$$e_{ij} = a_{ij} + k_{ij} *K*(M\text{-}1) \qquad (6)$$

or

$$e_{ij} = a_{ij} + (d_{ij} - a_{ij})*K*(M\text{-}1) \qquad (7)$$

Grain Angle Modification

[0058] Grain angle is measured or estimated using one or more of the following techniques: microwave, optical, tracheid effect on face plane, 2D angle, tracheid effect on face plane and edges, 3D angle, growth ring pattern analysis with vision images (color or gray-scaled images), tracheid effect and growth ring pattern analysis with vision images. This algorithm accounts for the presence of a knot and grain deviation in the same location. Grain angle is decomposed into two components: local average, and, local deviation.

[0059] Grain angle (GA) effect function for both average and the deviation, g(GA), reflects the relationship of grain angle vs. strength (or stiffness). This is derived from Hankinson's formula (Bodic 1982),

$$g(GA) = \frac{1}{R \cdot \sin^n(GA) + \cos^m(GA)} \tag{8}$$

where n, m, are empirical constants, initially n = m = 2, (optimized).
R is the ratio between the property of interest (strength or stiffness) parallel to perpendicular to the grain.

[0060] Constants R, n, and m are to be optimized, with a restriction that the g(GA=0) = 1 and 1 ≥ g(GA) > 0 for any GA. Modification function g(GA) is applied to CWE density by multiplication of

$$e'_{ij} = e_{ij} * g(GA_{ij}) \tag{9}$$

[0061] In case of grain deviation, g(GA) is further modified to account for a knot in the same location to eliminate a multiple CWE density reduction

$$g_{dev}(GA_{ij}, k_{ij}) = g(GA_{ij}) + (1 - g(GA_{ij}))\ k_{ij}/T \tag{10}$$

[0062] Where, T is a threshold value in terms of density.

[0063] Important to the property of this relationship is if k_{ij} = T, then grain deviation modification has no effect:

$$g_{dev}(GA_{ij}, k_{ij} = T) = 1 \tag{11}$$

[0064] Both local average and local deviation are applied independently to CWE density.

Moisture content modification

[0065] The moisture content effect function, m(MC), reflects the known effect of moisture content on strength or stiffness. This relationship is modeled as a linear (downward) for MC < MC_{sat} =~ 25%, and constant, m(MC) = m_{sat}, for MC >= MC_{sat}. Ratio m(MC_{sat})/m(0) corresponds to the ratio between a property (MOE, MOR, UTS) at saturation to oven dry, P = S_{sat}/S_o. Based on literature, this ration is about 0.5 for UTS and MOR and 0.7 for MOE. Since the basis for our computations is property at MC = 12% then m(12%) = 1.0.

[0066] Therefore the requirements for the m(MC) are:

a. MC effect function is linear with a negative slope in the MC range from zero to saturation, and constant afterwards,

$$m(MC) = \begin{cases} A - B * MC & \text{for} \quad MC < MC_{sat} \\ m_{sat} & \text{for} \quad MC \geq MC_{sat} \end{cases} \qquad (12)$$

b. Property ratio

$$P = \frac{S_{Sat}}{S_0} = \frac{m(0)}{m_{Sat}} \qquad (13)$$

[0067] Initially,

$$P = 0.5 \text{ for MOR and UTS (strength)} \qquad (14)$$

$$P = 0.7 \text{ for MOE (stiffness)}$$

c. MC effect function is unity at nominal moisture content of 12%

$$m(12\%) = 1.0 \qquad (14a)$$

[0068] Solution for m(MC), linear model

[0069] Solving equations (12) to (15), gives

$$B = (P - 1)/(0.12 - MC_{sat} - 0.12*P) \qquad (15)$$

and

$$A = 1 + 0.12 * B \qquad (15a)$$

[0070] For example, for P = 0.5 and MC_{sat} = 0.25,
A = 1.3158
B = 2.632
$m(MC_{sat})$ = 0.6579

[0071] FIGURE 3 shows the linear model using the above constants and two nonlinear models:

$$m(MC) = 0.65 + 0.3 * e^{-12*MC} \qquad (16)$$

$$m(MC) = 0.65 + 9.29^{-5.45*MC} \qquad (17)$$

Pith modification

[0072]

$$e'_{ij} = e_{ij} * p(\text{amount of pith present}) \qquad (18)$$

[0073] Where p() represents effect of pith on strength and stiffness.

Growth ring thickness modification. Predicted based on X-ray and Vision

[0074]

$$e'_{ij} = e_{ij} * g(\text{growth ring thickness}) \qquad (19)$$

[0075] Where g () represents effect of growth ring thickness on strength and thickness

Place within tree modification.

[0076] Place within tree quality parameter is predicted based various scanning technologies

$$e'_{ij} = e_{ij} * t(\text{place within tree modification quality parameter}) \qquad (20)$$

[0077] Where t() is a function representing effect of position within tree.

Other wood characteristics modification, rot, wane, check, resin content, compression wood, etc.

[0078] This set of modifications follow similarly to the modification analogues set out above for grain angle, moisture content, etc.

3D Clear Wood Equivalent

[0079] This approach expands the two-dimensional CWE model as described above to three-dimensions (3D). Virtual pixels are defined in 3D. Knots, checks, and other defect modifications are done based on 3D-defect detection. Other multiple sided defects such as checks are also included. This includes two approaches:

a) Density collected in 2D, knots, checks modifications entered as 3D, resulting with 3D grid of clear wood equivalent density
b) Density collected in 3D with a CT scanner, knots, checks, and other 3D-defect modifications entered as 3D objects, resulting with 3D grid of clear wood equivalent density.

Clear Wood Equivalent Based on Grain Angle

[0080] This approach follows the one of CWE density described to this point, but the density is replaced with grain angle. First a grain angle is assigned to a grid element. Then the GA is modified by density, knots, moisture content, and other defects. Grain angle CWE is then used in actual models to predict strength and stiffness. This refers primary to lumber grading, but is not limited to this type of products.

Stiffness Prediction Using Moment of Inertia

[0081] Stiffness (Modulus of Elasticity) is predicted based on approximated cross sectional moment of inertia J_i computed from clear wood equivalent model.
[0082] In general, moment of inertia I is defined in x direction for any cross-section with an area A (Popov 1968)

$$I = \int_A (c - x)^2 dA \qquad (21)$$

[0083] Where c is center of gravity of the cross-section A.

[0084] In our case, I is approximated by J_i in terms of density, reflecting both geometry of the cross-section as well as local stiffness

$$J_i = \Delta x^3 \sum_{j=1}^{N} (c_i - j)^2 \cdot e_{ij} \qquad (22)$$

[0085] Where Δx represents pixel increment in x-axis direction and center of gravity is given as

$$c_i = \frac{\sum e_{ij} \cdot j}{\sum e_{ij}} \qquad (23)$$

[0086] To increase processing speed, c_i does not have to be computed for every cross-section, but assumed to be equal to nominal center of the cross-section.

[0087] Two different approaches are given here to compute MOE from the J_i profile. In both cases MOE is computed on a section of J_i profile. The section is then moved along the board main axis X and MOE computed for another section of the board, as illustrated in FIGURE 1F. This procedure yields a MOE profile along the main axis X.

[0088] First, a simple solution is given where MOE is simply weighted average of the J_i

$$MOE = \sum_{i=1}^{M} W_j \cdot J_j \qquad (24)$$

[0089] Where W_j is optimized windowing (sectioning) function.

[0090] Although, the equation (24) provides a simply and fast way of MOE prediction, a more sound but slower approach is to derive MOE directly from moment of inertia I. Following derivation follows well-known theory of mechanical behavior of solids (Popov 1968).

[0091] Moment of inertia is assumed to be a variable quantity within a span s, as shown in FIGURE 1F. For a board section loaded with force F, as in FIGURE 1G, equations for moments are

$$M(x) = Fw(x) \qquad (24a)$$

Where

$$w(x) = \frac{x}{2} \qquad \text{for } 0 < x \le s/3 \qquad (24b)$$

$$w(x) = \frac{s}{6} \qquad \text{for } s/3 < x \le s2/3 \qquad (24c)$$

$$w(x)=\frac{1}{2}(s-x) \qquad \text{for } s2/3 < x \le s \tag{24d}$$

[0092] The basic equation for beam deflection is

$$\frac{M(x)}{E(x)I(x)}=\frac{dV^2(x)}{dx^2} \tag{24e}$$

[0093] Where E(x) represent MOE in location x,
I(x) moment of inertia profile,
V(x) deflection profile.

[0094] A further simplification combines E and I into one quantity J(x), which reflect a local stiffness of the cross-section.

$$J(x) = E(x)\, I(x) \tag{24f}$$

[0095] The equation (24e) simplifies into

$$\frac{M(x)}{J(x)}=\frac{dV^2(x)}{dx^2} \tag{24g}$$

[0096] Following, the equation (24g) is solved for deflection V_{max} at x = s/2 using direct integration method, applying boundary conditions, and converting to discrete format gives

$$K=\frac{V_{\max}}{F}=\Delta x^2\left(\sum_{N/2}\sum_{N/2} y_i-\frac{1}{2}\sum_{N}\sum_{N} y_i\right) \tag{24h}$$

[0097] Where Δx in a discrete increment in direction of the X axis,

$$y_i=\frac{w_i}{J_i} \tag{24i}$$

w_i is discrete representation of w(x),

[0098] J_i is discrete representation of J(x), the moment of inertia estimation computed from clear wood equivalent density.

[0099] On the other hand, for a uniform beam with loading conditions as in FIGURE 1g, the solution for E is

$$E=\frac{23Fs^3}{1296IV_{\max}} \tag{24j}$$

or for the same cross-section and span (24j) simplifies to

$$E = D\frac{F}{V_{\max}} \tag{24k}$$

[0100] Where D is a constant representing a size of a board cross-section.

[0101] Therefore a quantity to estimate is $\frac{F}{V_{\max}}$ only.

[0102] This, compared with the solution (24h), yields final MOE estimation E_{est}

$$E_{Est} = D\frac{1}{K}$$

Strength Prediction

[0103] Strength is predicted lengthwise for a section (window) along nominal main board axis X (nominal grain direction). Therefore a particular predicted strength is assigned to a center of a window lengthwise, as shown in FIGURE 1E. These sections may overlap resulting with a complete strength profile for a wood product, such as lumber. Window length correspond to approximate size of typical wood fracture and generally increases with lumber width size (greater width size, greater the window). The final strength value assigned to a tested product is minimum strength within the strength profile.

[0104] Strength is computed on the basis of a running window along wood main axis (length), as illustrated in FIGURE 1C, involving following steps:

a) get minimum CWE within a longitudinal slice, e_j^{MIN} where the slice consists of virtual pixels in the same width position

$$e_j^{MIN} = Min_{i=0}^{i=W-1}(e_{ij}) \tag{25}$$

Where i is pixel index within window, i = 0... W-1
and W is window size in virtual lines
b) compute overall CWE density for the window as a weighted sum

$$e = \sum_{j=1}^{K} w_j \cdot e_j^{MIN} \tag{26}$$

[0105] Where w_j is cross-sectional weight, greater at wood edges and less in the middle. The weight function is different for UTS and MOR and in general subject to model optimization.

c) computes trength from CWE density tension strength (UTS) relationship

$$UTS = f^{UTS}(e) \tag{27}$$

[0106] And bending strength (MOR)

$$MOR = f^{MOR}(e) \tag{28}$$

where f^{UTS} and f^{MOR} are optimized relationships between CWE and UTS and MOR.

[0107] The density to tension and bending strength functions are based on experimental data conducted on clear wood specimens and/or are in general the subject of model optimization.

[0108] In particular, the following model may be used

$$\mathrm{UTS} = \mathrm{A}\ \mathrm{e}^{\mathrm{p}} = f^{UTS}(e) \tag{29}$$

and

$$\mathrm{UTS} = \mathrm{B}\ \mathrm{e}^{\mathrm{r}} = f^{UTS}(e) \tag{30}$$

where A, p, B, r are empirical (optimized) constants.

d) Final wood strength is a minimum of all windows strength values

MC modeling based on Microwave and X-ray density measurement

[0109] Moisture content is predicted based on microwave and/or X-ray density, for:

(a) Microwave amplitude, and in particular: amplitude when microwave is polarized in transverse direction, amplitude when microwave is polarized in longitudinal direction, in form

$$mc = K\, a^{n}, \tag{31}$$

where K and n are empirical constants, and a is microwave amplitude.

(b) Microwave amplitude and X-ray density, and in particular, amplitude when microwave is polarized in transverse direction and X-ray density, amplitude when microwave is polarized in longitudinal direction and X-ray density, in form:

$$mc = K\, a^{n}\, d^{m} \tag{32}$$

where K, m, and n are empirical constants, a is microwave amplitude, and d is X-ray density.

Model Optimization

[0110] Most models described here require optimization of the parameters (constants). Initial values for these parameters are taken from literature, using known relationships or from empirical data. Fine-tuning of these values for a specific species/size involves parameter optimization for maximum correlation with actual strength or stiffness, minimum prediction error, etc.

[0111] Any method for multidimensional function optimization may be used, including genetic algorithms, random walk, and similar techniques, Powell's methods, and Gradient methods.

[0112] Models may be optimized for:

a) All sizes and species,
b) Same sizes of the same species or species group, and
c) Particular size and species.

Stiffness Estimation from Machine Induced Wood Vibration

[0113] Vibration of a wood piece as it passes through a grading machine 10 is used to estimate stiffness (MOE). Vibration profile may be collected with a laser/camera scanner, here referred to as a 3D sensor. Vibration is induced by machine feeding mechanics.

Machine Geometry and Wood Dynamics

[0114] As wood behavior is linked with machine geometry and its position, the 3D-profile is segmented into different sections limited with characteristic points.

[0115] A simplified grading machine geometry is show in FIGURE 4. Wheel sets 11, 12, 13, and 14 follow the direction of the lumber flow X'.

[0116] Wood piece 15 enters the machine from right to left, passing through wheel sets 11 and 12 and into the field of view of 3D 15 sensor as shown in Figures 4 and 5A-D. First collected profile point is at characteristic point A in the field of view of sensor 15. From point A until the wood meets in feed guide 13a (characteristic point B), the leading end of the wood piece is fully unconstrained or free. This defines a first 3D profile section, AB. Following on downstream in direction X ' as seen in Figures 6a-6d, more characteristic points are defined as follows, where, at point:

C the leading end of wood 15 meets wheel set 13
D the leading end of wood 15 meets wheel set 14
E the trailing end of wood 15 leaves wheel set 11
F the trailing end of wood 15 leaves wheel set 12
G the trailing end of wood 15 leaves 3D sensor 16 and sections,
AC unconstrained
CD semi-constrained
DE fully-constrained
EF semi-constrained
FG unconstrained.

[0117] From Figures 5a-5d and 6a-6d, it may be noted that only sections AB (or AC) and FG is statically undistorted by the machine. Because of unconstrained conditions, a free vibration takes place in these sections.

[0118] For the *"S-shaped"* wood in Figures 6A-D, one could expect a wood behavior, resulting with the following 3D profile:

a. In section AC (or AB) unconstrained, Z is less than the reference (base) line X", and free vibrations with large amplitude take place. The frequency of vibration decreases because of increasing span.

b. As the wood passed through characteristic point B or C, it is adjusted up, resulting with Z values greater than reference in semi-constrained section CD. Vibration amplitude in this section is somewhat reduced and higher in frequncy than in section AB.

c. In fully-constrained section DE, wood behavior is somewhat undefined. However because of the constrained condition, reduced amplitude and increased frequency is expected.

3D Profile Sections

[0119] The scenario of wood behavior and a resulting 3D profile is put to the test by segmenting the profile into sections using characteristic points and comparing the expectations with the actual wood shape. Figure 7 shows the 3D profile of FIGURE 5A-D and 6A-D with characteristic points and trend lines for every section. The characteristic points were defined based on machine geometry. For example, the distance between point A and C correspond to the distance between 3D sensor 16 and center of the wheel set 13. Points A, B, C, and D were measured in reference to the start of 3D-profile sensor profile whereas points G, F, and E were measured in reference to the end of the 3D-profile.

[0120] Visual examination of the segmented profile in Figure 7 confirms presence of distinct sections in the signal. Expected frequency and amplitude of unconstrained sections AB and FG, adjustments as points B, (or C), and F, and relatively leveled fully constrained section DE are confirmed.

Free Vibration of the Wood

[0121] Assuming a uniform cantilevered beam model, the lowest mode of vibration will have frequency

$$f = 2Pi\ (1.875)^2\ (EI/ma^4)^{1/2} \qquad (38)$$

Where
Pi=3.14
E is elastic modulus
a is the span
I wood cross-sectional moment of inertia
m is distributed mass.

[0122] Frequency therefore is strongly affected by the span, as f is proportional to $1/a^2$. Because span changes as the wood passes through the machine, the vibration frequency decreases in the start section (AB) and increases in end section (FG). This explains 3D signals at the wood start and the end shown in Figures 5A-D. This equation may be used for stiffness extraction.

[0123] Frequency for the semi-constrained and full-constrained conditions will have a more complex solution. However, the general relationship to E, I, and m, is similar, and sufficient to construct E (MOE) prediction model in general form.

$$E = K\, f^2\, m/\, I \qquad (39)$$

where K is a constant than contains effect of type of constraint as well as span a effect. I is constant for a particular lumber size and m could be also assumed constant or measured, with X-ray for example.

Claims

1. A method of predicting strength and stiffness of a wood piece, the method comprising:

a) Measuring the wood piece with a multiplicity of sensors, each of said sensors outputting measurement data;
b) Estimating, based on said measurement data, a characteristic including one or more of the following: clear wood density, grain angle, moisture content, growth ring angle, location in the tree from which the wood was cut, size of actual cross-section, species, and three dimensional geometry, wherein said estimating further includes estimating a fiber quality, the fiber quality being at least one of microfibril angle, juvenile wood, biodeterioration, and reaction wood;
c) Detecting a size, location and classification of a wood defect including one or more of the following: knots, biodeterioration, reaction wood, juvenile wood, manufacturing and drying defects, pith, pitch and wet pockets, wherein said manufacturing and drying defects comprise at least one of sawcuts, checks, and shake;
d) Subsequently inputting information from said measuring, estimating and detecting steps into a physical model of the wood piece;
e) **Characterized in that** said physical model of wood piece is constructed based on clear wood equivalent (CWE) by approximating equivalent properties of a section of the wood piece divided into a grid of virtual pixels, measuring and assigning a reference density or grain angle to each pixel and modifying the reference density or grain angle of each pixel for defects including one or more of the following: knots, biodeterioration, reaction wood, juvenile wood, manufacturing and drying defects, pith, pitch and wet pockets; and
f) Predicting strength and stiffness of the wood piece based on the effect of said estimated information from said step of estimating said characteristic and said detected information from said step of detecting a defect on mechanical behavior of the wood piece.

2. The method of claim 1 wherein said measuring comprises measuring material characteristics of the wood piece including one or more of the following: growth ring thickness; grain angle deviation; clear wood density; knot location; knot density; knot type; knot size; location in the tree from which the wood piece was cut.

3. The method of claim 1 further including calculating a clear wood density equivalent, said calculating comprising:

a) Measuring material density in a plurality of dimensions;
b) Estimating the characteristic and the fiber quality;
c) Reducing clear wood equivalent density by the effect of the characteristic and the fiber quality on mechanical behavior of wood;
d) Detecting size, location and classification of the defect; and
e) Further reducing clear wood equivalent density by the effect of the defect on mechanical behavior of wood.

4. The method of claim 1 further including calculating a clear zero grain angle wood equivalent, the calculating comprising

a) Measuring of grain angle in a plurality of dimensions;
b) Constructing clear wood zero grain angle equivalent by assigning a nominal density value which is an average for a wood species whenever grain angle relative to a longitudinal axis of the piece is zero, and less wherever the grain angle deviates from zero and accordingly to grain angle effect on mechanical behavior of the wood piece;
c) Reducing clear wood equivalent density by the effect of the characteristic using theoretical and empirical relationships of the characteristic on mechanical behavior of wood; and
d) Further reducing clear wood equivalent density by the effect of wood defects in their respective locations of occurrence and the effect on mechanical behavior of the wood piece.

5. The method of claim 3 or 4 further comprising dividing the wood piece into a grid of virtual pixels, virtually removing density occupied by a knot, and replacing said virtually removed density by a density of clear wood mechanically equivalent to the removed knot.

6. The method of claim 3 wherein said calculating a clear wood density equivalent is applied to a limited section of the wood piece, and wherein the limited section is translated along the grain direction axis of the wood piece.

7. The method of claim 1 further including estimating bending and tension strength of at least a portion of the length of the wood piece by determining a minimum of a lengthwise strength profile of the wood piece.

8. The method of claim 1 wherein said collecting information relating to fiber quality includes measuring a vibration frequency of the wood piece, wherein said vibration frequency is a result of vibration induced only by feeding of the wood piece in an infeed feeding the wood piece to the sensors and without any explicit vibration-inducing impact means.

9. The method of claim 7 further comprising estimating bending and tension strength of the wood piece by measuring a vibration frequency of the wood piece wherein said vibration frequency is a result of vibration induced only by feeding of the wood piece in an infeed feeding the wood piece to the sensors and without any explicit vibration-inducing impact means.

10. The method of claim 9 further comprising measuring said vibration signal by dividing the vibration signal into different sections corresponding to the support and constraint conditions of the wood piece on the infeed or the outfeed rolls.

11. The method of claim 2 wherein said material characteristics comprise at least one of clear wood density or knot density, and wherein said at least one is measured by a scanner using a radiation source.

12. The method of claim 1 wherein said moisture content is estimated using microwave measurement.

13. The method of claim 12 wherein said microwave measurement is measured when an applied microwave radiation is polarized in a direction transverse to a longitudinal axis of the wood piece.

14. The method of claim 12 wherein microwave measurement is corrected for temperature.

15. The method of claim 1 wherein said moisture content is estimated using X-ray measurement.

16. The method of claim 1 wherein said predicting of stiffness of the wood piece is based on Moment of Inertia.

17. The method of claim 5 further including creating a three-dimensional (3D) wood equivalent model by dividing said grid of virtual pixels in three dimensions.

18. The method of claim 1 wherein said physical model is optimized by fine-tuning the initial values of the parameters for maximum correlation with actual strength or stiffness.

Patentansprüche

1. Verfahren zum Vorhersagen der Festigkeit und Steifigkeit eines Holzstückes, wobei das Verfahren:

a) das Messen des Holzstücks mit einer Vielzahl von Sensoren, wobei jeder der Sensoren Messdaten ausgibt;
b) das Bewerten, basierend auf den Messdaten, eines Merkmals, welches eines oder mehrere der folgenden umfasst: reine Holzdichte, Maserungswinkel, Feuchtigkeitsgehalt, Jahresringwinkel, Stelle im Baum, aus der das Holz geschnitten wurde, Größe des tatsächlichen Querschnittes, Art und dreidimensionale Geometrie, wobei die Bewertung ferner die Bewertung einer Faserqualität umfasst, wobei die Faserqualität mindestens eine von Mikrofibrillenwinkel, Jungholz, Biodeterioration und Reaktionsholz ist;
c) das Ermitteln der Größe, Lage und Klassifikation eines Holzfehlers, der einen oder mehrere der folgenden umfasst: Astknoten, Biodeterioration, Reaktionsholz, Jungholz, Herstellungs- und Trocknungsfehler, Mark-, Harz- und Feuchtigkeitseinschlüsse, wobei die Herstellungs- und Trocknungsfehler zumindest einen von Sägeschnitten, Spalten und Rissen umfassen;
d) das anschließende Eingeben von Informationen aus dem Mess-, Bewertungs- und Ermittlungsschritt in ein physikalisches Modell des Holzstücks;
e) **dadurch gekennzeichnet, dass** das physikalische Modell des Holzstücks basierend auf dem reinen Holzäquivalent (CWE) durch Nähern äquivalenter Eigenschaften eines Abschnittes des Holzstückes, unterteilt in ein Gitter aus virtuellen Pixeln, Messen und Zuordnen einer Referenzdichte oder eines Maserungswinkels zu jedem Pixel und Modifizieren der Referenzdichte oder des Maserungswinkels jedes Pixels in Bezug auf Fehler, die einen oder mehrere der folgenden umfassen: Astknoten, Biodeterioration, Reaktionsholz, Jungholz, Herstellungs- und Trocknungsfehler, Mark-, Harz- und Feuchtigkeitseinschlüsse, konstruiert wurde; und
f) das Vorhersagen der Festigkeit und Steifigkeit des Holzstückes basierend auf der Auswirkung der bewerteten Information aus dem Schritt der Bewertung des Merkmals und der ermittelten Information aus dem Schritt der Ermittlung eines Fehlers auf das mechanische Verhalten des Holzstückes
umfasst.

2. Verfahren nach Anspruch 1, wobei das Messen das Messen der Materialmerkmale des Holzstückes umfasst, welche eines oder mehrere der folgenden umfassen: Jahresringdicke; Maserungswinkelabweichung; reine Holzdichte; Astknotenstelle; Astknotendichte; Astknotenart; Astknotengröße; Stelle im Baum, aus der das Holzstück geschnitten wurde.

3. Verfahren nach Anspruch 1, das ferner das Berechnen eines reinen Holzdichteäquivalents umfasst, wobei das Berechnen:

a) das Messen der Materialdichte in einer Vielzahl von Dimensionen;
b) das Bewerten des Merkmals und der Faserqualität;
c) das Verringern der reinen Holzäquivalentdichte um die Auswirkung des Merkmals und der Faserqualität auf das mechanische Verhalten des Holzes;
d) das Ermitteln der Größe, Lage und Klassifikation des Fehlers und
e) das weitere Verringern der reinen Holzäquivalentdichte um die Auswirkung des Fehlers auf das mechanische Verhalten des Holzes

umfasst.

4. Verfahren nach Anspruch 1, ferner umfassend das Berechnen eines reinen Null-Maserungswinkel-Holzäquivalents, wobei das Berechnen

a) das Messen des Maserungswinkels in einer Vielzahl von Dimensionen;
b) das Konstruieren eines reinen Null-Maserungswinkel-Holzäquivalents durch Zuordnen eines nominalen Dichtewertes, der ein Durchschnitt für eine Holzart ist, wenn ein Maserungswinkel bezogen auf eine Längsachse

des Stückes null ist, und weniger, wo der Maserungswinkel von null abweicht, und folglich der Auswirkung des Maserungswinkels auf das mechanische Verhalten des Holzstückes;
c) das Verringern der reinen Holzäquivalentdichte um die Auswirkung des Merkmals unter Verwendung theoretischer und empirischer Beziehungen des Merkmals auf das mechanische Verhalten des Holzes und
d) das weitere Verringerung der reinen Holzäquivalentdichte um die Auswirkung der Holzfehler in ihren jeweiligen Stellen des Auftretens und die Auswirkung auf das mechanische Verhalten des Holzstückes.

5. Verfahren nach Anspruch 3 oder 4, ferner umfassend das Unterteilen des Holzstückes in ein Gitter aus virtuellen Pixeln, das virtuelle Entfernen der von einem Astknoten eingenommenen Dichte und das Ersetzen der virtuell entfernten Dichte durch eine Dichte reinen Holzes, die mechanisch zu dem entfernten Astknoten äquivalent ist.

6. Verfahren nach Anspruch 3, wobei das Berechnen eines reinen Holzdichteäquivalents auf einen begrenzten Abschnitt des Holzstückes angewendet wird und wobei der begrenzte Abschnitt entlang der Achse der Maserungsrichtung des Holzstückes überführt wird.

7. Verfahren nach Anspruch 1, ferner umfassend das Bewerten der Biege- und Zugfestigkeit von zumindest einem Teil der Länge des Holzstückes durch Bestimmen eines Minimums eines Längenfestigkeitsprofils des Holzstückes.

8. Verfahren nach Anspruch 1, wobei das Sammeln von Informationen in Bezug auf die Faserqualität das Messen einer Schwingungsfrequenz des Holzstückes umfasst, wobei die Schwingungsfrequenz das Ergebnis einer Schwingung ist, die nur durch das Zuführen des Holzstückes einer Zuführung, die das Holzstück den Sensoren zuführt, und ohne irgendwelche expliziten Vibration auslösenden Stoßvorrichtungen ausgelöst wird.

9. Verfahren nach Anspruch 7, ferner umfassend das Bewerten der Biege- und Zugfestigkeit des Holzstückes durch Messen einer Schwingungsfrequenz des Holzstückes, wobei die Schwingungsfrequenz das Ergebnis einer Schwingung ist, die nur durch das Zuführen des Holzstückes einer Zuführung, die das Holzstück den Sensoren zuführt, und ohne irgendwelche expliziten Vibration auslösenden Stoßvorrichtungen ausgelöst wird.

10. Verfahren nach Anspruch 9, ferner umfassend das Messen des Schwingungssignals durch Unterteilen des Schwingungssignals in verschiedene Abschnitte, entsprechend den Auflager- und Zwanglaufbedingungen des Holzstückes auf den Einzugs- oder Auslaufwalzen.

11. Verfahren nach Anspruch 2, wobei die Materialmerkmale mindestens eines von reiner Holzdichte oder Astknotendichte umfassen und wobei mindestens eines durch einen Scanner unter Verwendung einer Strahlungsquelle gemessen wird.

12. Verfahren nach Anspruch 1, wobei der Feuchtigkeitsgehalt unter Verwendung von Mikrowellenmessung bewertet wird.

13. Verfahren nach Anspruch 12, wobei die Mikrowellenmessung gemessen wird, wenn eine angewandte Mikrowellenstrahlung quer zur Längsachse des Holzstückes polarisiert wird.

14. Verfahren nach Anspruch 12, wobei die Mikrowellenmessung in Bezug auf die Temperatur korrigiert wird.

15. Verfahren nach Anspruch 1, wobei der Feuchtigkeitsgehalt unter Verwendung von Röntgenstrahlenmessung bewertet wird.

16. Verfahren nach Anspruch 1, wobei die Vorhersage der Steifigkeit des Holzstückes auf dem Trägheitsmoment basiert.

17. Verfahren nach Anspruch 5, ferner umfassend das Erzeugen eines dreidimensionalen (3D) Holzäquivalentmodells durch Unterteilen des Gitters aus virtuellen Pixeln in drei Dimensionen.

18. Verfahren nach Anspruch 1, wobei das physikalische Modell durch Feinabstimmung der Ausgangswerte der Parameter für die maximale Korrelation mit der tatsächlichen Festigkeit oder Steifigkeit optimiert wird.

Revendications

1. Méthode de prévision de la solidité et de la rigidité d'une pièce en bois, ladite méthode comprenant :

    a) la mesure de la pièce en bois avec une multiplicité de capteurs, chacun desdits capteurs produisant des données de mesure;
    b) l'estimation, basée sur lesdites données de mesure, d'une caractéristique comprenant un ou plusieurs des éléments suivants: densité du bois net de défauts, angle de grain, teneur en humidité, angle des anneaux de croissance, emplacement dans l'arbre duquel le bois a été coupé, taille de la coupe transversale réelle, espèces et géométrie tridimensionnelle, dans laquelle ladite estimation inclut de plus une estimation de la qualité des fibres, ladite qualité des fibres étant relative à au moins un des éléments suivants : angles des microfibrilles, bois juvénile, biodétérioration et bois de réaction ;
    c) la détection de la taille, de l'emplacement et de la classification d'un défaut du bois, comprenant un ou plusieurs des éléments suivants: noeuds, biodétérioration, bois de réaction, bois juvénile, défauts de fabrication et de séchage, moelle, poches de résine et poches humides, dans lesquels lesdits défauts de fabrication et de séchage comprennent au moins un des éléments suivants : coupes de scie, gerces et fentes ;
    d) l'entrée ultérieure des informations provenant desdites étapes de mesure, d'estimation et de détection dans un modèle physique de la pièce en bois;
    e) **caractérisé en ce que** ledit modèle physique de pièce en bois est basé sur l'équivalent de bois net de défauts (CWE) en approximant les propriétés équivalentes d'une section de la pièce en bois divisée en une grille de pixels virtuels, mesurant et attribuant une densité ou un angle de grain de référence à chaque pixel et en modifiant la densité ou l'angle de grain de référence pour chaque pixel pour les défauts comprenant un ou plusieurs des éléments suivants : noeuds, biodétérioration, bois de réaction, bois juvénile, défauts de fabrication et de séchage, moelle, poches de résine et poches humides, dans lesquels lesdits défauts de fabrication et de séchage comprennent au moins un des éléments suivants : coupes de scie, gerces et fentes ; et
    f) la prédiction de la solidité et de la rigidité de la pièce en bois, basée sur l'effet de ladite information estimée provenant de ladite étape d'estimation et sur l'information détectée provenant de ladite étape de détection de défaut de comportement mécanique de la pièce en bois.

2. Méthode selon la revendication 1, dans laquelle ladite mesure comprend la mesure des caractéristiques matérielles de la pièce en bois incluant un des éléments suivants : épaisseur des anneaux de croissance, déviation de l'angle de grain, densité du bois net de défaut, emplacement des noeud, densité des noeuds, type de noeud, taille de noeud, emplacement dans l'arbre duquel le bois a été coupé.

3. Méthode selon la revendication 1 comprenant de plus le calcul d'un équivalent de densité de bois net de défauts, ledit calcul comprenant :

    a) la mesure de la densité du matériau dans une pluralité de dimensions ;
    b) l'estimation de la caractéristique et de la qualité des fibres ;
    c) la réduction de la densité de l'équivalent de bois net de défauts par l'effet de la caractéristique et de la qualité des fibres ;
    d) la détection de la taille, de l'emplacement, de la classification du défaut ; et
    e) la réduction supplémentaire de la densité de l'équivalent de bois net de défauts par l'effet du défaut de comportement mécanique du bois.

4. Méthode selon la revendication 1 comprenant de plus le calcul d'un équivalent de bois à angle de grain nul, ledit calcul comprenant :

    a) la mesure de l'angle de grain dans une pluralité de dimensions ;
    b) la construction d'un équivalent d'angle de grain nul de bois net de défaut en attribuant une valeur de densité nominale, qui est la moyenne pour une essence de bois, lorsque l'angle de grain relatif à un axe longitudinal de la pièce est nul, et inférieure, quand l'angle de grain diffère de zéro, et selon l'effet de l'angle de grain sur le comportement mécanique de la pièce en bois ;
    c) la réduction de la densité de l'équivalent de bois net de défauts par l'effet de la caractéristique en utilisant des relations théoriques et empiriques liant la caractéristique au comportement mécanique du bois ; et
    e) la réduction supplémentaire de la densité de l'équivalent de bois net de défauts par l'effet des défauts du bois dans leurs emplacements d'occurrence et l'effet sur le comportement mécanique de la pièce en bois.

5. Méthode selon la revendication 3 ou 4, comprenant de plus la division de la pièce en bois en une grille de pixels virtuels, la suppression virtuelle de la densité occupée par un noeud, et le remplacement de ladite densité virtuellement supprimée par une densité de bois net de défauts mécaniquement équivalent au noeud supprimé.

6. Méthode selon la revendication 3, dans laquelle ledit calcul d'un équivalent de densité de bois net de défauts est appliqué à une section limitée de la pièce en bois, et dans laquelle la section limitée est translatée le long de l'axe de la direction des grains de la pièce en bois.

7. Méthode selon la revendication 1, comprenant de plus l'estimation de la résistance à la flexion et à la rupture en traction d'au moins une portion de la longueur de la pièce en bois en déterminant un minimum du profil, sur ladite longueur, de la résistance de la pièce en bois.

8. Méthode selon la revendication 1, dans laquelle ladite collecte d'informations relatives à la qualité des fibres inclut la mesure d'une fréquence de vibration de la pièce en bois, dans laquelle ladite fréquence de vibration est le résultat de la vibration induite seulement par l'alimentation de la pièce en bois jusqu'aux capteurs et sans aucun moyen explicite de percussion générant des vibrations.

9. Méthode selon la revendication 7, comprenant de plus l'estimation de la résistance à la flexion et à la rupture en traction de la pièce en bois en mesurant une fréquence de vibration de la pièce en bois, dans laquelle ladite fréquence de vibration est le résultat de la vibration induite seulement par l'alimentation de la pièce en bois jusqu'aux capteurs et sans aucun moyen explicite de percussion générant des vibrations.

10. Méthode selon la revendication 9, comprenant de plus la mesure dudit signal de vibration en divisant le signal de vibration en différentes sections correspondant à l'appui et aux conditions de contrainte de la pièce en bois sur les cylindres d'entrée et de sortie.

11. Méthode selon la revendication 2, dans laquelle lesdites caractéristiques matérielles comprennent au moins un des éléments suivants : densité du bois net de défaut ou densité de noeud, et dans laquelle au moins l'un des deux est mesuré par un scanner utilisant une source de radiation.

12. Méthode selon la revendication 1, dans laquelle ladite teneur en humidité est estimée à l'aide d'une mesure utilisant les microondes.

13. Méthode selon la revendication 12, dans laquelle ladite mesure utilisant les microondes est effectuée lorsqu'une radiation microonde appliquée est polarisée dans une direction transversale à un axe longitudinal de la pièce en bois.

14. Méthode selon la revendication 12, dans laquelle la mesure microonde est corrigée en fonction de la température.

15. Méthode selon la revendication 1, dans laquelle ladite teneur en humidité est estimée à l'aide d'une mesure utilisant les rayons X.

16. Méthode selon la revendication 1, dans laquelle ladite prévision de la solidité et de la rigidité d'une pièce en bois est basée le moment d'inertie.

17. Méthode selon la revendication 5 comprenant de plus la création d'un modèle tridimensionnel équivalent du bois en divisant ladite grille de pixels virtuels en trois dimensions.

18. Méthode selon la revendication 1, dans laquelle ledit modèle physique est optimisé par un réglage fin des valeurs initiales des paramètres pour une corrélation maximale avec la solidité ou la rigidité réelle.

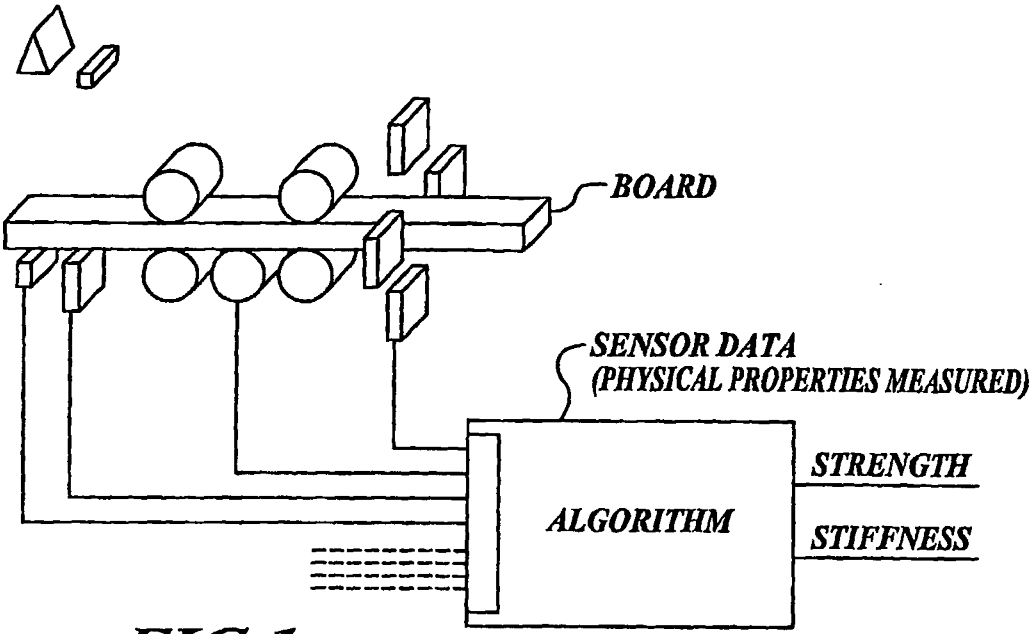


FIG.1

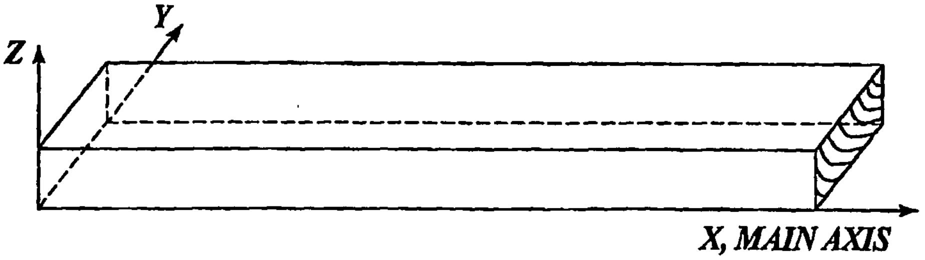


FIG.1A

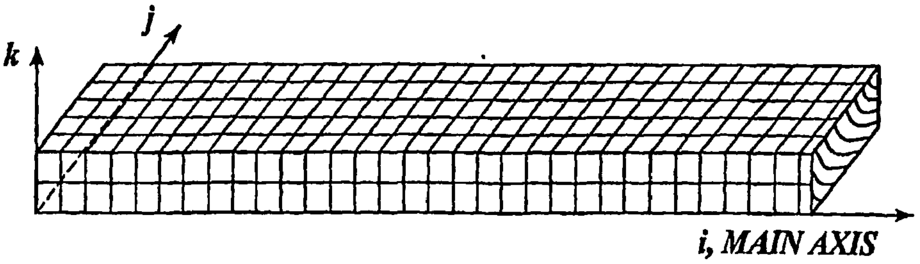


FIG.1B

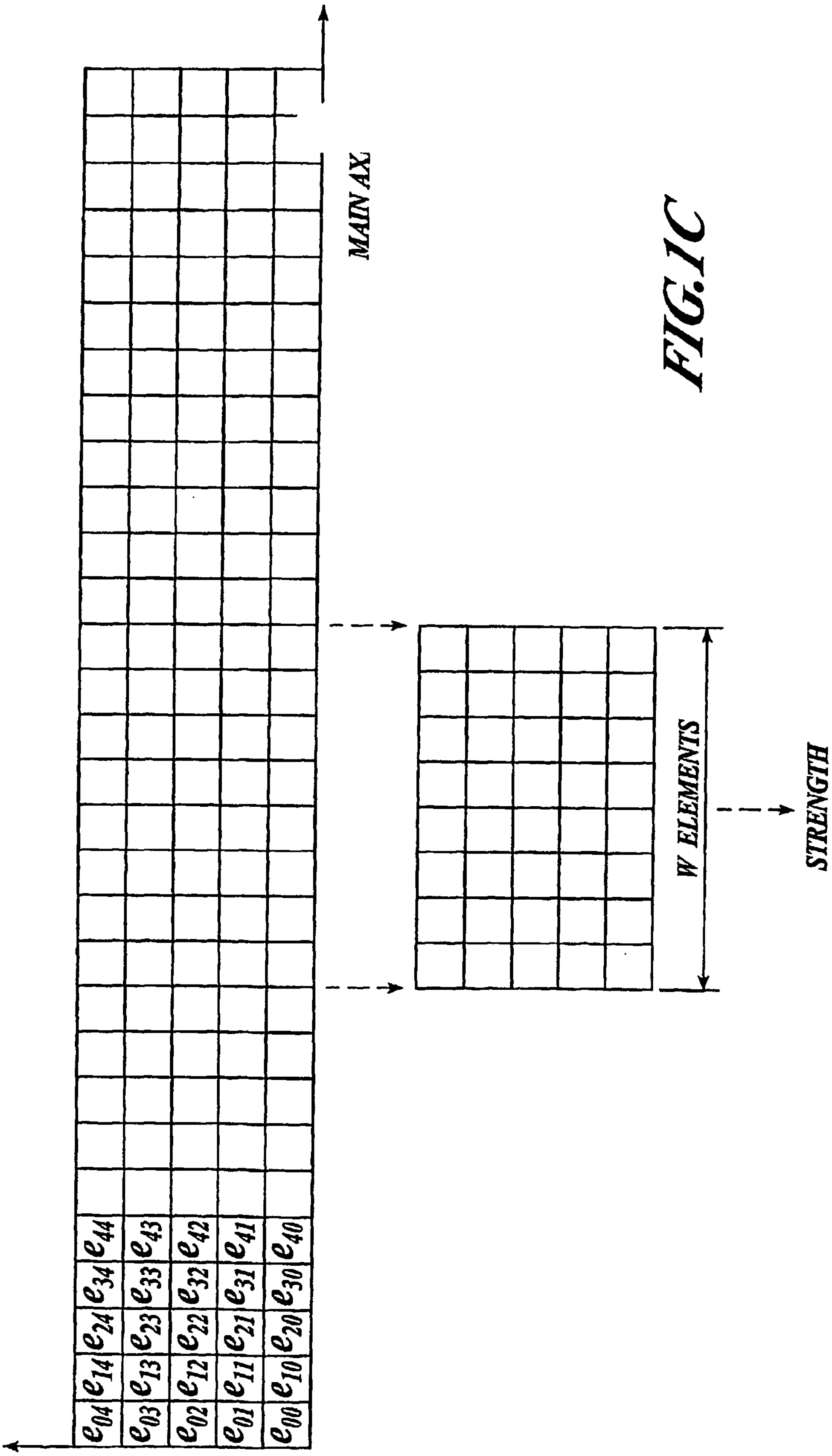

e04 e14 e24 e34 e44
e03 e13 e23 e33 e43
e02 e12 e22 e32 e42
e01 e11 e21 e31 e41
e00 e10 e20 e30 e40
MAIN AX
W ELEMENTS
STRENGTH

FIG.1C

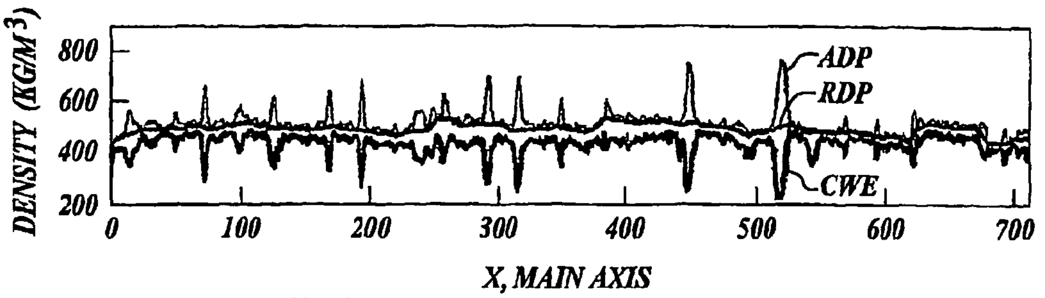


FIG.1D

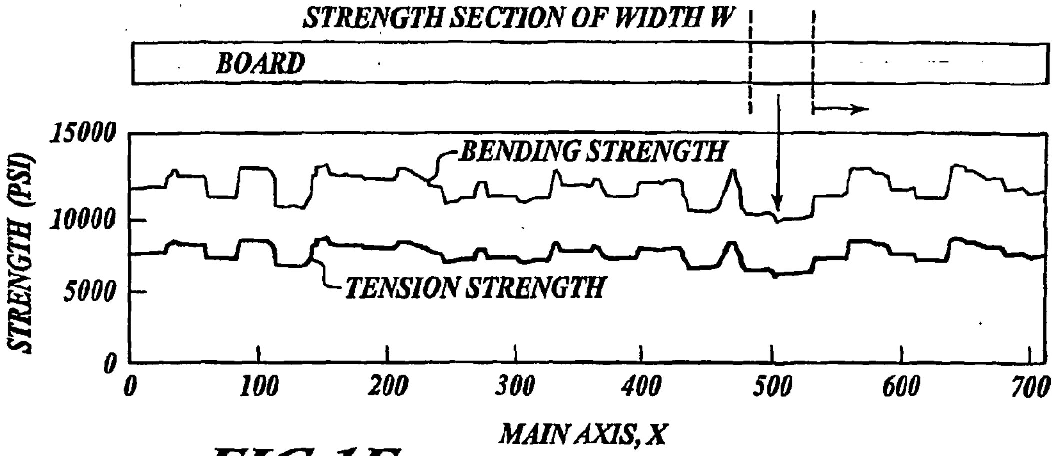


FIG.1E

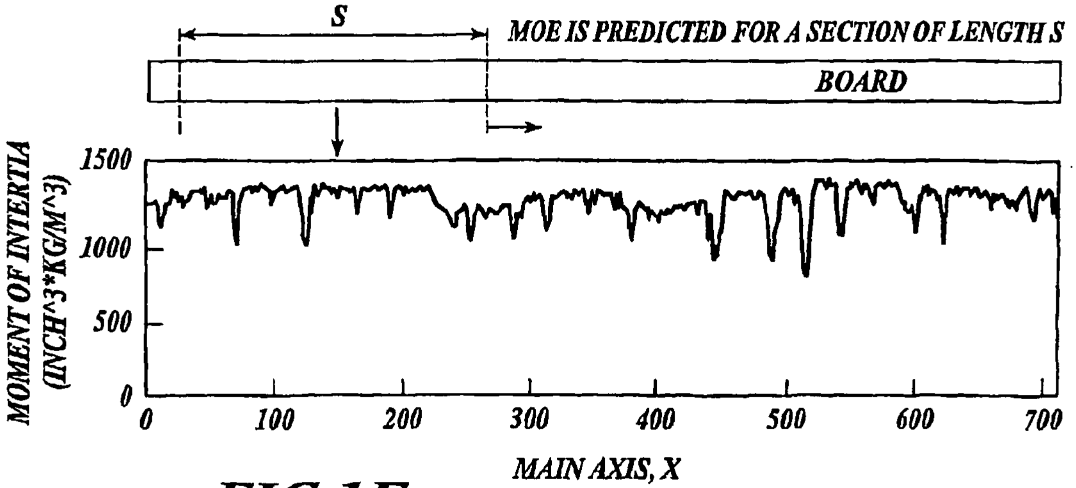


FIG.1F

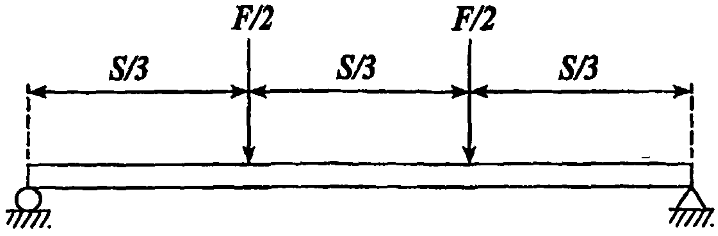


FIG.1G

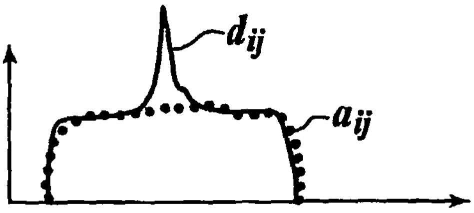


FIG.2A

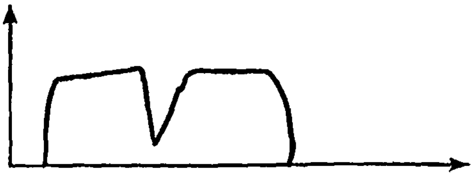


FIG.2B

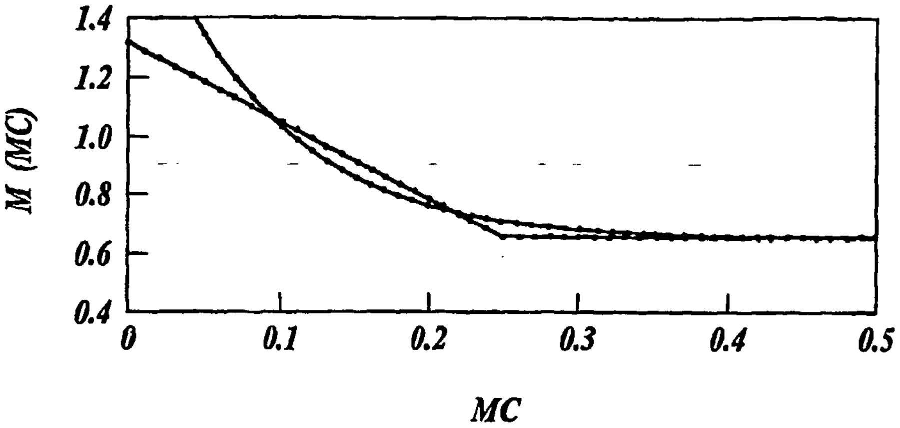

1.4
1.2
1.0
0.8
0.6
0.4
M (MC)
0
0.1
0.2
0.3
0.4
0.5
MC

FIG. 3

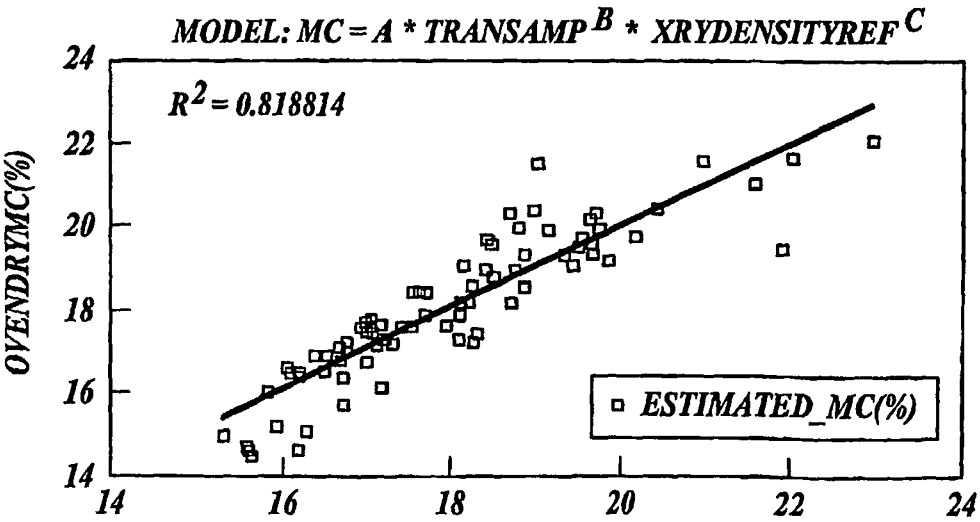

MODEL: MC = A * TRANSAMP^B * XRYDENSITYREF^C
R^2 = 0.818814
OVENDRYMC(%)
24
22
20
18
16
14
14
16
18
20
22
24
□ ESTIMATED_MC(%)

FIG. 3A

FIG.4

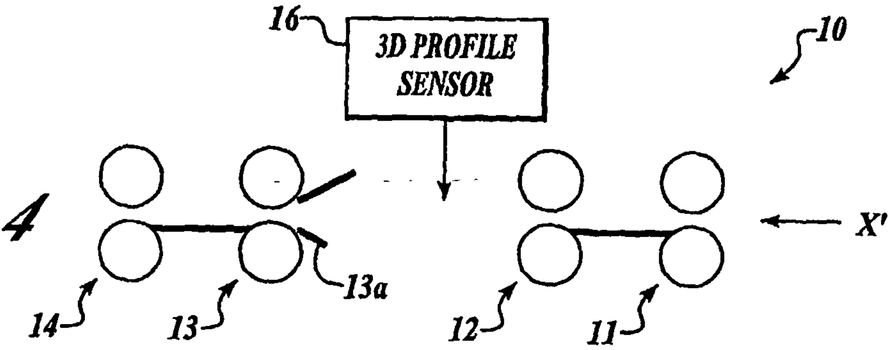


FIG.5A

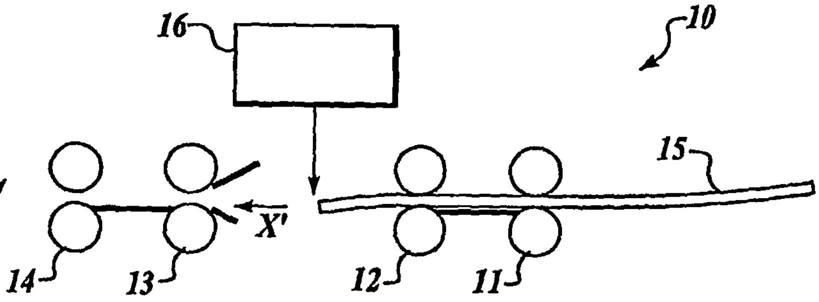


FIG.5B

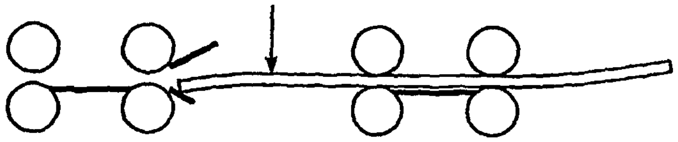


FIG.5C

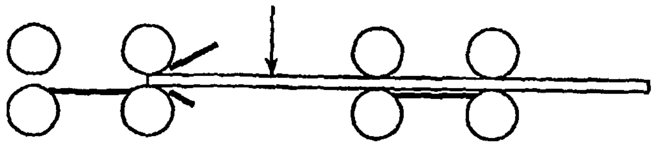
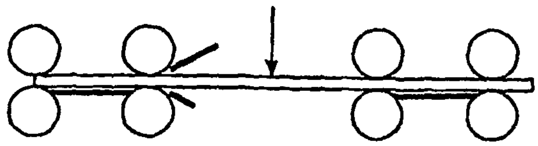


FIG.5D



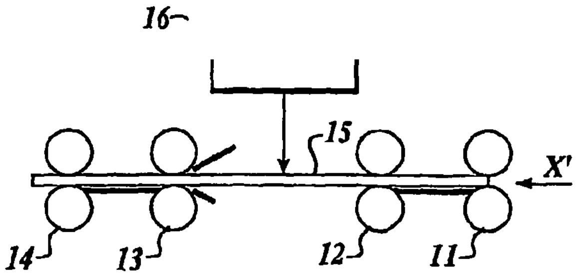


FIG. 6A

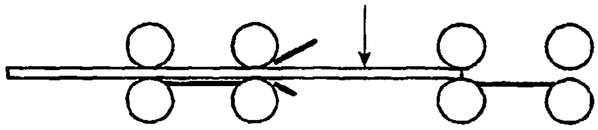


FIG. 6B

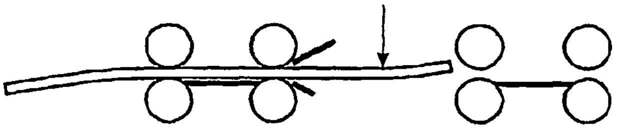


FIG. 6C

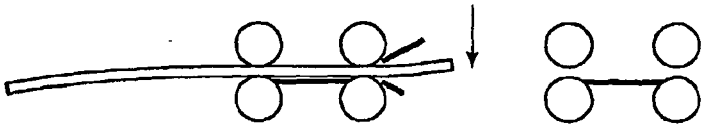


FIG. 6D

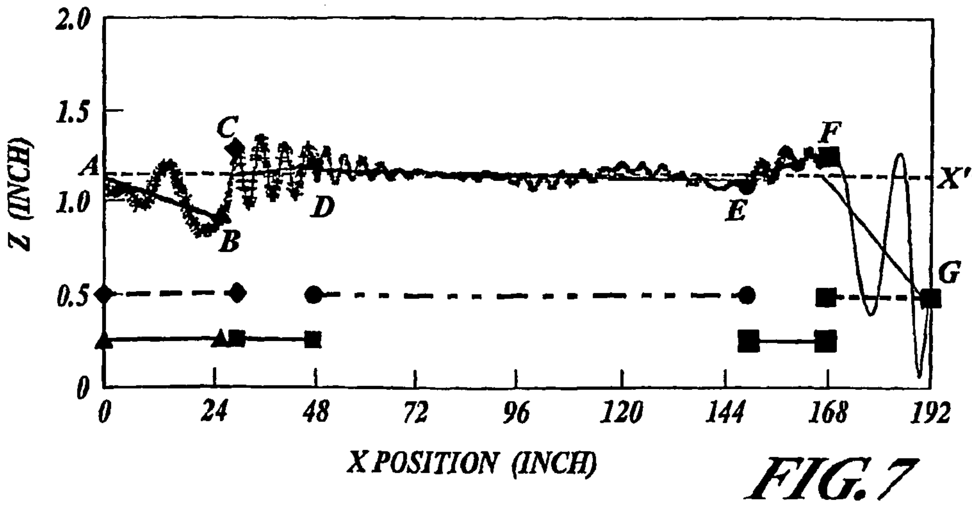


FIG. 7

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US 4926350 A, Bechtel **[0005]**