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(54) **METHOD FOR IN-SITU NONDESTRUCTIVE MEASUREMENT OF YOUNG'S MODULUS OF PLATE STRUCTURES**

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5,033,304 A	*	7/1991	Rosen	73/597
5,127,268 A	*	7/1992	Klineq	73/597
5,154,081 A		10/1992	Thompson et al.	
5,251,486 A	*	10/1993	Thompson et al.	73/597
5,369,997 A		12/1994	Roberts et al.	
5,408,882 A	*	4/1995	McKinley et al.	73/597
5,456,114 A	*	10/1995	Liu et al.	
5,533,399 A	*	7/1996	Gibson et al.	73/579
5,578,757 A		11/1996	Roth	
5,741,971 A		4/1998	Lacy	
5,804,727 A	*	9/1998	Lu et al.	73/597
5,929,315 A	*	7/1999	Dunegan	73/1.82
6,062,083 A	*	5/2000	Dunegan	73/587
6,092,421 A	*	7/2000	Bar-Cohen et al.	73/624
6,173,613 B1	*	1/2001	Dunegan	73/587

* cited by examiner

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(56) **References Cited**

U.S. PATENT DOCUMENTS

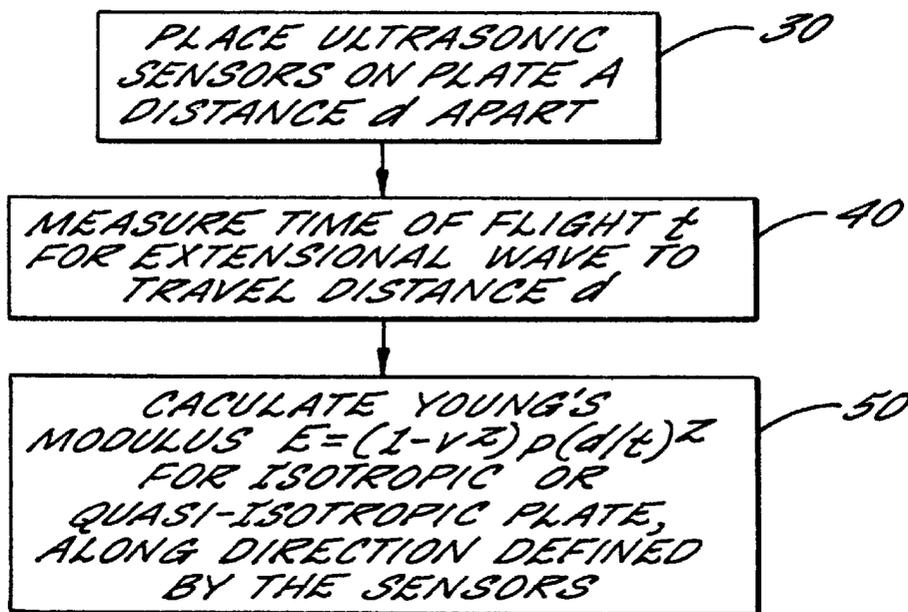
3,720,098 A		3/1973	Dixon	
4,307,616 A		12/1981	Vasile	
4,457,174 A	*	7/1984	Bar-Cohen et al.	73/598
4,562,736 A	*	1/1986	Iwasaki et al.	73/587
4,688,429 A	*	8/1987	Holroyd	73/602
4,845,989 A		7/1989	Titlow et al.	
4,899,589 A	*	2/1990	Thompson et al.	73/597
5,031,457 A	*	7/1991	Kline	73/597

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(57) **ABSTRACT**

A method for determining stiffness of a composite laminate plate entails disposing a device for generating an acoustical pulse against a surface of the plate and disposing a detecting device against the same surface spaced a known distance from the pulse-generating device, and using the pulse-generating device to emit a pulse so as to create an extensional wave in the plate. The detecting device is used to determine a time of flight of the wave over the known distance, and the wave velocity is calculated. A Young's modulus of the plate is determined based on the wave velocity. Methods for both anisotropic and quasi-isotropic laminates are disclosed.

17 Claims, 2 Drawing Sheets



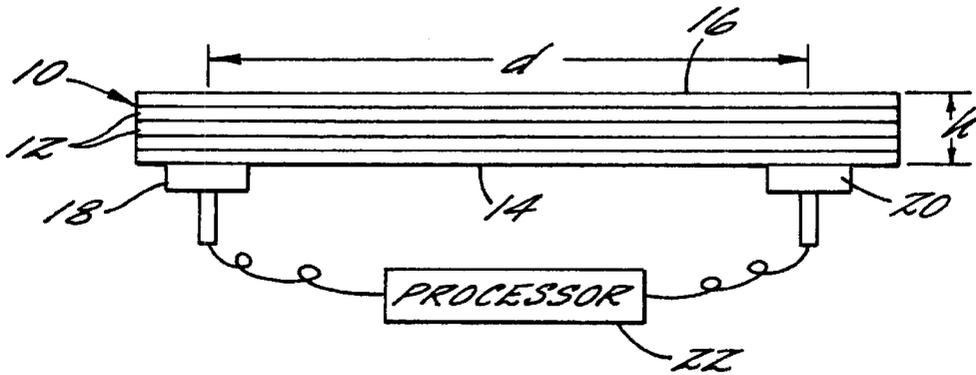


FIG. 1.

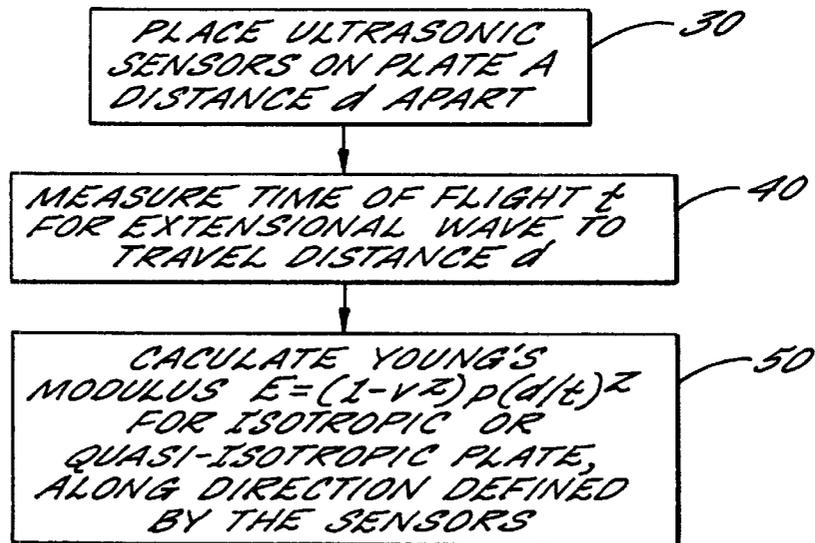


FIG. 2.

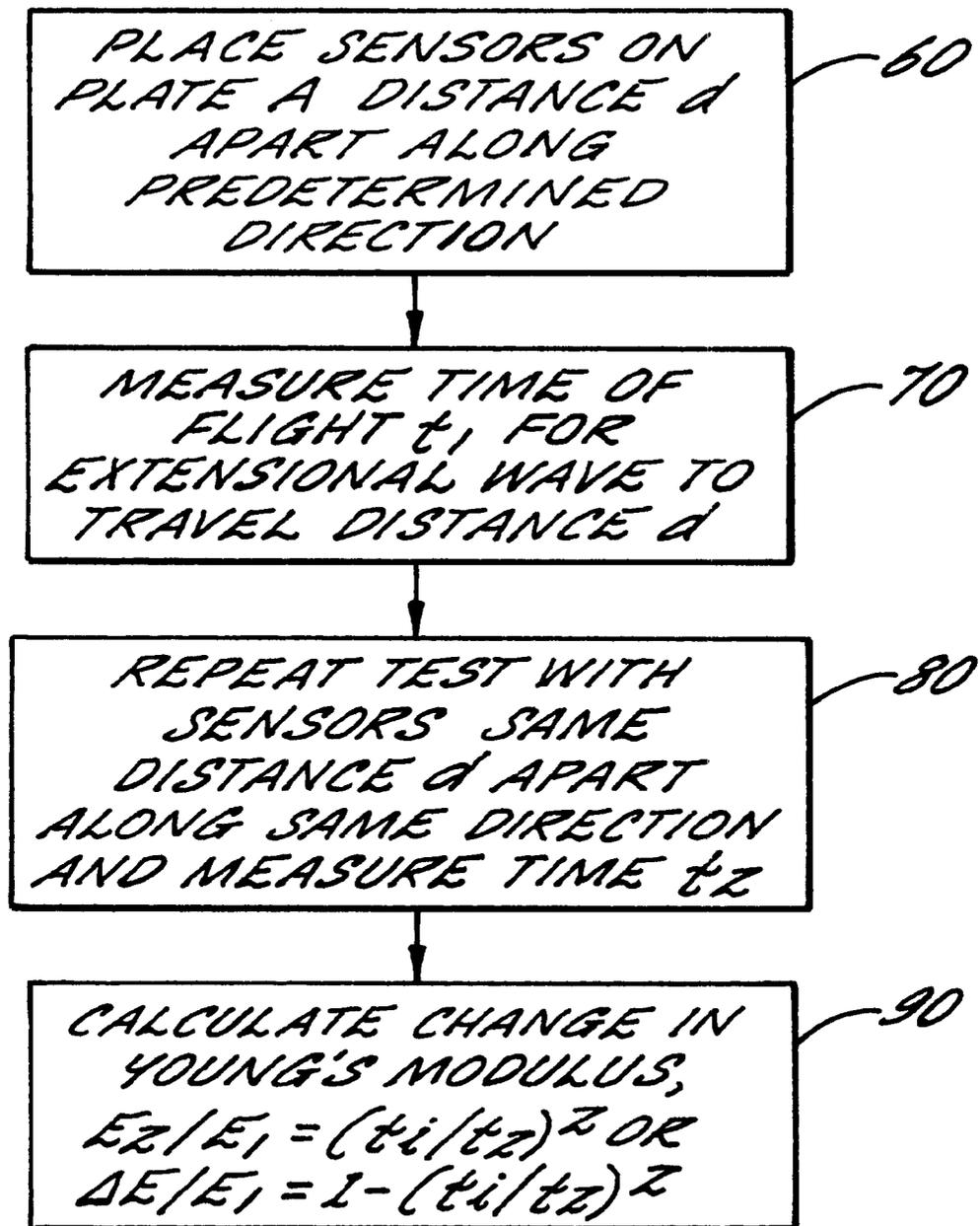


FIG. 3.

METHOD FOR IN-SITU NONDESTRUCTIVE MEASUREMENT OF YOUNG'S MODULUS OF PLATE STRUCTURES

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The invention described herein was made in the performance of work under NASA Cooperative Agreement NCC8-39 and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958 (42 U.S.C. 2457).

FIELD OF THE INVENTION

The invention relates to nondestructive test methods for determining stiffness properties of plate structures. The invention relates more particularly to such methods employing propagation of acoustic waves through a plate structure of homogeneous or composite laminate form for determining Young's modulus of the plate structure.

BACKGROUND OF THE INVENTION

In a variety of mechanical or structural devices or assemblies, it is frequently desired to be able to determine changes in material properties of a given part, because such changes can be indicative of degradation of the part. For example, material stiffness is an important parameter affecting the performance of a structure. While structures are typically designed based on a known initial stiffness of the materials making up the structure, various factors can cause the materials to lose stiffness. Stress, fatigue, and environmental attack such as thermal and/or oxidation processes are just a few of the mechanisms by which a material can be degraded in terms of material stiffness. Fiber/matrix composite materials are particularly susceptible to stiffness degradation, chiefly through a process known as micro-cracking in which microscopic cracks develop in the matrix material that binds the fibers together. Such micro-cracking can cause deleterious changes in mechanical properties, stress concentration, and redistribution within the composite material, which in turn can lead to performance degradation, delamination, and fiber damage. It is difficult, however, to detect micro-cracking using the types of nondestructive testing methods that heretofore have been available.

Prior to the present invention, there was no known non-destructive testing device suitable for use in the field, such as a hand-held device, for quantitatively determining changes in stiffness of a plate such as a composite laminate plate along an in-plane direction of the plate. The prior art teaches various methods for determining stiffness of isotropic materials using ultrasonic wave propagation through the material. For example, U.S. Pat. No. 5,741,971 to Lacy discloses a method for nondestructively measuring a Young's modulus of a bulk isotropic material, such as cements or completion gels used in the petroleum industry for interzone isolation and fracture containment in drilling operations. The method involves using the through-transmission technique in which an ultrasonic transducer is disposed adjacent one end of a sample slug of the bulk material and another ultrasonic transducer is disposed adjacent an opposite end of the sample. The length of the sample between the two transducers is known. An ultrasonic pulse is generated by one of the transducers so as to cause an ultrasonic compression or longitudinal wave to be propagated beginning at one end of the sample, and the other transducer detects the wave when it arrives at the opposite end of the sample. The elapsed time between initiation of the

wave at one end of the sample and arrival of the wave at the other end of the sample is measured. Based on this time and the known length of the sample, a velocity of the wave through the sample is calculated. A Young's modulus for the material is then calculated based on the wave velocity and the known density and Poisson's ratio of the material. The method of Lacy and the theory behind it are applicable only to isotropic materials. Lacy's method requires placing transducers on two opposite sides of the sample, and thus would be difficult to apply to in-situ testing of a structure where it may be difficult or impossible to access both sides of the structure. Even if both sides of the structure could be accessed, the through-transmission technique of Lacy still cannot give a measurement of Young's modulus in an in-plane direction, but can only provide an indication of stiffness in the thickness direction, which is the less interesting of the two directions.

U.S. Pat. No. 5,154,081 to Thompson et al. discloses a method for ultrasonic measurement of material properties for metal plates, involving using two transducers and a receiver arranged non-collinearly on one side of the plate. The two transducers generate Lamb waves that propagate along two different directions to the receiver. Based on differences in calculated velocities of the two Lamb waves, Thompson deduces material properties such as grain orientation and stress. The method is applicable only to metals, and does not provide a material stiffness measurement.

There has been a need, therefore, for a nondestructive method for measuring in-plane stiffness properties of plates including homogeneous isotropic plates and composite laminate plates. Additionally, there has been a need for such a method that can be used for in-situ examination of a plate where it may not be possible to access both sides of the plate.

SUMMARY OF THE INVENTION

The above needs are met and other advantages are achieved by the present invention, which provides a method for quantitatively evaluating in-plane stiffness properties of a plate in a nondestructive manner that is applicable to in-situ use, necessitating access to only one side of the plate. The method broadly comprises imparting energy to the plate at a first point located on a first of the major surfaces of the plate so as to cause an elastic wave to originate at the first point and propagate along the plate as a plate wave or guided wave. The plate wave generally consists of two wave modes, i.e., extensional and flexural wave modes. At a second point on the same surface of the plate and spaced from the first point along an in-plane direction, the extensional-mode wave, which travels faster than the flexural wave, is detected when it arrives. A velocity of the extensional wave along the in-plane direction of the plate is determined. Based on this velocity, a material stiffness of the plate along the in-plane direction is calculated.

The wave velocity can be determined by measuring the distance d between the first and second points and the elapsed time t required for the extensional-mode wave to travel the distance d from the first point to the second point, and dividing the distance d by the time t . Based on the velocity, a stiffness parameter for the plate along the in-plane direction is determined. The determination of the stiffness parameter is based on elastic wave propagation. The method can be applied to both homogeneous isotropic plates and composite laminate plate structures.

In accordance with a preferred embodiment of the invention applicable particularly to homogeneous isotropic plates, the stiffness parameter calculation in accordance with the

invention comprises calculating the Young's modulus based on the distance d and the time t . More particularly, the Young's modulus E is calculated based on the equation

$$E=(1-\nu^2)\rho(d/t)^2,$$

where ν is a predetermined Poisson's ratio for the material of the plate and ρ is a predetermined density of the material of the plate.

Preferably, the elastic wave is generated by applying acoustic energy to the plate. For example, a device for emitting acoustic pulses can be disposed against the plate surface and activated to create an acoustic pulse. An ultrasonic transducer or acoustic emission sensor can be used for this purpose. The extensional wave mode is detected with a second sensor placed a known distance from the first sensor against the same surface of the plate. It will thus be appreciated that unlike prior art methods employing the through-transmission technique in which a longitudinal wave is propagated from one side of a material to the other, the method of the invention is suitable for in-situ applications where it may not be possible or practical to locate sensors on both sides of the structure.

The methods described above are applicable primarily to isotropic plates and to quasi-isotropic composite laminate plates in which the plies are arranged in a lay-up such that the resulting laminate exhibits isotropic elastic behavior in the plane of the plate. The invention also provides a method for determining Young's moduli of a composite laminate plate in the more general case of anisotropic laminates. This method involves solving a set of simultaneous equations to determine Young's moduli for the plate along two orthogonal in-plane x - and y -directions corresponding to the zero-degree and 90-degree fiber directions of the laminate. The equations relate the Young's moduli to the extensional wave velocities along these directions and to Poisson's ratios and in-plane stiffness parameters for the plate. More specifically, one embodiment of the invention entails determining extensional wave velocities C_x and C_y along the x - and y -directions of a composite laminate plate, and solving the set of equations:

$$C_x=\sqrt{A_{11}/\rho h} \quad \text{Eq. (1)}$$

$$C_y=\sqrt{A_{22}/\rho h} \quad \text{Eq. (2)}$$

$$E_{xx}=\frac{\sigma_{xx}}{\epsilon_{xx}}=\frac{A_{11}A_{22}-A_{12}^2}{hA_{22}} \quad \text{Eq. (3)}$$

$$\nu_{xy}=-\frac{\epsilon_{yy}^o}{\epsilon_{xx}^o}=\frac{A_{12}}{A_{22}} \quad \text{Eq. (4)}$$

$$E_{yy}=\frac{A_{11}A_{22}-A_{12}^2}{hA_{11}} \quad \text{Eq. (5)}$$

$$\nu_{yx}=\frac{A_{12}}{A_{11}} \quad \text{Eq. (6)}$$

where h is the plate thickness, A_{ij} ($i, j=1$ and 2) are the in-plane stiffnesses of the plate as defined in the composite laminate theory, ρ is the plate density, and ν_{xy} , and ν_{yx} are Poisson's ratios for the plate along the x - and y -directions. The plate density and Poisson's ratios will generally be known or can readily be determined. Thus, these equations can be solved for the Young's moduli. It can be shown, for quasi-isotropic composite plates, that this set of equations can be greatly simplified and reduced to the equation

$$E=(1-\nu^2)\rho(d/t)^2$$

set forth above.

The invention also provides a method for quantitatively determining a change in Young's modulus for a plate. The method comprises performing a first test in which energy is imparted to the plate at a first point located on the plate surface and detecting when the extensional-mode wave reaches a second point located on the same surface and spaced a predetermined distance from the first point, and measuring a first-elapsed time t_1 required for the extensional-mode wave to travel from the first point to the second point. A second test is then performed in the same manner, making sure that the distance between the two points is the same as for the first test. A second elapsed time t_2 required for the extensional-mode wave to travel between the two points is measured. A change in Young's modulus for the plate is calculated based on a degree of difference, of the times t_1 and t_2 . More particularly, it is assumed that the density and Poisson's ratio for the material of the plate are constant or its change is negligible between the first test and the second test. A ratio of Young's moduli for the first and second tests is calculated based on a ratio of the times t_1 and t_2 . Advantageously, the ratio of Young's moduli is calculated by the equation

$$E_2/E_1=(t_1/t_2)^2,$$

where E_1 is Young's modulus for the first test and E_2 is Young's modulus for the second test. The first and second tests may be performed at two different times, in which case the change in Young's modulus represents a change in material stiffness over time. Thus, the method of the invention can be used for periodic inspection as a way of monitoring the health of a structure. The information regarding changes in material stiffness can be used for prediction of remaining life of the structure or other purposes.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects, features, and advantages of the invention will become more apparent from the following description of certain preferred embodiments thereof, when taken in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic depiction of a testing apparatus positioned on a plate structure for measuring a time of flight of an extensional wave along the plate in accordance with a method of the invention;

FIG. 2 is a flowchart showing a method for determining Young's modulus of a plate structure in accordance with an embodiment of the invention;

FIG. 3 is a flowchart showing a method for determining a change in Young's modulus of a plate structure in accordance with another embodiment of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

The present invention now will be described more fully hereinafter with reference to the accompanying drawings; in which preferred embodiments of the invention are shown. This invention may, however be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

The present invention is premised on a unique application of the theory of extensional wave behavior in plate struc-

tures and the composite laminate theory. It is known from theoretical work on wave behavior in composite laminate plates that for symmetric and orthotropic laminate plates, the extensional wave velocity in the x-direction (i.e., along the 0° ply direction) is given by

$$c_x = \sqrt{A_{11}/\rho h} \quad \text{Eq. (1)}$$

where A_{11} is the in-plane stiffness in the x-direction, ρ is the plate density, and h is the plate thickness. Similarly, the extensional wave velocity in the y-direction (along the 90° ply direction) is given by

$$c_y = \sqrt{A_{22}/\rho h} \quad \text{Eq. (2)}$$

where A_{22} is the in-plane stiffness in the y-direction. By symmetric laminate is meant a laminate in which the plies are arranged so as to be symmetric about a central plane dividing the plate thickness in half, and in which for every ply of + θ orientation there is an identical ply of - θ orientation. Such a ply lay-up is also commonly referred to as a balanced symmetric ply lay-up.

It is also known that for a balanced symmetric laminate, the Young's modulus in the x-direction is given by

$$E_{xx} = \frac{\sigma_{xx}}{\epsilon_{xx}} = \frac{A_{11}A_{22} - A_{12}^2}{hA_{22}} \quad \text{Eq. (3)}$$

and the Poisson's ratio is given by

$$\nu_{xy} = -\frac{\epsilon_{yy}^o}{\epsilon_{xx}^o} = \frac{A_{12}}{A_{22}} \quad \text{Eq. (4)}$$

Similarly, the Young's modulus in the y-direction is

$$E_{yy} = \frac{A_{11}A_{22} - A_{12}^2}{hA_{11}} \quad \text{Eq. (5)}$$

and the Poisson's ratio is

$$\nu_{yx} = \frac{A_{12}}{A_{11}} \quad \text{Eq. (6)}$$

The Poisson's ratios ν_{xy} and ν_{yx} are material constants and can be determined by mechanical methods or can be calculated from the lamina (single ply) data. Likewise, the density ρ is a material constant and can readily be determined. Thus, Equations (1) through (6) represent a set of six simultaneous equations having seven unknowns, namely, c_x , c_y , A_{11} , A_{22} , A_{12} , E_{xx} , and E_{yy} . However, consider the situation, where the extensional velocities c_x and c_y are known. Then, the equations can be solved to determine the Young's moduli E_{xx} and E_{yy} . In other words, the Young's modulus along a defined direction of a plate can be determined if the extensional wave velocity along that direction is known.

The extensional velocity along a defined direction of a plate can be experimentally determined by causing an extensional wave to propagate along the plate and measuring the time of flight required for the wave to travel a known distance along the plate. The quantitative stiffness determination of the present invention is applicable primarily to thin plates in which the thickness of the plate is much smaller than the length and width dimensions of the plate. Qualitative results may be obtained, however, even for non-plate structures using the same methodology as that described

herein. It is anticipated that quantitative results could even be obtained for non-plate structures by using empirically derived correction factors.

FIG. 1 schematically depicts a testing apparatus that can suitably be used for initiating an extensional wave and measuring a time of flight. A composite laminate plate **10** is schematically depicted as composed of a plurality of plies **12** laid atop one another. FIG. 1 is a view looking at the plate edgewise. The major surfaces **14** and **16** of the plate define a plate thickness h therebetween. In accordance with a preferred embodiment of the invention, a pair of sensors **18** and **20** are disposed against one of the major surfaces of the plate, such as the surface **14** as shown. The sensors **18** and **20** each comprises a device for converting an electrical pulse into an acoustical pulse or signal and vice versa, such as a 50 kHz to 2 MHz ultrasonic transducer or acoustic emission sensor. The sensor **18** is connected to a suitable processor **22** which provides an electrical pulse to the sensor **18** and receives a signal from the sensor **18** indicating that an acoustical pulse has been initiated. The processor **22** includes a clock that begins measuring an elapsed time upon receipt of this signal in a proper sampling rate according to the accuracy required for the modulus measurements, in a range of above 5 MHz. The time required for the extensional wave to travel between the two sensors **18** and **20** is equal to the sensor spacing d divided by the sound velocity c . Thus, as an example of determining the proper sampling rate, consider a case in which the sensor spacing d is 0.05 m and the material's velocity of sound propagation c is 6000 m/s. Accordingly, to observe a two percent change in modulus, a minimum sampling rate of about 10 MHz would be required. The higher the sampling rate, the smaller the change in modulus that can be measured.

Upon activation of the sensor **18**, an extensional wave will begin to be propagated through the plate **10**. After an elapsed time t measured from when the sensor **18** is activated, the extensional wave will arrive at the location of the second sensor **20**. Upon, detection of the wave, the second sensor **20** sends a signal to the processor **22**, and the elapsed time between initiation of the acoustical pulse at the first sensor location and arrival of the extensional wave at the second sensor location is determined by the processor **22**. The distance d between the sensors **18** and **20** is known. Accordingly, an extensional wave velocity can be determined by dividing the distance d by the elapsed time t .

The wave velocity determined in this manner is the velocity along a particular direction of the plate **10** defined by the orientation of the sensors **18**, **20** with respect to each other. In the general case of an anisotropic composite laminate, the in-plane stiffnesses A_{11} and A_{22} in the x- and y-directions are different, and thus the extensional wave velocities are different in different directions, as indicated by Equations (1) and (2) above. Examination of Equations (3) and (5) also reveals that the Young's moduli are different in the x- and y-directions. The present invention provides a method for determining the Young's moduli along the x- and y-directions by measuring the extensional wave velocities along these directions, and using the measured velocities in the above Equations (1) to (6) to deduce the Young's moduli. This method is applicable to the general case of an anisotropic laminate. It should be noted that the x and y axis directions coincide with the zero-degree and 90-degree fiber directions of the laminate, respectively. Such a coordinate system gives the simplest form of equations for the Young's modulus measurements that practically are most convenient for engineering evaluation. Thus, it will be understood that in order to evaluate the modulus of a plate along the x-axis

direction using the equations given above, the sensors must be aligned along the direction corresponding to the zero-degree fiber direction.

In many composite structures, however, quasi-isotropic ply lay-ups are used because of their advantageous properties. For a quasi-isotropic laminate, the in-plane stiffnesses A_{11} and A_{22} are equal. Accordingly, Equations (1) and (2) indicate that the extensional velocities in the x- and y-directions will be equal and can be denoted simply as c_e . Similarly, Equations (4) and (6) indicate that the Poisson's ratios ν_{xy} and ν_{yx} will be equal and can be denoted simply as ν . The in-plane stiffness A_{11} can be expressed in terms of the extensional velocity c_e by rearranging Equation (1), and the term A_{22} in all of the equations can be replaced by A_{11} . From Equation (4), A_{12} can be expressed in terms of A_{11} and Poisson's ratio ν . Making the appropriate substitutions, Equations (3) and (5) both reduce to the same equation,

$$E = (1 - \nu^2) \rho c_e^2 \quad (7)$$

Thus, the Young's moduli along the x- or y-directions are equal and can be determined by measuring the wave velocity along either direction and using Equation (7). Thus, in the case of quasi-isotropic composite laminates, a simplified method can be used to deduce stiffness necessitating only a single measurement of wave velocity along any direction in the plane.

FIG. 2 is a flowchart illustrating a method in accordance with one embodiment of the invention applicable particularly to homogeneous isotropic or quasi-isotropic composite laminate plates. As indicated at **30**, suitable acoustic devices such as contact ultrasonic transducers or acoustic emission sensors are placed against the same surface of a plate to be tested such that the sensors are a known distance d apart and are appropriately aligned relative to the fiber directions of the laminate. One of the sensors is activated to emit an acoustical pulse or signal to initiate a plate wave, and the other sensor detects the arrival of the extensional-mode wave component of the plate wave (which travels faster than the flexural-mode component and thus is the first to arrive at the sensor). From the sensor information, a time of flight t is measured as indicated at **40**. Then, at **50**, the Young's modulus E for the plate is calculated based on Equation (7) above, where the wave velocity c_e is equal to d/t .

This method can be further simplified for applications where repeated measurements of the time of flight t are made on a periodic basis, for example, as part of a regular health-monitoring inspection program. In this case, it may be desired only to determine a quantitative change in Young's modulus from one inspection or time to another. If Equation (7) is expressed in terms of time of flight t by substituting d/t for the wave velocity c_e , a Young's modulus for an i -th measurement is given by

$$E_i = (1 - \nu^2) \rho \left(\frac{d}{t_i} \right)^2 \quad (8)$$

Consider that at some earlier measurement, an original Young's modulus would have been given by

$$E_o = (1 - \nu^2) \rho \left(\frac{d}{t_o} \right)^2 \quad (9)$$

Next, it is assumed that for each inspection, the sensors are placed the same distance d apart from each other along the same direction. It is further assumed that the density and Poisson's ratio do not change from one inspection to the

next. This assumption is considered to be close to reality, inasmuch as the type of material changes of most interest in composite laminates are micro-cracking and other microscopic damage, and thus the changes in Poisson's ratio should be negligible. Accordingly, the ratio of Young's modulus at the i -th measurement to the original Young's modulus, is given by

$$\frac{E_i}{E_o} = \left(\frac{t_o}{t_i} \right)^2 \quad (10)$$

This can also be expressed in terms of a fractional change as

$$\frac{\Delta E}{E_o} = 1 - \left(\frac{t_o}{t_i} \right)^2 \quad (11)$$

FIG. 3 is a flowchart illustrating a testing sequence based on the Equations (10) and (11). As indicated at **60**, sensors are placed on the plate surface a distance d apart from each other along a predetermined direction. At **70**, the time of flight t_1 of an extensional wave is measured with the sensors. The test is repeated as indicated at **80**, making sure that the sensors are placed the same distance d apart along the same direction as for the prior test, so as to measure a second time of flight t_2 . At **90**, the change in Young's modulus is calculated using either Equation (10) or (11), or both, based on the ratio of the two times of flight.

From the foregoing, it will be appreciated that the invention provides a method for nondestructively determining quantitative stiffness information for homogeneous and composite laminate plate structures using extensional wave propagation. The method is readily applicable to in-situ inspection because sensors are placed on the same surface of the structure being tested, and therefore it is not necessary to have access to both sides of the plate structure. The sensors advantageously can be permanently bonded on a structure in a critical location for frequent inspection, thereby facilitating testing and also assuring that the sensor spacing and orientation are always fixed in the appropriate manner.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. For example, although the foregoing description focuses primarily upon the unique problems associated with evaluating composite laminate plates, the method of the invention is equally applicable to homogeneous isotropic plates, as will be recognized by those skilled in the art. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. A nondestructive method for quantitatively evaluating a material stiffness of a composite laminate plate along an in-plane direction, the plate having a plurality of plies arranged in a balanced symmetric ply lay-up and having opposite major surfaces defining a thickness of the plate therebetween, the method comprising:

- propagating an elastic extensional-mode wave through the plate along said in-plane direction;
- determining a velocity of the extensional-mode wave along said in-plane direction of the plate; and

calculating a material stiffness of the plate along said in-plane direction based on the wave velocity.

2. The method of claim 1, wherein propagating the extensional-mode wave comprises:

imparting energy to the plate at a first point located on a first of the major surfaces of the plate so as to cause the extensional-mode wave to originate at said first point and propagate along the plate.

3. The method of claim 2, wherein determining the wave velocity comprises:

detecting when the extensional-mode wave reaches a second point located on said first major surface and spaced in said in-plane direction from the first point;

determining a distance d between the first and second points along said first major surface of the plane in said in-plane direction;

measuring an elapsed time t required for the extensional-mode wave to travel the distance d from the first point to the second point; and

calculating the wave velocity based on the distance d and the time t.

4. The method of claim 3, wherein calculating the material stiffness comprises calculating a Young's modulus along said in-plane direction.

5. The method of claim 4, adapted for evaluating a quasi-isotropic composite laminate plate, wherein the Young's modulus E is calculated based on the equation

$$E=(1-\nu^2)\rho(d/t)^2,$$

where ν is a predetermined Poisson's ratio for the material of the plate and ρ is a predetermined density of the material of the plate.

6. The method of claim 3, wherein detecting when the extensional-mode wave reaches the second point comprises using an acoustic energy detector disposed against the first major surface of the plate at the second point.

7. The method of claim 2, wherein imparting energy to the plate comprises using acoustic energy to create the extensional-mode wave.

8. The method of claim 2, wherein imparting energy to the plate comprises disposing a device for emitting acoustical energy against the first major surface of the plate at the first point and activating the device to emit acoustic energy.

9. A nondestructive method for quantitatively evaluating Young's moduli of a composite laminate plate along two orthogonal in-plane x- and y-directions of the plate, comprising:

propagating an extensional wave through the plate;

determining a velocity c_x of the extensional wave along said x-direction;

determining a velocity c_y of the extensional wave along said y-direction;

determining Young's moduli E_{xx} and E_{yy} , respectively along the x- and y-directions by solving a set of simultaneous equations relating the extensional wave velocities, the Young's moduli, and Poisson's ratios and in-plane stiffness parameters for the plate to one another.

10. The method of claim 9, wherein the Young's moduli E_{xx} and E_{yy} are determined by solving the set of equations:

$$C_x=\sqrt{A_{11}/\rho h}$$

$$C_y=\sqrt{A_{22}/\rho h}$$

$$E_{xx} = \frac{\sigma_{xx}}{\epsilon_{xx}} = \frac{A_{11}A_{22} - A_{12}^2}{hA_{22}}$$

$$\nu_{xy} = -\frac{\epsilon_{yy}^o}{\epsilon_{xx}^o} = \frac{A_{12}}{A_{22}}$$

$$E_{yy} = \frac{A_{11}A_{22} - A_{12}^2}{hA_{11}}$$

$$\nu_{yx} = \frac{A_{12}}{A_{11}}$$

where h is a thickness of the plate, ρ is a known density of the plate, and ν_{xy} and ν_{yx} are known Poisson's ratios for the plate.

11. A nondestructive method for quantitatively evaluating a change in Young's modulus of a composite laminate plate along an in-plane direction, the plate having a plurality of plies arranged in a balanced symmetric ply lay-up and having opposite major surfaces defining a thickness of the plate therebetween, the method comprising:

(1) performing a first test including steps (a) through (c) comprising:

(a) imparting energy to the plate at a first point located on a first of the major surfaces of the plate so as to cause an extensional-mode wave to originate at said first point and propagate along the plate in said in-plane direction;

(b) detecting when the extensional-mode wave reaches a second point located on said first major surface and spaced a predetermined distance in said in-plane direction from the first point; and

(c) measuring a first elapsed time t_1 required for the extensional-mode wave to travel from the first point to the second point;

(2) performing a second test including steps (d) through (f) comprising:

(d) imparting energy to the plate at a third point located on a first of the major surfaces of the plate so as to cause an extensional-mode wave to originate at said third point and propagate along the plate in said in-plane direction;

(e) detecting when the extensional-mode wave reaches a fourth point located on said first major surface and spaced from the third point by the same said predetermined distance along said in-plane direction; and

(f) measuring a second elapsed time t_2 required for the extensional-mode wave to travel from the third point to the fourth point; and

(3) calculating a change in Young's modulus for the plate along said in-plane direction based on a degree of difference of the times t_1 and t_2 .

12. The method of claim 11, wherein the first and second tests are performed at two different times, whereby the change in Young's modulus represents a change over time.

13. The method of claim 11, wherein the calculation of change in Young's modulus is based on an assumption that density and Poisson's ratio for the material of the plate are constant between the first test and the second test.

14. The method of claim 11, wherein calculating the change in Young's modulus comprises calculating a ratio of Young's moduli for the first and second tests based on a ratio of the times t_1 and t_2 .

15. The method of claim 14, wherein the ratio of Young's moduli is calculated by the equation

$$E_2/E_1=(t_1/t_2)^2,$$

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where E_1 is Young's modulus for the first test and E_2 is Young's modulus for the second test.

16. A method for quantitatively evaluating a material stiffness of an isotropic or quasi-isotropic plate along an in-plane direction, the method comprising:

disposing a first device for emitting acoustical energy on a first major surface of the plate and activating the device to cause an elastic extensional-mode wave to be propagated through the plate along said in-plane direction;

disposing a second device for detecting the extensional-mode wave on said first major surface of the plate spaced a distance d from the first device along said in-plane direction and using the second device to detect arrival of the extensional-mode wave;

measuring the elapsed time t between initiation of the extensional-mode wave by the first device and detection of the extensional-mode wave by the second device; and

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calculating Young's modulus E of the plate along said in plane direction based on the equation

$$E=(1-v^2)\rho(d/t)^2,$$

where ρ is a predetermined density of the plate and v is a predetermined Poisson's ratio of the plate along said in-plane direction.

17. The method of claim 16, further comprising permanently bonding the first and second devices to said first major surface of the plate, and periodically performing tests with the devices to determine Young's modulus at a plurality of sequential times, whereby the spacing between the devices and the devices' orientation relative to the plate are assured to be fixed from one test to another.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,575,036 B1
DATED : June 10, 2003
INVENTOR(S) : Huang et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page.

Item [56], **References Cited**, U.S. PATENT DOCUMENTS, insert the following:

-- 6,053,034 4/2000 Tsui et al. --.

Signed and Sealed this

Seventh Day of October, 2003

A handwritten signature in black ink, appearing to read "James E. Rogan", written over a horizontal line.

JAMES E. ROGAN
Director of the United States Patent and Trademark Office