TV HOLOGRAPHY AS A POSSIBLE TOOL FOR MEASURING TRANSVERSE VIBRATION OF LOGS: A PILOT STUDY

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ABSTRACT

Vibration analysis on a short spruce log was performed by using TV holography, which is a laser interferometry technique applying video recording. This is a non-contact vibration measurements method capable of detecting amplitude of the scale of nanometers. It also allows for real-time inspection of vibrations and full-field measurements. The log was put into vibration by a periodic force acting on a point on the log surface. Resonant vibrations were found by varying the excitation frequency and running the TV holographic system in a phase modulation mode. Several bending modes, familiar from classical beam theory, were identified during the experiments. In addition, another type of vibration was discovered, in which the primary motion was in the transverse plane of the log, causing deformation of the cross-sectional shape. The results show that the method is suitable for measuring vibration patterns on logs. This information may be used for nondestructively predicting interior structural properties.

Keywords: Nondestructive evaluation, vibration analysis, TV holography, laser interferometry

INTRODUCTION

Quality inspection of logs before sawing has always been important for sawmillers. Today, sawmills have visual inspection systems yielding knowledge about the exterior features of the logs. This information can be used for optimizing the sawing pattern, i.e. finding the combination of boards that maximizes the value yield. The shape and volume of the logs are the constraints in this optimization.

The quality of sawn lumber is, however, also influenced by the log's interior features. Indeed, defects, such as knots and decay, crucially affect the strength properties of lumber and also the visual appearance, which in some cases is even more important. A complete knowledge of these interior defects would, according to literature, make possible increases in value yield of 7–15% (Wagner and Taylor 1975; Harless et al. 1991; Steele et al. 1987).

Several technologies have been considered to detect the anomalies. Tomographic techniques such as X-ray (or gamma) computed tomography (CT) (Taylor et al. 1984; Holøyen and Birkeland 1987) and nuclear magnetic resonance (NMR) (Wang and Chang 1986) can locate interior defects with a spatial resolution far beyond the requirements. This type of scanning is still, however, too slow to be operated in an online sawmill system. Scanning systems involving ultrasonics have also been proposed and studied (Han 1991) for the same purpose.

This paper presents a new approach to the problem, namely to study the resonant vibrations of logs, and to see how the surface vibration patterns correlate to internal structural properties. Vibration analysis is different from the above techniques because there is no spatial scanning involved. In CT-scanning, the attenuation of X-rays following different, known paths through the object, is measured. In ultrasonics, even the path of propagation through the object may be unknown, since ultrasonic pulses do not necessarily follow straight lines, but tend to follow the grain. The vibration method described only imposes the signal, which is a vibrating mechanical force, at a single point on the object surface. The vibrational response on the entire object surface is measured simultaneously. Global dynamic properties of the object are measured, and a determination of some physical property into distinct volume elements as done in tomography is beyond the scope of the method. Nevertheless, local anomalies can be sensed due to their impact on the global vibration modes.

The scope of this paper is to present TV holography as a possible tool for performing vibration analysis. As will be seen, the technique is capable of measuring vibration patterns with good spatial resolution and over large regions. Later work will show whether vibration patterns actually represent a good basis for nondestructive assessment of interior properties.

THEORY OF VIBRATION

Natural vibration of wooden objects reflects the elastic property of wood. A set of vibration modes, or eigenmodes, constitutes the dynamic nature of an elastic object. Each eigenmode is characterized by its modal parameters, which are the resonant frequency, the dampening factor, and the mode shape. The resonant frequency is the frequency by which the mode is excited at its maximum, and it depends on the elastic parameters and the density distribution and geometry of the object. The dampening factor is for ideal elastic objects zero, but for real objects there is always some dampening.

The mode shape is the spatial deflection pattern of the vibrating object surface. Since the deflection pattern is time-varying, it must be described by two numbers; the amplitude, defined as the maximum deflection, and the relative phase of vibration. Points of zero amplitude are nonvibrating and are called nodal points.

Whereas the resonant frequency and the dampening factor can be computed from a local measurement on the object surface, a mapping of the mode shape requires measurements to be taken over the entire surface. Sometimes, however, the mode shapes are known a priori, and a single sensor situated on the object is sufficient to do the modal analysis.

When an elastic object is struck with a hammer, numerous vibration modes are excited concurrently. Another means of excitation is by letting a periodic force act upon the object. Then, by varying the frequency, the resonances can be sought out and the modes excited separately.

In general, the resonant frequencies and the mode shapes depend on the structural properties of the object and the boundary conditions. With known boundary conditions, one could extract information about the interior of a log on the basis of its dynamic behavior, i.e. the vibration.

There are two major methods of searching for the effect of interior defects on the eigenmodes. One approach is to build a physical model involving the anatomical structure of the log and the actual elastic parameters. One will have to deal with the orthotropicity of wood including the cylindrical principal axes of symmetry. By excluding knots, this problem should be possible to solve analytically. An analytical model would be fruitful in explaining the nature of the vibrations. However, when knots are involved, it is more realistic to deal with the problems numerically by using a finite element method.

The other method is—on the basis of experiments—to seek relations between qualitative classes of mode shapes and the distribution of defects. This is a phenomenological approach and it does not attempt to explain the vibrations. Despite the lack of a physical model, this approach might still be interesting from a technological point of view.

TV HOLOGRAPHY

Holographic interferometry enables accurate, full-field mapping of small dynamic surface displacements. The object is illuminated with laser light, and the scattered light is brought to interference with a reference signal.

In conventional holography, data are recorded on photographic film, which is a time-consuming process not suitable for vibration

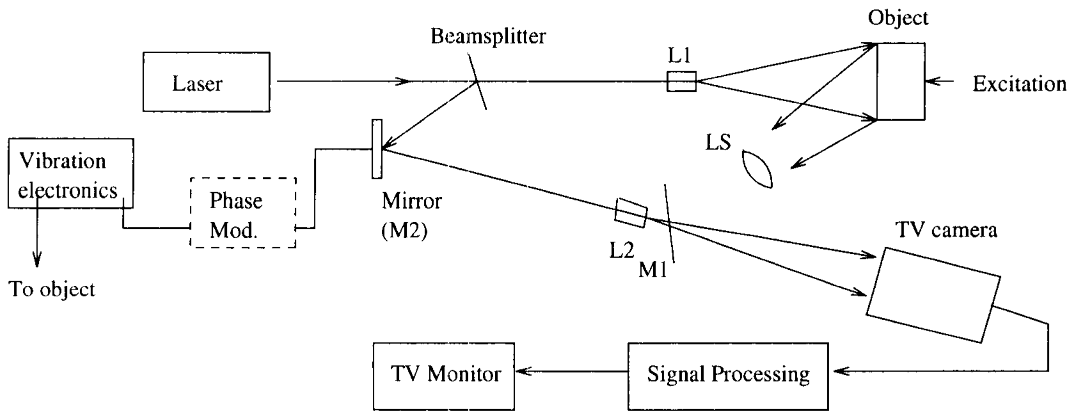

FIG. 1. ESPI setup based on a uniform reference wave.

analysis. TV holographic systems, or Electronic Speckle Pattern Interferometry (ESPI), applies video techniques for direct recording and display and may thus perform real-time measurements of dynamic displacements. ESPI is shown to be capable of measuring the vibration amplitudes between 0.01 nm and 10 μm over an area up to 1 m^2 (Løkberg 1984).

In general, TV holographic measurements can detect object surface deformation (Vikhagen 1990) and vibration. Here, only vibration will be considered, and indeed, only the special case of sinusoidally excited vibrations.

The basic principles of TV holography for vibration analysis

The most common method for doing ESPI vibration analysis is uniform reference ESPI (Løkberg 1984) which is illustrated in Fig. 1.

The light from the laser is split into two parts by means of a beamsplitter. The transmitted beam is expanded by a lens (L1) to illuminate the (entire) object. The object is imaged by a lens system (LS) onto the TV camera reflected by the mirror (M1).

The part of the beam reflected by the beamsplitter, the reference beam, is reflected from the reference mirror (M2). The reference beam is expanded similarly to the object beam, and they are combined and interfere at the TV camera.

Interference means that the two waves combine by the rules of superposition. The resultant intensity is dependent on both the amplitudes and the phase difference of the two waves.

The intensity in the interference pattern is transformed into a corresponding charge distribution on the TV camera and converted into a current variation—the video signal—as the target is scanned. The video signal is further processed before being displayed on the monitor.

Harmonic vibration-computation of amplitude and phase

To measure sinusoidally excited objects, the most commonly used technique is the time average method (Løkberg 1984) in which the object is simply recorded while it is vibrating. The time integration period is approximately the inverse of the video scanning frequency, 25 frames per second.

We assume the object to be vibrating with a single frequency f and with amplitude and phase distributions $a_0(x,y)$ and $\Phi_0(x,y)$. Then the local, time-varying displacement $u_0(x,y,t)$ can be written:

$$u_0(x,y,t) = a_0(x,y)\cos[2\pi ft + \Phi_0(x,y)]. \quad (1)$$

To find how the recorded image intensity I(x,y) relates to the vibration, we can directly use the results developed for conventional ho-

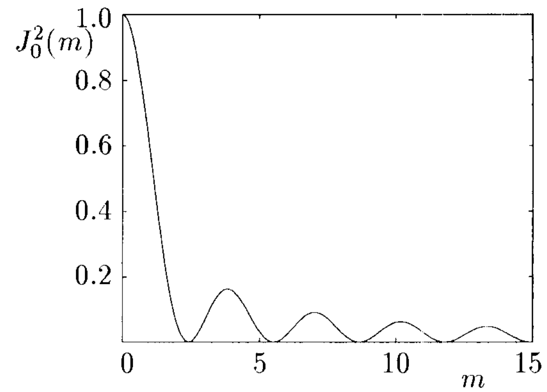

FIG. 2. The Bessel function of the first kind and zeroth order squared.

logram interferometry. From Løkberg and Slettemoen (1981) we get

$$I(x,y) \propto I_0(x,y)J_0^2[(2\pi/\lambda)a_0(x,y)\cdot(\cos\theta_1 + \cos\theta_2)], \quad (2)$$

where

$I_0(x,y)$ = intensity of interference image at rest,
J_0 = The zero order Bessel function of the first kind,
λ = wavelength of laser light,
θ_1, θ_2 = angles between displacement vector of the vibration and illumination-observation direction, respectively,

and we have assumed the number of vibration cycles recorded during each TV exposure to be an integer, or very large, that is $f \gg 25$ Hz.

We see from Eq. 2 that it is the amplitude of the vibration $a_0(x,y)$ that determines the measured intensity, whereas phase information $\Phi_0(x,y)$ is lost in the recording process. The intensity function is plotted in Fig. 2. As can be seen, $J_0^2(m)$ has an absolute maximum when the vibration amplitude is zero, i.e. there is no movement. The function also has local maxima for m = 3.8, 7.0, 10.2, 13.4, ... The recorded image of a vibration is a pattern of fringes where the areas of brightest intensity—corresponding to zero amplitude—are the nodal points/areas, and the fringes represent contours with equal amplitude.

If the object surface is perpendicular to the illumination and the observation direction, the angle factor in Eq. 2, $\cos\theta_1 + \cos\theta_2 \simeq 2$. The distance between neighboring maxima in the intensity function is approximately equal to π. Thus the second maximum corresponds to a vibration amplitude of about $\lambda/4$, and the fringes in general represent isoamplitude lines with an increment of $\lambda/4$. Furthermore, the visibility of the fringes decreases with increasing amplitude of vibration. With a laser wavelength at 0.5146 μm, this method allows for measuring amplitudes down to about 0.03 μm and up to a few micrometers depending on the noise. This is a rather poor range and for complex vibration modes, knowledge about the relative phase of vibration $\Phi_0(x,y)$ is also necessary to make a complete interpretation of the vibration.

A more detailed description of the vibration pattern can be obtained by combining time average ESPI with the so-called phase modulation principle. In Fig. 1, the reference mirror M2 is also put into vibration by the same device that supplies the excitations of the object. The vibrations of the mirror, described by the deflection $u_R(t)$, can therefore similarly be expressed by its frequency f, amplitude a_R, and phase θ_R

$$u_R(t) = a_R \cos(2\pi ft + \theta_R). \quad (3)$$

The resulting intensity distribution $I_{mod}(x,y)$ can be expressed as (Løkberg 1984)

$$I_{mod}(x, y) \propto I_0 J_0^2[(4\pi/\lambda)(a_0^2(x, y) + a_R^2 - 2a_0(x, y)a_R\cos[\Phi_0(x, y) - \Phi_R])^{1/2}]. \quad (4)$$

The intensity function in Eq. 4 is similar to the one in Eq. 2 with the same Bessel function. However, the argument now also contains the vibration phase $\Phi_0(x,y)$. By shifting the phase of vibration of the reference mirror with respect to the vibrating object, both amplitude and phase of the object vibration can be resolved from Eq. 4. If the object vibrates in a pure mode, only two phase shifts are necessary to compute the amplitude and phase distribution. This is because a standing wave pattern has only two phases separated by 180°.

By changing the amplitude of the mirror vibration, a_R, we see from Eq. 3 that the zero point for the vibration measurement can be shifted. The vibration amplitude can be optimized so that the zero point lies in the steepest part of the Bessel function, which is between the first maximum and the first zero point (see Fig. 2.). In this region, the intensity function is almost linear and very small vibrations can be detected. With sensitive photodetection, amplitudes down to 0.01 nm have been measured in this manner (Løkberg 1984). Moreover, the reconstruction formulas for vibration phase and amplitude become linear.

The vibration patterns can be observed in real-time by changing the reference mirror frequency to differ slightly from the excitation frequency of the object. This is very useful when scanning through a frequency range looking for the eigenmodes.

APPLICATION OF TV HOLOGRAPHY ON VIBRATION ANALYSIS OF WOOD

Although TV holography is an ultimate tool for measuring mode shapes of complex, small-displacement vibrations, its practical application in wood technology has been limited. One of the fields of applications is in acoustical testing of wooden instruments. Ek and Jansson (1986) used the TV holography system "Vibra Vision" with and without phase modulation to map the eigenmodes of violin plates. Similar work has been carried out at the Department of Applied Optics at the Norwegian Institute of Technology, Trondheim.

Vibration analysis, in general, has become increasingly focused in the field of non-destructive evaluation of wooden beams (Hearmon 1966; Chui 1991; Ohlsson and Perstorper 1991) For prismatic objects as are wooden beams bending modes can be described analytically. The resonant frequency can be expressed by the dimensions and the density and two elastic constants, namely the longitudinal modulus of elasticity and one of the shear moduli. When the resonant frequency is measured experimentally for, in this case, two modes, the elastic constants can be resolved. Additionally, torsional and axial vibration modes can be exploited in the assessment of the elastic parameters (Ohlsson and Perstorper 1991). It should be noted that for these techniques the vibrational response is measured only at one, or a few, spots on the object surface, leaving the actual mode shape unknown. Consequently, the identification of the different modes is not straightforward, but must be based on either a priori knowledge about the relation between resonant frequencies or on experience. Alternatively, the boundary conditions can be fixed by supporting the object at the nodal points of one specific mode in order to dampen all other modes. Only average dynamic properties can be derived from such single-point measurements, and in order to locate interior defects, one needs explicit knowledge about the mode shapes.

EXPERIMENTS

A RETRA 1000 (Conspec A/S, Trondheim) TV holography system was used for the vibration analysis. An Argon laser with the wavelength $\lambda = 514.6$ nm and power of about 200 mW supplied the interferometer (which in principle is the setup in Fig. 1) by an optical fiber. Four different phase shifts for each measurement were taken, at 0°, 90°, 180°, and 270°. The interferometer has built-in phase modulation. The system includes software to provide phase and amplitude mapping of the vibration.

An 80-cm long and 20-cm thick Norway spruce log was barked and covered with a retroreflective paint to improve upon the signals. The log and the interferometer were placed on a stabilized table with the longitudinal axis of the log perpendicular to the center of the laser beam. The entire front side of the log was illuminated by the expanded laser light. In addition, a small mirror (see Fig. 3) was placed

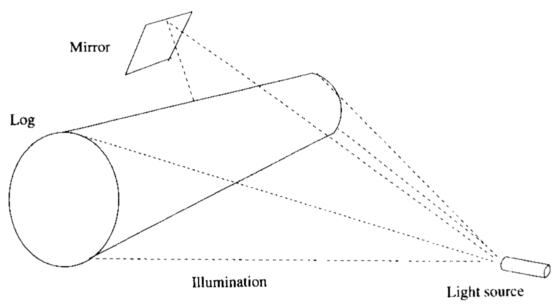

FIG. 3. Illumination of the log and the mirror. The mirror is imaging part of the back side of the log.

behind the log, ensuring that part of its back surface was illuminated and hence could be measured. The log was placed on rubber supports at the ends and excited sinusoidally by means of a nail-formed electromagnetic shaker put against the back surface, thereby imposing transverse vibrations.

The forced vibrations were in the frequency range of 500–5,000 Hz, which is in the audible range. By operating the system in phase modulation mode, with the reference mirror frequency slightly different from the excitation frequency, resonant vibrations could be seen in real-time. The eigenmodes were then recorded with the four phase shifts and averaged until the signal-to-noise ratio was satisfactory. The signal-to-noise ratio is proportional to the illumination, and it can be seen from the images presented later that this ratio is low at the log edges.

The signal processing unit calculated the vibration pattern in terms of amplitude and phase images. In the reconstruction formula, it was assumed that the object surface is perpendicular to the laser beam. This condition is satisfied only at the front part of the log since its boundary is cylindrical. Nevertheless, on the visible part of the log, the phase is correctly reconstructed. According to Eq. 2, the amplitude value should be multiplied by the cosine of the angle. However, when, only the mode shapes are of interest, and not the numeric value of the amplitudes, one does not have to carry out the amplitude correction.

RESULTS AND DISCUSSION

The frequency and the position of the transducer were varied, and several resonant frequencies were found. Some of the low frequency modes were classical in the respect that they appear in rod-shaped elastic objects described in classical theory of elasticity (Landau and Lifshitz 1959).

Figure 4 shows the mode shape of a classical

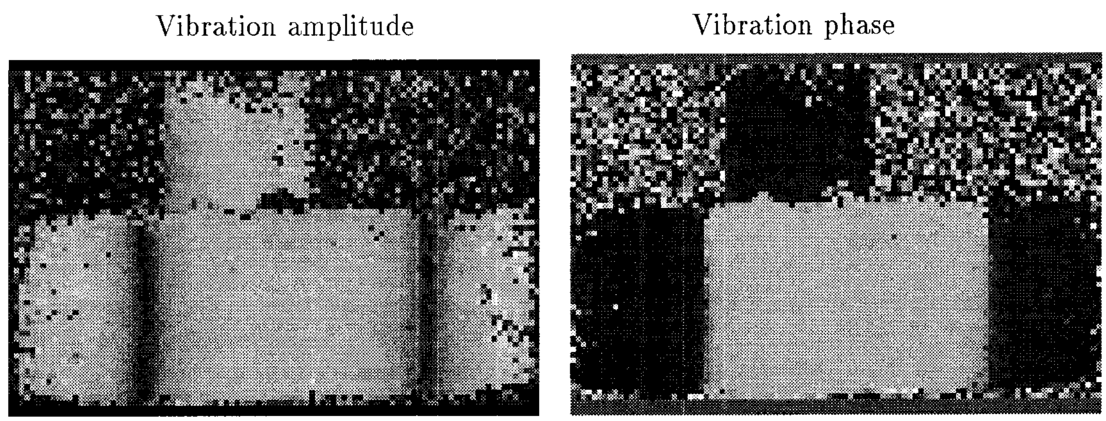

FIG. 4. The vibration pattern of a simple mode, with amplitude mapped in the left image and the phase in the right. The log is recognizable in both images, and the square above it is the mirror placed above the log imaging part of its back side. In the amplitude image, there are two black lines denoting zero amplitude, which are the node lines. In the phase image, the front log surface has three regions, with the ends separated from the middle by 180°. This mode is known as the first bending mode.

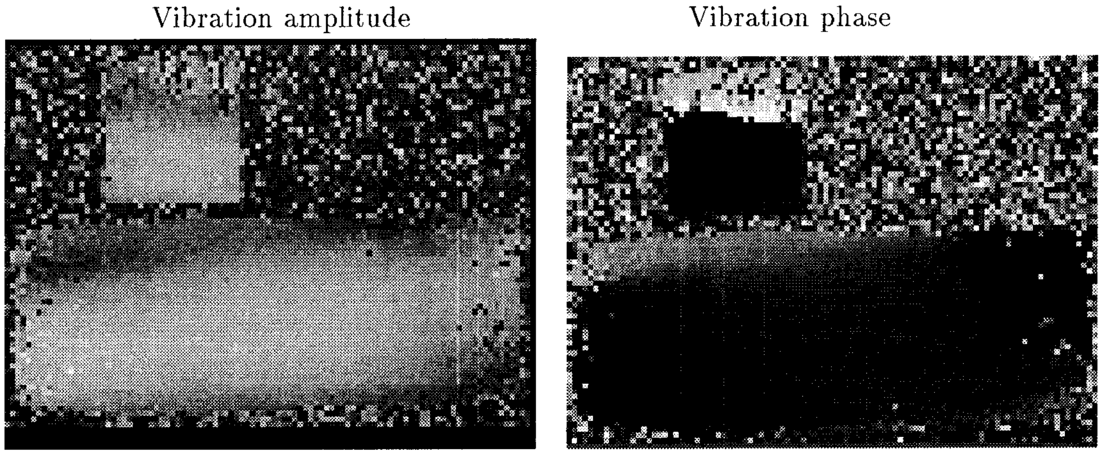

FIG. 5. Vibration mode occurring at 1134 Hz.

mode. Both the log and the mirror are recognizable in the two images containing the amplitude value and the relative phase of vibration. The log is located in the lower part of the images with the mirror on top imaging the log's back side. The remainder of the images is noise. The two vertical, zero-amplitude lines are the so-called nodal lines. They represent nonvibrating areas. The phase has a shift of 180° on the nodal lines, which means that the surface to left of a nodal line moves in the opposite direction compared to the area to right of it.

This type of vibration is characterized as *bending* and is familiar within wood technology from the theory of vibrating rods (Bodig and Jayne 1982). The mode in Fig. 4 is the first bending mode for a rod with free-ends boundary condition, according to the tabulated nodal positions (Bodig and Jayne 1982, page 273). The resonance frequency was 790 Hz. Higher order bending modes were also identified, although they were not as regular in shape. This is to be expected since bending theory does not apply to slenderness ratios, that is length-to-depth ratio, as small as 4 such as this case. Shear deformations tend to disturb the classical bending behavior. It should be noted for the bending mode that, in the mirror, the phase value is opposite to the corresponding position at the front, which means that the back side moves in synchronization with the front; the shape of the cross section is, as a first approximation, kept constant.

Apart from the bending modes another type of vibration was also found. Figure 5 shows the simplest mode shape of this type which occurred at 1134 Hz. A striking feature of this vibration pattern, compared to that of the bending modes, is the absence of vertical node lines. This implies that the whole front side moves synchronously, and the deflection seems to be independent of the longitudinal position. Additionally, the phase in the mirror is equal to the phase at the front, which means that opposite sides of the log move in opposite directions. Furthermore, the top and bottom of the log seem to contract as the front and back extend. A cross section of the log vibrating in this manner is illustrated in Fig. 6. This pulsating kind of vibration, with deformation of the cross-sectional shape as the primary motion, also occurred at higher frequencies. Higher frequencies yielded more complex mode shapes, and knots seemed to affect the vibration patterns. This can be explained by the fact that these vibration modes involve radial deformation, and the knots represent areas of higher radial stiffness than does clearwood.

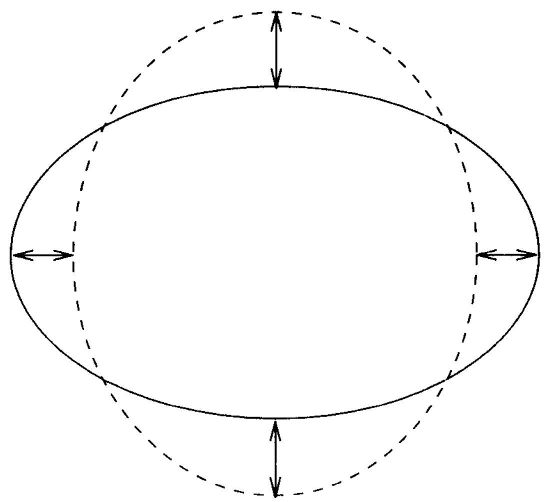

FIG. 6. Mode with the primary deformation in the transverse plane (cross section of the log).

CONCLUSIONS

TV holography has proven to be capable of measuring vibrations on the surface of an 80-cm-long spruce log. The length of the log may, with the described setup, be increased to two meters.

The results indicate that two types of transverse vibration modes can occur in logs. One type is the classical bending, known from nondestructive testing of wooden beams. The other involves normal deformation in the radial and tangential directions. This latter type of movement may be sensitive to knots, which represent parts of the log having increased radial stiffness and thus the tendency to counteract the vibration.

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