Partial modal analysis for health assessment of living trees

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ABSTRACT

Rot in living trees cause substantial losses in forestry. Traditionally forest stands have been evaluated by visual assessment. In this paper a new non-destructive assessment method based on the impact excitation method is proposed.

The trunks of living trees were excited by an impact hammer, and the vibrations were measured. A detector function describing the expected frequency for a sound tree was derived by analyzing the resonance frequencies, circumferential mode shapes and propagation velocity of a surface wave.

Experiments were carried out on the 93 trees of species Norway spruce. The partial mode shape was used to ensure that the corresponding resonance frequencies are compared to each other. It was found that the detector was successful and outperformed assessments by forestry experts.

The joint information on modes and propagation velocity can be used to discriminate sound trees from decayed trees.

Wave propagation velocity is lower for decayed wood.

1. INTRODUCTION

Most trees are susceptible to fungi. The fungus attacks host tree via roots that are in contact with root systems of already infected trees, or via spores entering the trunk through injuries. The wood structure decays when the fungus converts constituents of the cell walls into moist and swampy [1] nutritious carbons. The uninjured outer wood of a living tree is generally more resistant to decay than the inner wood. In butt rot often there are no external signs unveiling the decay.

During the progress of decay, the mechanical properties of the wood are altered. The modulus of elasticity and shear, and the density, decrease. Thus, wave propagation velocities, which are dependent on the square root of the ratio of the modulus to the density, are lower for decayed wood than for sound [4].

Responses from trunks of living Norway spruce to impacts of hammer blows were measured and resonance frequencies and mode shapes were determined. Furthermore, the propagation velocity of surface wave traveling along the circumference has been estimated.

The circumferential mode shapes are used to enable a comparison of resonance frequencies on a tree-to-tree basis. Then, based on a subset of sound trees, a prediction function yielding the expected resonance frequency of a certain mode, given the circumference and the propagation velocity, is formed. This prediction function is used in a detector, whose performance is evaluated for 93 trees.

2. MATERIAL AND METHODS

2.1. Material and Measurement Setup

Preliminary measurements/observations

The circumference and two perpendicular diametric measures were measured, remarks were made on factors that might influence the outcome of the experiments, e.g. strange cross section geometry, resin exudation, unusually many dead branches, and injuries

Excitation

Excitation is applied by hand force using impact hammer (weight 0.2 kg) onto a screw that is firmly attached to the sapwood at a position midway between two consecutive sensors.

Response

Twelve accelerometers positioned equidistantly around the cross sections. The responses of the cross sections in terms of the radial components of the vibrations were sampled from the sensor outputs (rate F_S=100 kHz) and stored for post-processing.

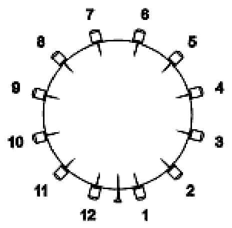


Figure 1 a: Distribution of accelerometers and a screw around the cross section

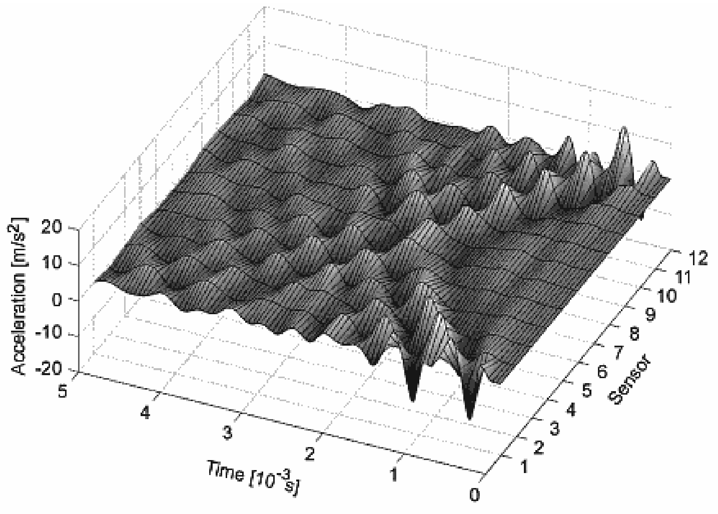


Figure 1 b: Initial response from a sound tree

Classification

After the set of experiments, the status of each tree was determined by studying the tree fell cut at ground level. The trees were classified into five groups:

Sound I	No signs of decay and no comments on injuries etc.
Sound II	No signs of decay, but comments on injuries or limited resin exudation.
Decay I	Incipient decay. Light-shaded discoloration of the still hard wood.
Decay II	Advanced decay. Dark-shaded discoloration of the still hard wood and minor changes of the texture.
Decay III	Final stage of decay. Soft, moist and brownish wood.

2.2. Modal Analysis of Isotropic Cylinders

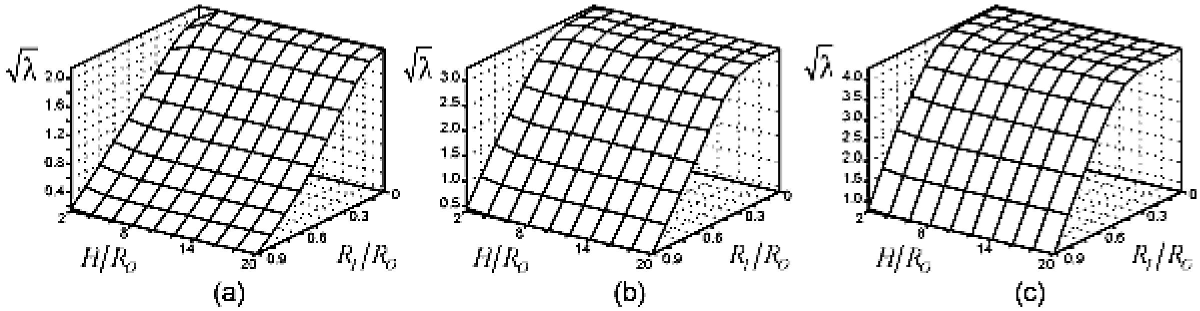
Finite Element Model

Using the Ritz analysis, the kinetic and potential energies T and V, respectively, are calculated over the body, with the coefficients of the power series serving as a generalized coordinate system. The principle of conservation of energy is invoked. An energy function $L=V_{max}-T_{max}$ is formed, and minimized with respect to the unknown coefficients of the power series. This results in a generalized eigenvalue problem, from which the eigenvectors yield the coefficients for the power series, and the associated eigenvalues the resonance frequencies.

Calculations based on Ritz' method have been performed for a large number of cases of height-to outer radius ratio H/R_O and inner radius-to-outer radius R_I/R_O, The non-dimensional frequency $\lambda^{1/2}$ is related to the dimensional frequency in Hz by:

$$\boxed{F = \frac{\lambda^{1/2}}{2\pi R_O}\sqrt{\frac{G}{\rho}}} \qquad (1)$$

F → Dimensional frequency
G → Modulus of shear
ρ → Density
$\lambda^{1/2}$ → Non-dimensional frequency



Mode 2 Mode 3 Mode 4

Figure 3: Non-dimensional frequencies for the lowest resonance frequency of the circumferential mode shape

Inference

1. For $H/R_O > 6$ – No substantial influence on frequencies and all cross sections of the cylinder vibrate in an in-phase motion.
2. For an increasing ratio of R_I/R_O, the resonance frequency of the lowest mode (m=2) is altered at an earlier stage than m=3, and m=3 earlier than m=4.

3. For cylinders with sufficiently large ratio H/R_O, the frequency may be considered dependent only on the ratio R_I/R_O, and the best indicator for this ratio is the mode m=2.

H/R_O ranging from 2 to 20 and R_I/R_O ranging from 0 (solid cylinder) to 0.9. The results are based on a Poisson's ratio of 0.3 and free-free end conditions [2].

2.3. Modal Model and Signal Analysis

Assumptions and Approximations

1. Though wood is non-homogeneous and orthotropic, for freshly cut spruce logs undergoing continuous sinusoidal excitation in the radial direction, circumferential modes arise in the vicinity of the cross section where the exciting force is applied. Thus, the modal model of the measured response is derived from the HILE case [5].
2. Wood is considered linearly elastic for a certain range of the exciting force. It has been established that the impacts by the hammer blows by hand force are within the linear region: the effect of varying exciting force is limited to a common scaling of the signals measured around the cross section.
3. The sampled signal $y_k(n)$ from the output of sensor k, positioned at angle θ_k taken from the point of excitation, is modeled by a sum of exponentially damped sinusoids:

$$s_k(n) = \sum_{i=1}^{I} W_{i,k} \alpha_i^n \cos(2\pi f_i n + \psi_i) \qquad (2)$$

$$y_k(n) = s_k(n) + \eta_k(n) \quad n = 0, 1, 2 \ldots \qquad (3)$$

$$W_{i,k} = A_i \cos(m_i \theta_k + \phi_i) \qquad (4)$$

Parameters for the i^{th} natural frequency

n → Sample time index
$\eta_k(n)$ → Measurement noise
A_i → Amplitude
α_i → Damping
f_i → Normalized frequency (F/F_S)
ψ_i → Temporal phase
m_i → Circumferential mode #
ϕ_i → Spatial orientation
$W_{i,k}$ → Weight function

Evaluation of Modal Parameters

The resonance frequencies, damping factors, temporal phases, and weights are estimated using Prony's method (Kumaresan and Tufts 1982), a high-resolution frequency analysis method based on linear prediction. It is capable of resolving closely spaced frequency components, but the estimates of damping factors and amplitudes are highly influenced by the presence of noise. With the sensors equidistantly distributed along the circumference [$\theta_k=(2k-1)\pi/12$], the parameters A_i, m_i and ϕ_i are estimated from the set of weights $W_{i,k}$, $k=1...12$, using the discrete Fourier transform. The analysis is performed at the onset of steady-state; approximately 4×10^{-3} s for the response in Fig.1 (b).

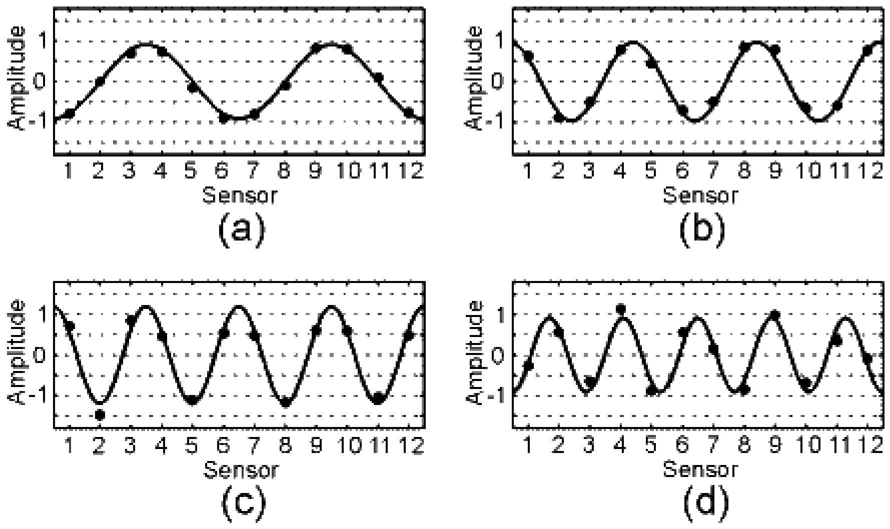


Figure 4: Mode shape identified from the Prony Weights for Sound tree

(a) m=2 found at 780 Hz, (b) m=3 at 1136 Hz, (c) m=4 at 1408 Hz, and (d) m=5 at 1627 Hz circumference 0.90 m

Evaluation of Propagation Velocity

As can be noted in Fig.1 (b), there seems to be a surface wave propagating from the point of excitation in both directions along the circumference. The propagation velocity is estimated using a technique based on Delay-and-Sum beam-forming (Johnson and Dudgeon 1993), with the summation replaced by singular value decomposition. This allows a robust criterion to be defined for when the sensor outputs are aligned to each other.

To reduce interference, the wave heading in one of the directions is suppressed by spatiotemporal filtering. It has been shown that the algorithm is capable of producing estimates with only small errors even when the sensor locations are randomized in the vicinity of the presumed positions (Axmon 2000).

Interpretation of Modal Analysis Results

The results from the modal analysis of the trees are shown in Fig.5 (a), where the resonance frequency of the mode m=2 is plotted versus the circumference. The mode m=2 was found for 93 of 94 trees, m=3 for

70, m=4 for 38 and m=5 for 16. For the tree in Sound I with the least dimensions, no modes were detected. It is obvious that the resonance frequencies of the sound trees, despite the varying dimensions, are approximately proportional to the reciprocal of the circumference. Proportionality would by expected for HILE cylinders of substantial ratio H/R_O and with similar ratios of R_I/R_O. The spread is, however, large. One of the assumptions made is that the loss of elasticity due to decay may be modeled as introducing a hole in the trunk of a sound tree; many of the decayed trees possess lower frequencies than sound trees of matching dimensions, but there is a considerable overlap between the groups.

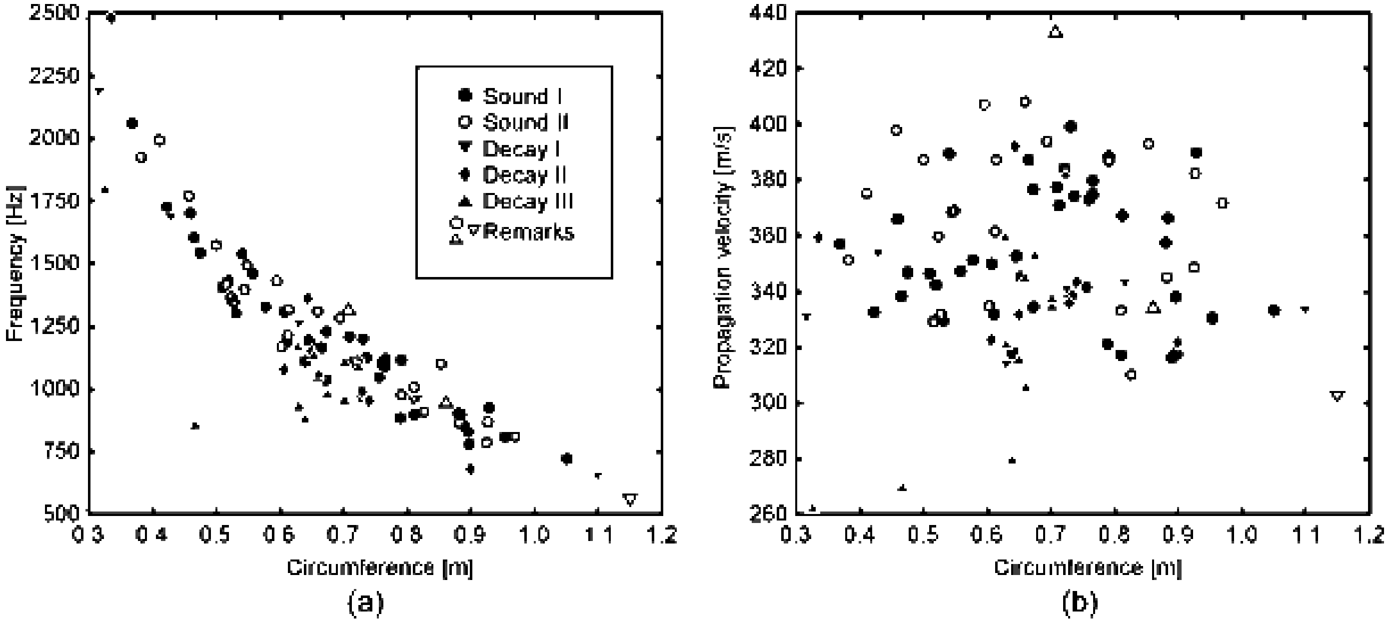


Figure 5: Analysis results

(a) Resonance frequencies for the circumferential mode m=2

(b) Propagation velocities of the surface wave. Based on 93 trees (65 sound, 28 decayed)

The results concerning the propagation velocity are shown in Fig.5 (b). It can be noted that many of the decayed trees exhibit velocities below the average of sound trees. The velocities of sound trees are almost uniformly distributed over the interval 315 to 395 m/s. There is, however, a tendency of decreasing velocity for increasing circumference.

2.4. Regression Analysis

It is expected for sound trees that if they behave like HILE cylinders, $\hat{x}_p$ will not depend on the circumference or the propagation velocity. However, the linear regression for Sound I shows [Fig.6 (a)] that the weights seem to increase with increasing circumference, and decrease with increasing velocity.

$$\hat{x}_p = \frac{\hat{F}_p \hat{C}_p}{\hat{v}_p} \tag{5}$$

Parameters for the pth tree

$\hat{x}_p$ → Weights for non-dimensional frequency

$\hat{F}_p$ → Resonance frequency

$\hat{C}_p$ → Circumference

$\hat{v}_p$ → Propagation velocity

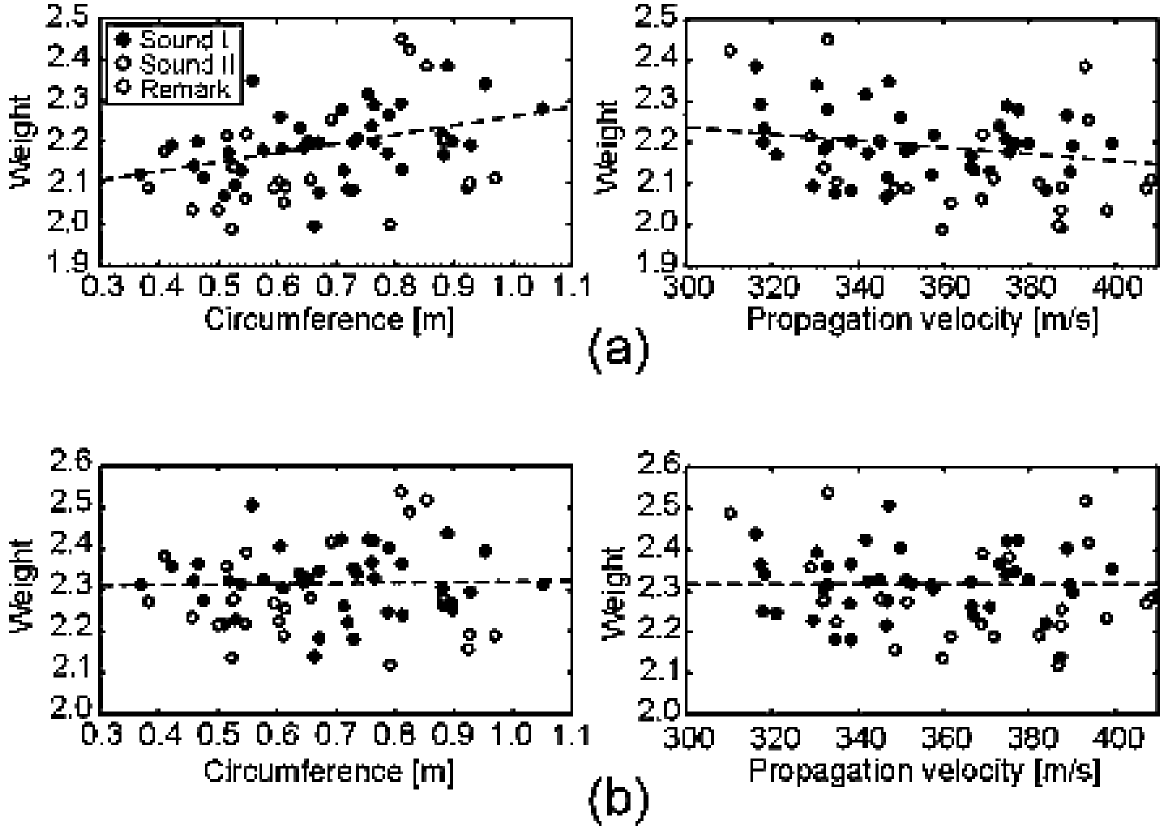


Figure 6: Linear regression (line) for Sound:

Non-dimensional frequencies (a) prior to and (b) after adjustment for dependency on variables circumference and velocity.

$$\hat{F}_p = G(C_p, v_p, a_0, a_1, a_2) + e_p \qquad (6)$$

$$G(C_p, v_p, a_0, a_1, a_2) = \frac{a_0}{C} v(1 - a_1 C)(1 - a_1 v) \qquad (7)$$

$$\breve{x}_p = \frac{\hat{x}_p}{(1 - \hat{a}_1 \hat{C}_p)(1 - \hat{a}_2 \hat{v}_p)} \qquad (8)$$

Parameters for the pth tree of 42 Sound I trees

$\hat{F}_p$ → Resonance frequency

$G(C_p, v_p, a_0, a_1, a_2)$ → Expected frequency of a sound tree

e_p → Residual

$\hat{C}_p$ → Circumference

$\hat{v}_p$ → Propagation velocity

$\breve{x}_p$ → Adjusted weights for non-dimensional frequency

The regression model is given by equation (7). The parameters a_0, a_1 and a_2 are estimated for the trees in Sound I using non-linear regression based on Gauss-Newton's method (Rawlings 1988). The estimates are $\hat{a}_0=2.32$, $\hat{a}_1= -1.00\times 10^{-1}\ \text{m}^{-1}$ and $\hat{a}_2=3.23\times10^{-4}\ \text{sm}^{-1}$.

2.5. Detector

The pth tree in the database is considered sound only when the following two conditions on which the detector is based are met:

1. A threshold, Δ, for the residual between the estimated frequency of the tree under test and predicted frequency of a sound tree with matching circumference and propagation velocity.
2. An additional threshold v_{low} applied to the velocity, since was observed that all sound trees studied had propagation velocities above 310 m/s

The performance of the detector is evaluated by means of the epidemiological measures sensitivity and specificity.

Sensitivity = (# of decayed trees detected as decayed) / (total # of decayed trees)

Specificity = (# of sound trees detected as sound) / (total # of sound trees)

As large figures as possible are desired; for non-overlapping groups, it is possible to achieve 100% jointly. However, when there is an overlap, there is a trade-off to be made.

3. RESULTS

For a residual threshold Δ in the range of 1 to 120 Hz and a velocity threshold v_{low}=310 m/s, all 93 trees were evaluated for a sensitivity and specificity analysis. A simultaneous sensitivity and specificity of approximately 74% was achieved for Δ=53 Hz. To increase the likelihood of that a tree detected as decayed actually is decayed, Δ>53 Hz should be used. Conversely, to increase the likelihood of that a tree detected as sound actually is sound, Δ<53 should be selected. However, in the former case, more of the decayed trees will be detected as sound, and in the latter, more of the sound trees will be detected as decayed. Trade-offs should be made on the basis of sensitivity and specificity.

4. CONCLUSIONS

Comparing the performance to the visual assessment reported, where five foresters assessed a large number of trees, it was found that requiring an agreement in the assessment, only 11% of the sound trees and 24% of the decayed trees were correctly identified by the experts. When instead using the majority's decision, i.e., when at least three of five foresters made the same assessment of a tree, 53% of the sound and 67% of the decayed trees are identified. These figures correspond to specificity and sensitivity, respectively. Hence, it is concluded that the proposed method is more reliable than visual tree assessment [6].

5. REFERENCES

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