Doctoral (PhD) thesis

APPLICATION OF THE FOURIER TRANSFORMATION ON THE DENSITY FUNCTION OF TREES

Csóka Levente

Sopron
2007

Introduction

Timber is a biosynthetic end product and, therefore, the making of wood is a function of both gene expression and the catalytic rates of structural enzymes. Thus, to achieve a full understanding of wood formation, each component of the full set of intrinsic processes essential for diameter growth (i.e. chemical reactions and physical changes) must be known and information on how each one of those components is affected by other processes.

Juvenile and mature wood refers to two main zones of the xylem. The younger juvenile wood produced in the crown has features which distinguish it from the older, more mature wood of the bole. Variations within a species are caused by genetic differences and regional differences in growth rate. Differences also occur between the juvenile and mature wood within single trees, and between the earlywood (springwood) and latewood (summerwood) within each annual growth ring.

Juvenile wood is an important wood quality attribute because depending on species, it can have lower density, has shorter tracheids, has thin-walled cells, larger fibril angle, and high – more than 10% – lignin and hemicellulose content and slightly lower cellulose content than mature wood. Wood juvenility can be established by examining a number of different physical or chemical properties.

Juvenile wood occupies the center of a tree stem, varying from 5 to 20 growth rings in size, and the transition from juvenile to mature wood is gradual. This juvenile wood core extends the full tree height, to the uppermost tip.

Juvenile wood is unsuitable for many applications and has great adverse economic impact. Juvenile wood is not desirable for solid wood products because of warpage during drying and low strength properties and critical factors in producing high stiffness veneer. In the other hand, in the pulp and paper industry juvenile wood has higher than mature wood in tear index, tensile index, zero-span tensile index, and compression strength. For the same chemical pulping conditions, pulp yield for juvenile wood is about 25 percent less than pulp yield for mature wood.

The development of juvenile wood formation was studied by many authors in the last 50 years who formulated several hypotheses. Juvenile wood become especially interesting for forestry because of the short rotation cycle, typical of plantation forestry. The percentage of juvenile wood is consequently greater within the tree stem, which has a major effect on wood property and product quality, especially in conifers. The juvenile wood boundary can be determined by examining a number of different physical or chemical properties.

Many studies in the area of wood anatomy use only one or two wood attributes to define the demarcation between juvenile and mature wood. Such methods have been widely accepted as the norm for assessing wood juvenility. Unfortunately these studies did not take the complexity of the stem into account. For example, for a long time, the measurement of annual ring width, specific gravity, tracheid length and microfibril angle have been the most prevalent methods. Studies in this area focused on the nonlinear, segmented regression method. Based on these methods, the transition is referred to as a zone of gradual changes, rather than a definite line. These studies have provided a common and simple tool for analyzing the growth variation, and are not restricted to certain species groups or types of data. The global nature of the above mentioned processes hides local density-distribution information, and makes the determination of distance-related changes impossible.

The complexity of the X-ray density profile is disregarded and this may lead to diverse results. The purpose why the X-ray density function (XDF) is quite complex is that it is treated to many different environmental factors, such as, rainfall, soil and site conditions, temperature, etc. The XDF of a tree is a result of the superposition of these factors and we may assume that each of the environmental components cause periodic changes in density along the radius. The wavelet transform handles the XDF in its intricacy because from a one-dimensional density set it creates a diffuse, two-dimensional distance-frequency image, using all of the information that had been recorded by the X-ray process. In that transform the density of annual rings and their distances from the pith are investigated simultaneously, that were so far considered independent properties. A complete description of the determination of the transition from juvenile to mature wood based on the X-ray density profile can be found in several publications.

The research has been documented and published in the following publications

1) Csoka, L., Zhu, J., Takata, K. (2004) Application of the second order Fourier transform on the density function of sugi trees. Faipar 52:12-18

2) Csoka, L., Zhu, J., Takata, K. (2005) Application of the Fourier analysis to determine the demarcation between juvenile and mature wood. J Wood Sci 51:309-311

3) Csoka, L., Divos, F., Takata, K. (2007) Utilization of Fourier transform of the absolute amplitude spectrum in wood anatomy. Applied Mathematics and Computation (under publishing: doi: 10.1016/j.amc.2007.03.073)

4) Csóka L. Fourier transzformáció alkalmazása a fa sűrűség eloszlási görbéin NyME-FMK, MTA-VEAB, STT 2006. Március 14. Sopron

5) Csoka, L., Zhu, J., Takata, K. Application of the second order Fourier transform on the density function of sugi trees. IWT, Akita Prefectrual University, Noshiro, Japan. May 11, 2004.

6) Feher, S., Takata, K., Csoka, L. Variation of wood density and MOE in plus tree clones planted in different sites. 55th Annual Meeting of the Japan Wood Res. Society, Kyoto, Japan. March 16-18, 2005.

7) Csoka, L., Divos, F., Takata, K., Grabner, M. Evaluate the demarcation between the juvenile and mature wood with different methodologies. JSPS Japan and Hungary Research Cooperative Program/Joint Seminar. Oct. 16-19, 2006. IWT, Akita Prefectrual University, Noshiro, Japan. IUFRO Unit 5.02.01 and 5.01.06

8) Varga, D., Takata, K., Feher, S., Kitin, P., Csoka, L. Wood density and growth ring structure in *Cryptomeria japonica*. JSPS Japan and Hungary Research Cooperative Program/Joint Seminar. Oct. 16-19, 2006. IWT, Akita Prefectrual University, Noshiro, Japan. IUFRO Unit 5.02.01 and 5.01.06

Many studies were based on the differences in the intra ring density profiles within the two main zones of the xylem. Recently, an excellent introduction to nonlinear mixed-effects model analysis was given that employs the average density profile to model the growth of Scots pine trees statistically. They treat the density function according to its nature as a time-series characteristic, but using only the average density of annual rings.

Our work focuses on developing an understanding of the growth of individual trees along the radius of its bole through different mathematical procedures. The Wavelet analysis is considered as a cost effective and fast analysis that is appropriate for large samples and may be capable of clear separation in the tree stem. The density function contains inherent information about changes in successive annual rings that may after an appropriate mathematical analysis procedures, be used to describe the wood's microstructure.

The prevalent wavelet analysis's utility lies in its ability to analyze localized variations of force within a time sequence. The density distribution is a type of time series in which the annual growth is recorded in distance domain from the pith to the bark. For each successive peak of density function we seek an answer to the question: which is the peak that would follow according to the natural logic of growing. Fourier analysis is a powerful tool for interpreting the meaning of this function, because it considers the complex interaction between annual ring with and density variation.

The density function is a result of the superposition of many different environmental factors, such as, rainfall, soil and site conditions, temperature, etc. We may assume that each of these factors cause periodic changes in density along the radius. If we can identify each of these effects, we shall have an ultimate understanding of the nature of wood formation that goes beyond simple annual ring analysis. Above all, it gives a true image not only of the structure, but also the essence of wood material itself. The wavelet transform is opened a new approach in processing geophysics and atmospheric events and similarly these usage of density function example provides a substantive addition to understand the growth of trees.

Spectral wavelet and Hurst analysis were performed on representative sugi trees (Cryptomeria japonica D. Don) X-ray density function to show that this density function carries information about anatomical variations.

Materials and methods

Sample preparation

Seventeen selected trees, from plantations and natural forest in Akita Prefecture, Japan, were investigated. The name of the tree is sugi (Cryptomeria japonica D. Don). The trees were harvested in different ages between 28 and 221 years. Tracheid lengths and annual ring structure were determined from those samples.

X-ray densitometry

Bark to bark radial strips of 5 mm thickness were prepared from the air-dried blocks cut from the sample disks. After conditioning at 20 oC and 65% RH, without warm water extraction, the strips were X-rayed onto film using 340 seconds of irradiation time. The current intensity and voltage were 14 mA and 17 kV, respectively. The distance between the X-ray source and the specimen was 250 cm. The developed films were scanned with a densitometer (JL Automation 3CS-PC) to obtain density measurements across the growth rings.
The growth ring parameters of ring width (RW), minimum density within a ring (Dmin), maximum density within a ring (Dmax) and ring density (RD: average density within a ring) were determined for each growth ring by a special computer software. The latewood is categorized by Mork's definition, as a region of the ring where the radial cell lumens are equal to, or smaller than, twice the thickness of radial double cell walls of adjacent tracheids. A threshold density of 0.55 g/cm3 was used as the boundary between earlywood and latewood.
The development of x-ray based density analysis should not only be focused on the ring but also on the structures within the ring. As noted by Barbour et al. (1997), it should be possible to detect structures within the ring that are produced during the earlywood or latewood formation. In addition, it allows accurate measurement of density distribution within samples, and can provide detailed information on the distribution of chemical elements.

Density function

Density function is a 1 dimensional continuous signal, which describes the density distribution from the pith of a wood sample to the bark. Wood density is related to ring growth and its variation has been represented on a density function. To gain any new information about the relationship between radial distance and density, we should investigate these factors together, otherwise these attributes show as independent properties. Densitometer provided the distance in millimeters. Distinctive density function characteristics are apparent near the pith and bark respectively.
Difficulties can arise in determining the sampling range due to differences in cambial activity. The first one to four rings of tree development are disregarded according to a method that we will discuss in a later article. Accurate determination of this sampling domain is one of the key requirements to improve our understanding of wood formation. For example, different approaches yielded widely varying estimates of juvenile and mature wood within individual trees. As results show there is only one sampling range that gives appropriate outcome.

Fourier analysis

Fourier transforms are classical tools in signal processing where the measurement of spectra is used to characterize time-dependent processes. Consequently, there are many ways of transforming signals and image data into alternative representations that are more amenable for certain types of analysis.

Wavelet analysis

The wavelet transform is a mathematical transform similar to the commonly known Fourier transform but it is a better alternative to complexity receive both distance and frequency information. Wavelet transformation uses windows of different sizes and positions to analyze a signal which gives fine resolution and controllable manner without restriction on the scale of detectable phenomena. The wavelet transform can be used to analyze time series that contain non-stationary power at many different frequencies.

Wavelet transform is capable of providing the distance and frequency information simultaneously. The nature of a tree's density function is always non-stationary and wavelet analysis was selected to extract the relevant distance-density information from the signal. In this paper the Morlet and Paul mother-wavelet basis transformation were selected for spectral analysis and resolving strong frequency components. In the course of wavelet transformation the factors of Morlet and Paul wavelet are very important, because these changes both peak height and range of effect. Basically in many geophysical phenomena an *omega* between 5 and 6 is used retain distance or time domain precision and were choose in our investigation too.

Hurst exponent

The statistical operation, Hurst exponent, measures the fractal dimension of a time set. According to the Hurst equation the parameter H is known as the Hurst exponent, and its values range from 0 to 1. The Hurst (rescaled range) analysis is non-parametric; there is no assumption or requirement of the shape of the underlying distribution. The set of XDFs are similar to log-normally distribution. Series with H values above 0.5 are persistent series which contain a memory effect. Each data value is related to some number of preceding values. The H plot gives some explanation of a cycle time, over which there is dependence upon the past. These data series reverse signs less frequently than would be true for white noise.

Main conclusions of this research work

The main conclusions of this doctoral work can be summarized as follows:

1) This part is the main theme of the thesis, which is the first consideration of the Fourier transform of the absolute amplitude spectrum in closed form:
$$\sum_j \cos(2\pi k_{0j} x) \Rightarrow \left| \sum_j e^{-i2\pi k_{0j}\ell} \right|$$
2) In the case of complex, continuous functions, the locally minimum points of the repeated Fourier spectrum refer to non-periodic places in the original dataset.
3) After it was verified that the repeated Fourier transform has strong connection with its original function it can be stated that this method is a possible tool in wood anatomy research.
4) It has been found that Wavelet transform method is a characteristic step of wood research. It has been proofed that with Wavelet transform it is possible to determine the demarcation between juvenile and mature wood on the basis of density function.
5) It has been verified with the autocorrelation and Hurst exponent analysis that X-ray based method gives authentic way about the growth of trees.
6) It has been assumed that in spite of the environmental circumstances of the different plantation sites, individual clone types can preserve their own characteristic.
7) On the basis of the completed research work it can be stated that juvenile and mature wood zone are well separate-able one and contradicts the frequent opinion that juvenile zone is gradually turn to mature wood.