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RAPID COMMUNICATION

Levente Csoka · Jianjun Zhu · Katsuhiko Takata

Application of the Fourier analysis to determine the demarcation between juvenile and mature wood

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Key words Fourier analysis · Juvenile/mature wood · X-ray densitometry · Tracheid length

Introduction

Juvenile wood produced in the crown has features that distinguish it from the older, more mature wood of the bole. Juvenile wood has important wood quality attributes because, depending on the species, it can have lower density and has shorter tracheids, thin-walled cells, larger fibrial angles, high – more than 10% – lignin and hemicellulose content, and a slightly lower cellulose content than mature wood.[1,2] Wood juvenility can be established by examining a number of different physical or chemical properties. Juvenile wood is not desirable for solid wood products because of warpage during drying, low strength properties, and other factors considered critical for producing high-stiffness veneer.[3]

Fourier transformation is an extremely useful mathematical tool that has been applied in the quantitative analysis of many physical processes. Fourier transformation can be represented as a series of sine and cosine functions.

Density spectra derived from X-ray imaging provide new information in the nondestructive testing of wood. Until recently, testing for wood juvenility required wood samples to be milled, dissolved in acids, and painstakingly analyzed for certain anatomical features. The new method proposed in this report opens a new possibility for minimizing the time required to analyze wood formation.

The main purpose of this report is thus to demonstrate how to distinguish juvenile wood from mature wood by Fourier analysis of density distribution curves. It is also the first study to employ Fourier analysis-assisted assays of the boundary line between juvenile and mature wood.

Materials and methods

Sample preparation

Eleven Japanese cedar trees (sugi; *Cryptomeria japonica* D. Don) from Akita Prefecture in Japan were selected for the assay. Trees were aged between 71 and 102 years (Table 1).

X-ray densitometry

Bark-to-bark radial strips, 5 mm thick, were prepared from the air-dried blocks cut from the sample disks. After conditioning at 20°C and 65% relative humidity (RH), without warm water extraction, the strips were X-rayed onto film for 340 s of irradiation time. The grain of the wood samples was arranged to be parallel to the X-ray beam. The current intensity and voltage were 14 mA and 17 kV, respectively, and the distance between the X-ray source and the specimen was 250 cm. The developed films (Fig. 1) were scanned with a densitometer (JL Automation 3CS-PC) to obtain density measurements across the growth rings (Fig. 2).

The development of X-ray-based density analysis should not only focus on the growth ring, but also on the structures within the ring.[4,5] As noted by Barbour et al.,[6] it should be possible to detect structures within the ring that are produced during 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.[7]

L. Csoka[1] (✉) · J. Zhu[2] · K. Takata
Institute of Wood Technology, Akita Prefectural University, Noshiro 016-0876 Japan

Present addresses:
[1] University of West Hungary, Sopron 9400, Hungary
Tel. +36-99-518-305; Fax +36-99-518-386
e-mail: lcsoka@fmk.nyme.hu
[2] Forestry and Pomology Research Institute, Shanghai Academy of Agricultural Sciences, Shanghai 201106, China

Table 1. Transition between juvenile and mature wood as determined by measuring tracheid length and application of Fourier analysis

Sample tree	Tree age (years)	Results from previous work[a]		Second FT spectrum	
		Annual ring number from pith	Distance from the pith (mm)	Annual ring number from pith	Distance from the pith (mm)
T6	75	21–22	71–74	21–22	73.15
T8	71	24–25	61–64	24–25	63.43
T9	73	22–23	54–56	22–23	55.14
T10	73	16–17	40–43	17–18	44.03
IV1	93	10–11	36–41	10–11	40.30
IV2	94	14–15	40–43	15–16	44.80
IV3	95	14–15	59–64	15–16	66.25
VI1	100	14–15	58–62	13–14	56.20
VI2	94	15–16	44–51	16–17	55.10
VI3	102	17–18	89–96	16–17	87.32
VI4	96	16–17	44–57	17–18	57.80

FT, Fourier transform

[a] See Zhu et al.[8]

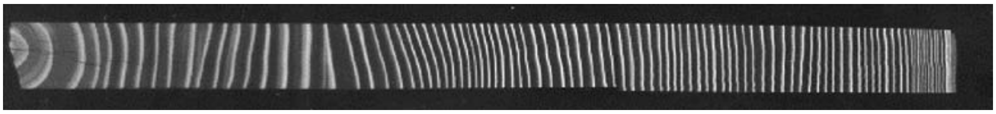

Fig. 1. X-ray image of the ninth sample

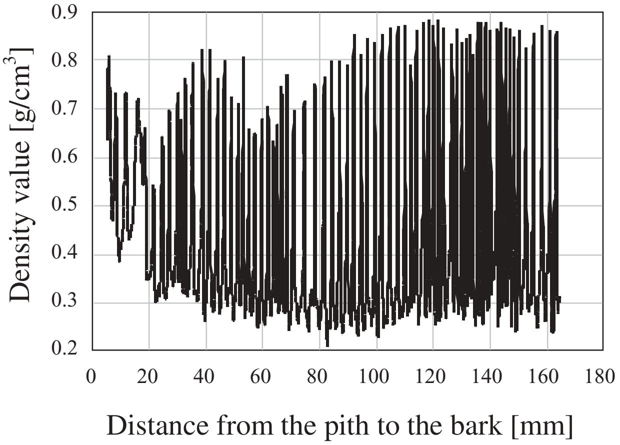

Fig. 2. Density distribution as determined by densitometer analysis of an X-ray image

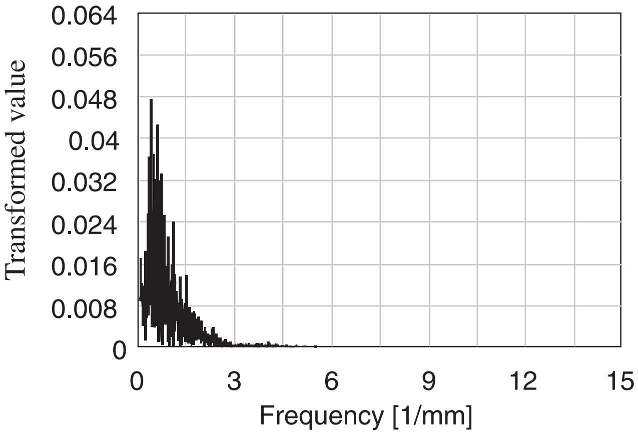

Fig. 3. Amplitude spectrum of the ninth sample

Fourier analysis

In this study, we propose that the density curves after scanning can be treated as vibration data (Fig. 2). Independent of the frequency, we can divide these curves into a Fourier series.

Fourier representation plays an extremely important role in the analysis of signals, and the Fourier transform provides a convenient method for mapping signals into another domain where they can be manipulated and analyzed. This is because a Fourier transform is an operation capable of converting functions from the time domain to the frequency domain. In such cases, Fourier transformation converts functions from distance to the reciprocal of distance (Fig. 3). The ability to transform signals from the distance domain makes the Fourier transform an important tool for interpreting density signals.

If $x(s)$ is a one-dimensional continuous function that can be integrated and having a real variable, then the Fourier-transformed function F is defined as follows:

$$F\{x(s)\} = X(\nu) \tag{1}$$

where the Fourier transformation converts the function from distance $x(s)$ to $X(\nu)$, the reciprocal of the distance function.

In mathematical notation, the F operator means:

$$X(\nu) = \int_{\text{pith}}^{\text{bark}} x(s)\exp(i2\pi\nu t)ds = \int_{\text{pith}}^{\text{bark}} x(s)e^{-i2\pi\nu t}ds \tag{2}$$

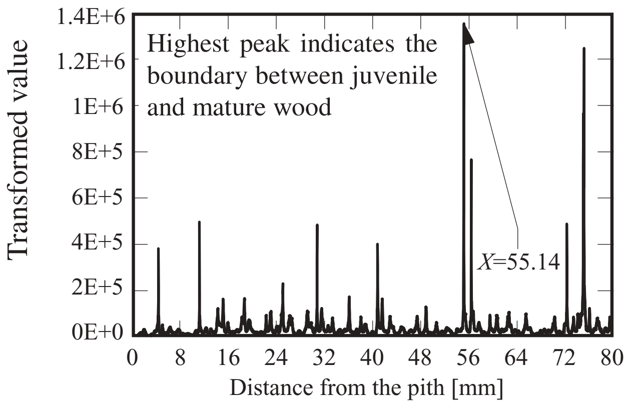

Fig. 4. Second Fourier transform spectrum of density distribution

where the real distance function is converted to a complex reciprocal of the distance function. The integral must be taken from the pith of the wood sample to the bark, the range of x.

It is thus possible that a Fourier transformation, followed by multiplication and a second Fourier transformation, can be executed faster than traditional operations employed to determine the transition between juvenile and mature wood.

The second Fourier function is defined as:

$$F\{X(v)\} = x'(s) \qquad (3)$$

Results and discussion

In the course of the second Fourier transformation of the density function, the location of the highest peak is particularly important (Fig. 4). In each of our measurements, the location of the highest peak was found to correspond to the transition point between juvenile and mature wood, as defined by the segmented regression method[8] in Table 1. The third and fourth columns of Table 1 contain annual ring number and distance from the pith, respectively. These results come from the segmented regression model, which is based on the tracheid length. The fifth and sixth columns of Table 1 contain the results derived from the second Fourier spectrum and were calculated from the original density curves of the samples. Substantial differences were found in the transitions between juvenile and mature wood between individual trees. Values for the transitions between juvenile and mature wood calculated from the second Fourier spectrum were consistent with the values obtained from tracheid lengths.

To obtain new information regarding the relationship between radial distance and density, these factors should be investigated simultaneously; otherwise, these attributes appear to be independent properties. In this study we assume that the process of changing numerous biological and physical characters in the cell (i.e., cell dimension, thickness of cell wall, cellulose and lignin contents in the cell wall, and growth rate) should be packed in the sequences of wood density in the radial direction. The second Fourier transform identifies the transition between the waves, the amplitude of which can be used to characterize biological change on cells and physical growth of trees. Consequently, the most notable properties of the second Fourier transformation are manifested as determining the transition between juvenile and mature wood.

Conclusions

This study illustrated the general and special properties of Fourier analysis, which are currently widely applied in numerous fields of science, from quantum mechanics to holography and optical processors. It is our hope that the method described in this study will be widely disseminated and that it will find application in a number of different scientific fields. Given the extent of correspondence with the segmented model in this study, this process can be used to gain greater insight into certain complicated analyses of wood structures, or to promote development in this field.

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