Application of Air-Coupled Ultrasound to Noncontact Evaluation of Paper Surface Roughness

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Abstract. An approach for characterizing paper surface quality by ultrasound as an alternative non-contact method is presented. In this work, an air-coupled ultrasound at frequency range from 0.3 MHz to 4.2 MHz has been applied to surface roughness characterization, where a series of sandpapers and pure papers having random and relatively wide range of root-mean-square of roughness $R_q$ from 2.0 to 92.8 µm are employed as specimens. The amplitude of reflected wave from each specimen is measured with pulse-echo configuration at normal incidence. A Kirchhoff-based scattering model is used to express the scattering phenomena from random rough surfaces and the relations between the normalized amplitude of the reflected wave and surface roughness parameters are then examined. It has been shown through the experiments that high frequency air-coupled ultrasound up to 4 MHz is useful to characterize surface roughness in the order of few microns of $R_q$. In addition, it has been suggested that an irregularity of paper surface geometry such as skewness could be characterized from the deviation of the normalized amplitude.

1. Introduction

Paper is an important material for storing information either by illustrations or written words. Print defects such as missing dots, ink bleeding and print mottle are usually associated with the printability of paper [1]. The surface roughness of paper is one of the most important factors influencing the printability [2].

Traditionally, the surface roughness of papers is often evaluated by air leak method [1]. This method is, however, not suitable for on-line use because the probe has to be contacted with paper surface in this method. As one of the alternatives for evaluating paper surface roughness, air-coupled ultrasound is considered to be a promising candidate because it is non-destructive, non-contact, convenient, fast, and sensitive to even soft matters such as cellulose fibre based materials e.g. papers and woods [3]. In addition, a wide frequency range of ultrasound may allow evaluating a wide range of surface roughness [4].

Although there are several works about the application of air-coupled ultrasound on paper characterization [4-7], a relatively lower frequency range less than 1 MHz is used in those works and paper roughness evaluations have not been sufficiently studied. It is expected to characterize surface roughness in the order of few microns of $R_q$ by high frequency air-coupled ultrasound.
roughness in the range of a few microns if a higher frequency larger than 1 MHz is used in air-coupled ultrasound measurements. In this work, an air-coupled ultrasound at frequency range from 0.3 MHz to 4.2 MHz has been applied to surface roughness characterization of a series of sandpapers. The feasibility of the use of such high frequency air-coupled ultrasounds for characterizing surface roughness of pure papers is then examined.

2. Theory

2.1. Kirchhoff’s scattering model

When an elastic wave is reflected from a rough surface, the reflected fields consist of a specularly reflected coherent and diffusely reflected incoherent component depending on the degree of roughness. Kirchhoff theory is employed to understand the relation between surface roughness and reflected wave intensity. For a plane wave incidence, the overall scattered field reflected from a Gaussian distributed rough surface, \( I \), can be written as

\[
I = I_{coh} + I_{incoh}
\]

where \( I_{coh} \) and \( I_{incoh} \) are the intensity of coherent and incoherent components, respectively. At normal specular angle (incident angle, \( \theta_i = \) reflected angle, \( \theta_r = 0^\circ \)), the intensity of coherent component \( I_{coh} \) is given by

\[
I_{coh} = I_0 \exp(-2k^2Rq^2)
\]

where \( I_0 \) and \( k \) are the reflected wave intensity from a perfect smooth surface and the wavenumber, respectively, and the root-mean-square of roughness, \( Rq \), is determined from

\[
Rq = \sqrt{\frac{1}{N} \sum_{i=1}^{N} h_i^2}
\]

where \( h \) and \( N \) are the height deviation from the mean value of the surface height profile and the number of data points, respectively.

2.2. Skewness

Skewness, \( Rsk \), is the measure of asymmetry of the height profile distribution and is given by

\[
Rsk = \frac{1}{NRq^3} \sum_{i=1}^{N} h_i^3
\]

Zero skewness means the height profile is symmetrically distributed and such profile is known as a Gaussian distribution i.e. a profile that has as many peaks as valleys. Positive skewness means the profile has a lot of high peaks while negative skewness means that the profile has a lot of deep valleys as shown in figure 1.

3. Experimental setup

Three types of air-coupled ultrasonic transducers with frequencies 0.4, 2 and 4 MHz from Japan Probe Co. are used in a pulse echo configuration with normal incident to a specimen surface at the specimen/transducer distance of 30, 17 and 3 mm, respectively. Each transducer is driven using a pulser/receiver BPR-4000 from Ritec Co. To reduce the measurement noise of the signals, the average values of the reflected amplitudes at different locations of each specimen are employed for evaluation. The specimens used in this study are a series of sandpapers having a relatively large range of \( Rq \) (2.7 ~ 92.8 µm) and several kinds of pure papers having a small range of \( Rq \) (3.0 ~ 6.1 µm), where the
roughness values are measured by a stylus profiler according to ISO 4288:1996 specifications. In addition, a smooth acrylic plate ($R_q = 0.02 \, \mu m$) is used as a reference surface for normalization.

### 4. Results and discussions

Figure 2(a) shows the measured results showing the relationship between the reflected amplitude of ultrasound and surface roughness for a series of sandpapers having Gaussian height distribution. It is noted that the roughness $R_q$ is normalized by multiplying with frequency $f$, to adequately examine the variations of the normalized amplitude at any frequency. It can be seen that the measured amplitudes agree well with the theoretical results from equation (2) illustrated by a solid line, for all frequency components. The normalized amplitudes in figure 2(a) are used to ultrasonically estimate the $R_q$ values for each specimen by using equation (2) and then compared with those measured by a stylus profiler as shown in Figure 2(b). It is found that both results agree well with each other within ±10% errors in the frequency range approximately 5 to 60 $\mu m \cdot MHz$. Based on this range, it is possible to make proper selections for the operating frequency and the corresponding measurable range of $R_q$ for performing an appropriate ultrasonic roughness estimation. For $R_q \cdot f$ less than 5 $\mu m \cdot MHz$, estimation errors are caused due to the accuracy in measuring the amplitude using the present measurement system. For $R_q \cdot f$ larger than 60 $\mu m \cdot MHz$, the errors may be caused due to the generation of the incoherent components in the reflected waves.

It has been found in Figure 2(b) that a higher frequency such as 4 MHz is appropriate for evaluating relatively small values of $R_q$, e.g. 2 to 6 $\mu m$, such as those for pure papers. Figure 3(a) shows the measured amplitudes by 4 MHz air-coupled ultrasound for pure paper surfaces having relatively small values of roughness. As we can see, the normalized amplitudes of each paper almost agree with the theoretical ones except for a few specimens having small $R_q$. Detailed investigations with the statistical descriptions of height profiles of each specimen measured by a stylus profiler are conducted. It is found that the normalized amplitudes reflected from paper surfaces with Gaussian distributed height profile, as shown in figure 3(c), are in good agreements with the theoretical ones while those that reflected from the surfaces having negatively skewed height profiles, as shown in figure 3(b), deviate markedly from the theoretical ones. Negatively skewed height profile means that

**Figure 2.** (a) Variations in the reflected wave amplitude from sandpapers with $R_q \cdot f$, (b) Comparison between the roughness estimated by a stylus and ultrasonic methods.
the paper specimen has a lot of deep valleys with small height variations at the reflection surface as shown in figure 3(b). This kind of surface is formed during the hard beating in a paper making process. The results shown in figure 3 suggest that paper surface skewness may be possible to be evaluated by a high frequency air-coupled ultrasound.

The measurement can be improved further by improving the ultrasonic beam profile to be more Gaussian and applying advanced signal processing methods. Although the ultrasonic response as a function of incidence angle is of interest, theoretical calculations show that normal incidence angle is the most sensitive to any roughness changes and it have been shown experimentally that the selection of incidence angle has no significant effect on the overall measurement results [10].

Figure 3. (a) Variation in the reflected wave amplitude from paper surface with $R_q$. (b) A typical height profile of a negatively skewed surface and its height distribution. (c) A typical height profile of a Gaussian distributed surface and its height distribution.

5. Conclusions
An air-coupled ultrasound at frequency range from 0.3 MHz to 4.2 MHz has been applied to a series of sandpapers and pure papers having random and relatively wide range of roughness $R_q$ from 2.0 to 92.8 µm, to examine the feasibility of characterizing paper surface roughness. It has been shown through the experiments that high frequency air-coupled ultrasound up to 4 MHz can be a useful means to characterize surface roughness in the order of a few microns of $R_q$. In addition, it is suggested that the air-coupled ultrasound has the potential to characterize an irregularity of paper surface geometry such as skewness. The quantitative evaluation of skewness will be conducted in a future work.

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