The effects of the transducer beam properties on the ultrasonic geometrical characterization of periodically corrugated surfaces

Jingfei Liu* and Nico F. Declerq

*Corresponding author’s address: Georgia Tech Lorraine, Georgia Institute of Technology, 2, rue Marconi, Metz, 57070, Lorraine, France, benjamin.jf.liu@gatech.edu

Periodically corrugated structures are common in many technological applications and in most cases the geometry of these corrugated structures are crucial for the designed functionality. As an effective nondestructive characterization method an ultrasonic imaging technique is investigated in this work for the purpose of accurately characterizing the geometry of periodic corrugations. Among many factors that affect the imaging quality the properties of the transducer beam dominate. The effects of the spatial and spectral properties of transducer beams on the accurate characterization of the characteristic dimensions of corrugations are investigated in details both theoretically and experimentally. The possibility to accurately characterize the corrugation characteristic dimensions, the condition for accurate characterization and the quantitative relationship between the characterization accuracy and the beam parameters are given. The ways to avoid the diffraction effects and reduce possible errors are also discussed. Experimental results are compared with optical measurements and good agreement is obtained. Both the general principles developed theoretically and the practical techniques proposed can work as a useful guidance for similar work.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Periodically corrugated structures are ubiquitous; they appear in everyday life as well as in sophisticated technological applications from large-scale architectural structures [1-2] to small-scale photonic or phonic crystals [3]. Generally the geometry of the corrugated structures is crucial for the designed functionality and therefore nondestructive characterization is of great interest during design as well as during the manufacturing process.

Ultrasound is generally accepted as a useful nondestructive characterization tool for surface integrity and quality determination [4-5] and has certain advantages when compared to optical microscopy such as its capability to determine not only the lateral dimensions of features, for instance the width of defects, but also features perpendicular to it, for instance the depth or height of defects. For this reason a thorough investigation is envisaged in this work on the actual ability of ultrasound to characterize surface dimensions and its limitations.

A long history preceding the current work can be found in the literature on interaction of sound with corrugated structures [6-7]. A considerable range of numerical techniques exists to simulate the interaction of sound with a periodic corrugation [8-9]. Determination of the geometric properties is normally done indirectly by comparison between the experimental and the numerical diffraction spectra. The results are, of course, strongly biased by the assumptions and idealizations made in the applied theoretical models; hence direct experimental measurements are desired.

From the experimental point of view limitations are of course imposed by the available scanning devices and transducers and by physical acoustic effects such as diffraction of sound caused by the considered structure. The diffraction effect does make it difficult to accurately characterize the corrugation periodicity, but the real challenge is an accurate determination of features at the sub-periodicity level, such as the profile (shape and depth) of the grooves. Acoustic microscopy could be considered for that purpose and will be successful for small depths (i.e. not deeper than the very short focal length of the acoustic objective) [10-11], but for the corrugation with large vertical dimension this technique will lose its accuracy due to its very short focal zone [12]. In addition, this technique is not time efficient in terms of scan and signal processing.

In what follows we theoretically investigate the effects of different ultrasonic beam properties, such as spectral and spatial properties, on characterization accuracy. Some principles and requirements are also develop for choosing proper testing equipment and avoiding diffraction effects.

EXPERIMENTS

Samples

Two brass blocks (Samples I and II) are investigated experimentally. Each sample has a geometric profile of periodic corrugation on its top surface and the thickness of the brass blocks is sufficiently large to enable windowing the signal reflected from top surface only. Optical microscopic images of the top and side surfaces of each sample are provided in FIGURE 1. It can be readily seen that each top surface is partially flat and partially corrugated. To ease explanations further in this paper the areas forming the higher part of the grooves are called plateaus, whereas those forming the lower parts are called valleys.

The corrugations as studied here can be primarily characterized by four geometric parameters: periodicity ($\Lambda$), plateau width ($\Lambda_P$), valley width ($\Lambda_V$), and corrugation height ($H$), i.e. the height difference between plateaus and valleys. From the side views of the three samples (FIGURE 1 (b) and (d)) it can be observed that the transition from plateaus to valleys is not exactly vertical, but inclined. These inclined surfaces scatter sound waves. These scattered waves barely contribute to the specular reflection from both the plateaus and the valleys, but as experiments expose in time domain they are more disposed towards sound reflected from the valley than from the plateau. These facts and the small horizontal dimensions of these inclinations, allow us to reasonably add their horizontal dimensions to those of the valleys ($\Lambda_V$). Given the aforementioned considerations the following relationship holds:

$$\Lambda = \Lambda_P + \Lambda_V$$  (1)

For the convenience of notation and explanation two directions are introduced: (i) ‘scan axis’, i.e. the direction perpendicular to the corrugation grooves; and (ii) ‘index axis’, i.e. the direction parallel to the corrugation grooves.
A direct measurement of 10 corrugations of each sample is performed on optic microscopic cross sectional (side) images. The average value (A) of the four geometric parameters of corrugation, together with their respective ratio of standard deviation to average value (SD/A), are listed in TABLE 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\Lambda$</th>
<th>$\Lambda_P$</th>
<th>$\Lambda_V$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A ($\mu$m)</td>
<td>SD/A (%)</td>
<td>A ($\mu$m)</td>
<td>SD/A (%)</td>
</tr>
<tr>
<td>I</td>
<td>185</td>
<td>4.5</td>
<td>75</td>
<td>6.7</td>
</tr>
<tr>
<td>II</td>
<td>309</td>
<td>0.9</td>
<td>111</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Experimental Setup

The ultrasonic scanner used in this experiment is a customer-designed high frequency scanner fabricated by ‘Inspection Technology Europe BV’. The transducer chosen for the scan is a ‘Valpey Fisher’ focused immersion transducer with parameters provided by the manufacturer: central frequency of 100 MHz, spherical focal length of 12.7 mm (0.5 inch) and transducer diameter of 2.54 mm (0.1 inch). All the experimental data are acquired using ‘Winspect’ software and are further processed using ‘Matlab’. For correctness the transducer parameters provided by the manufacturer were not used directly, but measurements have been taken instead. The measurement of the spectrum of an echo reflected from the smooth area of the samples reveals a -6 dB (compared with the maximum amplitude value) frequency coverage of 22 MHz to 72 MHz and hence a -6 dB bandwidth of 50 MHz. The measured central frequency turned out to be 45 MHz.

The scans are performed in water under pulse-echo mode for a rectangular scanning area of 12 mm (scan axis) by 4 mm (index axis). In order to obtain the highest resolution the transducer can possibly offer the time domain window for acquiring the reflections is set between 16.30 $\mu$s and 17.10 $\mu$s because their corresponding range of 12.06 $\mu$m to 12.65 $\mu$m is exactly in the focal zone of the focused beam. The spatial resolution of the scan for both axes is 20 $\mu$m and the temporal resolution is 0.002 $\mu$s, which corresponds to a sampling frequency of 500 MHz.

Data Processing Method

The purpose of the current research is to accurately determine the characteristic dimensions of the corrugation. In this work the measurement is based on the relative energy of the plateau and valley reflections, which is of course directly determined by the relative amplitude. Therefore, practically, we use the amplitude and the time-of-flight (TOF) of the reflections to obtain the corrugation geometry. The difference between the maximum amplitude of the plateau reflection and that of the valley reflection are obtained for imaging the whole scanned area. The time of flight (TOF) of the peak with maximum amplitude is also used for imaging the corrugations. Theoretically, these two techniques are supposed to give the same results because they are based on the same reflections. Both
techniques are equally capable of characterizing the lateral geometrical properties of corrugated surfaces, but the technique using TOF is capable of characterizing the vertical geometry, i.e. the corrugation height, by converting the TOF to distance in the direction of wave propagation given the sound velocity in the medium.

**DOMINATING FACTORS**

Many factors affect the quality of the final images of the corrugations under characterization. In this work we only focus the dominating ones, i.e. the properties of the transducer beam. Both spectral and spatial properties will be discussed in this section.

**Spectral Bandwidth and Spatial Resolution**

Although the spectra of the ultrasonic pulses used in experiments like ours are never exactly Gaussian per se, still they are to a good approximation Gaussian-like in most cases. We therefore apply knowledge based on Gaussian pulses to investigate corrugation geometry in a meaningful manner. According to the Fourier transform theorem concerning real signal frequency translation [13] a spectrum shifted by a value \( f_{shift} \) corresponds to the original time domain signal multiplied by a harmonic function in time not changing its time domain signal amplitude. Therefore, the time domain duration of an incident pulse (\( \tau \)) is only a function of the bandwidth of a transducer beam (\( \beta \)) and is not affected by the central frequency of the transducer.

\[
\tau \propto \frac{1}{\beta}
\]  

(2)

This means that a pulsed beam having a larger spectral bandwidth can produce a shorter time domain pulse. As is well-known in ultrasonics the time domain length of a pulse determines its ability to distinguish between two adjacent targets along the direction of wave propagation, i.e. its spatial resolution. Given the pulse duration (\( \tau \)) and sound speed in the medium (\( c \)) the spatial resolution of a pulse (\( R \)) can be obtained from Eq. (3).

\[
R = \frac{\tau c}{2}
\]  

(3)

Considering the spatial resolution (\( R \)) relative to the corrugation height (\( H \)), the reflections from corrugation surfaces can be categorized into two cases:

(i) If \( R > H \), the reflections from the plateau and valley surfaces overlap as shown in FIGURE 2 (a) and this makes it impossible to correctly characterize the two individual reflection surfaces.

(ii) If \( R \leq H \), the reflections from the plateau and valley surfaces can be properly separated from each other in the time domain waveform as shown in FIGURE 2 (b). The disconnection of these two reflected echoes enables the characterization of their originating surfaces.

For this study the pulse has a spatial resolution of 59.2 µm. Comparing this value to the corrugation heights of the three samples listed in TABLE 1 it can be concluded that Samples II and III can be reliably characterized, however Sample I cannot. Thus, in this work only the experimental results of Sample II and III are reported.

**FIGURE 2.** Reflections from the corrugated surfaces of (a) Sample I and (b) Sample II.
Central Frequency and Wavelength

This section deals with the central frequency as this is not only a determining factor in the detection resolution, but equally important in the possible occurrence of diffraction. With high frequency comes smaller wavelength. It is well known that small wavelengths are more sensitive to small surface defects than large wavelengths and they therefore lead to higher detection resolution of the surface geometry. For the purpose of obtaining higher detection resolution the transducers with high central frequency are preferred in this work. Another issue concerning wavelength is the effects of diffraction on the geometric characterization because the tested corrugations can possibly act as a diffraction grating.

The general rigorous condition for acoustic diffraction is that the wavelength of sound is in the same order of the periodicity of the grating [14-16]. In the current work the range of wavelengths of the incident pulse is from 21µm to 67µm. It can be verified this range does not cover the periodicities of our samples (185µm for Sample I, 309µm for Sample II) and hence diffraction has little effect on the accuracy of geometric characterization of the envisaged corrugations. In this respect one can clearly see that in order to avoid the effects caused by diffraction on the corrugated structure characterization, once again high frequency transducers are preferred.

Beam Diameter

In this study the ultrasonic pulse-echo mode is applied and the characterization of the corrugation geometry is therefore based on the properties of echoes reflected from corrugation surfaces. The basic requirement for accurate characterization of a surface corrugation using this testing mode is that the echo properties should be able to correctly show the alternating plateaus and valleys on which the center of the transducer beam is positioned. Three cases exist: (a) only a reflection from the plateau surface occurs, (b) only a reflection from the valley surface occurs, and (c) both reflections occur simultaneously due to a partial coverage of the beam on plateau and valley surfaces. Clearly the first two cases resolve the valleys from the plateaus. For the third case the resolution will depend on the relative energy of the two received echoes. As will be described below, the echo with higher energy (and therefore also a higher amplitude) determines the section (valley or plateau) scanned at that location. The third case (c) is prevalent and requires the necessary caution and understanding. For a theoretical investigation we assume (i) that a beam has a uniform intensity distribution throughout its cross section, which is reasonable for an actual beam within its focal zone and, for simplicity, (ii) that the plateau and valley surfaces have equal reflective properties. Under these two assumptions the reflected energy in the two echoes, is proportional to its respective reflection area that is directly related to the beam diameter for a given corrugation.

FIGURE 3 illustrates the effects of the beam diameter on the reflection energy. The results shown are obtained from the simulation on a corrugation with a ratio of plateau width to periodicity of 35.9% (i.e. Sample II). We define the minimum corrugation geometry (MCG) as the smaller one of plateau width and valley width. In this example MCG is equal to \( \Lambda_P \). Four beam diameters as shown in FIGURE 3 (a) are investigated and they represent four different cases (from left to right): (i) a beam diameter \( D < \text{MCG} \), (ii) \( D = \text{MCG} \), (iii) \( D \) slightly smaller than \( \Lambda \) and (iv) \( D = \Lambda \). The normalized energy, i.e. the ratio of the energy reflected from individual surface to the total reflected energy, of the two types of echoes for the four cases are shown in FIGURE 3 (b) to (e).

We formulate the following conditions without which an accurate characterization fails. When the incident beam is centered above a valley, the reflection coming from the valley must dominate. Similarly when the incident beam is centered above a plateau then the reflection coming from the plateau must dominate. Additionally when a beam is centered at the transition from valley to plateau, both reflections must equally manifest themselves. Whether or not these conditions are met depends on the beam diameter for a given corrugation. Consequently the beam radius must not be larger than the smallest of the plateau width (\( \Lambda_P \)) and the valley width (\( \Lambda_V \)) as summarized in EQUATION (4a); similarly the beam diameter must not be larger than two times the smallest of the plateau width (\( \Lambda_P \)) and the valley width (\( \Lambda_V \)) as shown in EQUATION (4b).

\[
R \leq \min \{ \Lambda_P, \Lambda_V \} \quad (4a)
\]

\[
D \leq 2 \min \{ \Lambda_P, \Lambda_V \} \quad (4b)
\]
FIGURE 3. Effects of beam diameter on the reflected echo energy. Image (a) is the schematics of the periodic corrugations (Sample II) for the simulation and the cross sections of four beams with different diameters. The lighter area is plateau and the darker area is valley. Image (b) to (e) show the normalized energy levels of plateau reflection, valley reflection and ideal plateau reflection for the four cases shown in (a) from left to right respectively. The beam diameter is 0.8 $\Lambda_p$ or 0.287 $\Lambda$ for (b), 2$\Lambda_p$ or 0.718 $\Lambda$ for (c), 2.4 $\Lambda_p$ or 0.862 $\Lambda$ for (d), and $\Lambda$ for (e).

By applying the condition for accurate characterization stated in EQUATION (4) to the samples investigated in this work, it can be concluded that Samples II is being able to be accurately characterized, while Sample I is not. It is necessary to note that EQUATION (4) suggests the beam diameter should be smaller than one corrugation
periodicity for accurately characterization. If so, we are dealing with a beam interacting with essentially one groove and not a corrugated surface. Hence diffraction will not influence the ability for accurate characterization of the corrugation geometry.

RESULTS AND DISCUSSIONS

The images of corrugation surface of Sample II obtained from the ultrasonic scans are shown in FIGURE 4 (a) and (b). For the purpose of comparison the image obtained with the technique using amplitude and the image obtained with the technique using TOF are shown together for each sample. The quantitative evaluation of the corrugation geometry based on the images indicates that the two techniques give the same results for both samples as predicted. The statistical results of the lateral corrugation dimensions, the average (A) and the ratio of standard deviation to average (SD/A) obtained based on 25 readings are listed in TABLE 2. As discussed above the technique using TOF is capable for characterizing the vertical geometry of corrugation and this vertical characterization is shown in FIGURE 4 (c). The statistical results of the corrugation height obtained based on 25 readings are also listed in TABLE 2.

By comparing the data listed in TABLE 1 and TABLE 2 it can be observed that difference for the measurement of corrugation periodicity is only 1.6%. The difference for corrugation height measurement is about 17.5%. The reason why this value is high is probably because the optical measurement only has access to the side of the sample, while the ultrasonic method can measure the inside corrugation.

![Figure 4](image_url)

**FIGURE 4.** The images characterizing Sample II based on (a) the difference between the maximum amplitude of the plateau reflection and that of the valley reflection and (b) the TOFs to the peaks with maximum amplitude. (c) is the distance between the transducer surface and the scanned surface at the index position of 2 mm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Λ (μm)</th>
<th>ΛP (μm)</th>
<th>ΛV (μm)</th>
<th>H (μm)</th>
<th>SD/A (%)</th>
<th>SD/A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>304</td>
<td>5.5</td>
<td>121</td>
<td>14.4</td>
<td>179</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>94*</td>
<td>0.1*</td>
</tr>
</tbody>
</table>

(*) values are obtained with the technique using TOF only.
CONCLUSIONS

In this work accurate characterization of the geometric properties of periodically corrugated surfaces using ultrasonic techniques is investigated both theoretically and experimentally. In the theoretical investigation the dominating factors for a high quality characterization are discussed in terms of their effects on the possibility and accuracy of characterization. As a summary, the important conclusions of the theoretical investigation are listed below:

(1) The possibility of geometric characterization of a corrugated surface using the proposed ultrasonic methods is determined by the relationship between the corrugation height and the spatial resolution of the transducer beam.
(2) The theoretical condition for accurate characterization of corrugation geometry is that the beam radius should be smaller than the smallest of the corrugation characteristic dimensions.
(3) A higher frequency transducer is highly recommended to increase the detection sensitivity, and hence the detection resolution.

The experimental work illustrates the effectiveness of the principles discussed in the theoretical part and further analyzes the possible reasons for the difference between ultrasonic measurements and optical measurements of all the characteristic dimensions of corrugation. This work proves that ultrasonic techniques are capable of accurately characterizing the lateral and vertical dimensions of corrugated surfaces.

ACKNOWLEDGMENTS

This work has been done in the context of project ANR-09-BLAN-0167-01 from the French "Agence Nationale de la Recherche".

REFERENCES