ON CHARACTERIZING OPERATING CONDITIONS OF ULTRASONIC SYSTEMS USING MTF
AND RELATED TECHNIQUES

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INTRODUCTION

For a given sample under test, the quality of the ultrasonic image obtained by scanning is greatly influenced by the choice of the equipment as well as by the operating conditions. The possibilities of choosing the different parameters is very wide, even if the basic ultrasonic system is determined. The parameters to select before starting an experiment include the transducer itself, its position relative to the sample, the different settings such as gain, attenuation and damping, the mode of detection, etc. The selection is usually dictated by qualitative indications which can be inaccurate or even misleading. Consequently it is very important to have, in such a case, clear quantitative criteria.

The quality of an imaging system is defined by the contrast and the resolution of the obtained image as compared to the object.

The performance of optical systems and components is routinely evaluated using the MTF (Modulated Transfer Function) criterion [1,2]. Lately, this criterion was adapted to characterize focused ultrasonic transducers [3,4,5]. In this work, it is shown how the MTF can be used to characterize and optimize the operating parameters of the entire ultrasonic system when used for specific applications.

The MTF is practically the expression of the degree of contrast transferred from the object to the image, by the imaging system, as a function of spatial frequency. Degradation of the contrast increases with increasing frequency, until it vanishes at a so-called "cut-off frequency".

The knowledge of the ultrasonic field around the transducer at various working conditions constitutes a valuable complementary information.

In this work, four examples of experimental characterization of working conditions, based on those techniques will be given:

1 - Use of a focused transducer in order to define surface features, at normal incidence (longitudinal waves);

2 - Use of a focused transducer in order to define bulk features, at normal incidence (longitudinal waves);
3 - Use of a tilted focused transducer in order to define bulk features, at a non-zero incidence angle (shear waves);
4 - Use of a focused transducer tilted at the Rayleigh angle, in order to define surface and subsurface features.

THEORETICAL CONSIDERATIONS

In Fig. 1, the results of the theoretical calculation [4] are summarized. The MTF functions for three detection methods (coherent, intensity and peak detection) are displayed as a function of the dimensionless spatial frequency:

\[
fs = \frac{\text{cycles}}{\lambda \times F\#} \tag{1}
\]

where \(\lambda\) is the frequency and \(F\#\) is the "f number" (focal distance divided by the aperture). The calculations are done for a single ultrasonic frequency (equivalent to a monochromatic radiation in optics).

From Fig.1 we can conclude that:
- the worst resolution (lowest cutoff frequency) is obtained with coherent detection;
- the best resolution - by intensity detection (double cut-off frequency).

The peak detection is in between.

The practical problem faced by the experimentalist, is to compare the experimental results, based on a multifrequency transducer (broad band), with the theoretical ones. There are two possibilities:
- Either take the entire RF signal at each point and filter it for the frequency of interest (by software or hardware);
- Or find the frequency spectrum of the system under test and calculate the expected theoretical MTF curves as a weighted average of all frequencies represented in the spectrum.

In this work the second approach was chosen. In Fig. 2(a), the frequency spectrum of the transducer is given. In Fig. 2(b), a set of 7 single frequency MTF curves is shown. The weighted average MTF curve for the spectrum of the tested operating conditions is shown too. The plots shown are the result of a calculation made for "intensity detection".

![Fig. 1. Theoretical calculation of MTF for three detection methods.](image-url)
Fig. 2. Example of derivation of weighted MTF derivation. a) Spectrum of Harisonic transducer I2-0504-S; b) MTF: 1, 3, 5, 7, 9, 11, 13 MHz and weighted average.

EXPERIMENTAL

1) Procedure

The experimental procedure for the characterization of ultrasonic transducers was described elsewhere [4]. It is based essentially on a line scan across the sharp edge of a glass plate.

When transducers are characterized by means of the MTF concept, care must be taken to avoid any influence of system features on the results [4].

In this work, however, the purpose is to characterize the working conditions. Therefore, the technique is basically the same, except that the precautions for avoiding the influence of the system are not required. Moreover it is important to perform the characterization at the tested working conditions, and this includes the pulser-receiver settings (attenuation, damping, etc.), the detection method (peak, intensity or coherent detection), the zero baseline and a possible saturation.

The procedure is based on a line scan across a sharp edge. The idea behind the procedure is to get an output that could be compared to the output that would have been obtained from a reflected infinitely narrow beam scanned across a perfectly sharp edge. In this ideal case the result would have been a step function, and therefore the contrast identical to that of the object features over all possible frequencies. The deviation from the step function in the practical scan, leads to the evaluation of the imaging quality of the system.

The mathematical process applied to the resulting data is as follows: The output scan is differentiated in order to obtain the LSF (Line Spread Function), which is the spatial impulse response. The LSF is then Fourier transformed. The modulus of the transform is the MTF - the contrast of the imaging system at the test conditions as a function of spatial frequency.
It will be shown in this work that the resolution of the image is changed - as expected - when the same focused transducer is to image features upon the surface, or in the bulk of a solid sample, either normally to the scanned plane (incident angle = 0) or inclined with respect to this plane (incident angle > 0). For the Rayleigh Waves experiment, a different transducer was used.

The practical applications of the above principles are described in the next paragraph.

2) Description of Experiments

For the performance of the first three experiments, a copper block was used as shown in Fig. 3. The transducer was an I2-0504-S from Harisonic, in which F# = 4 and the nominal frequency is 5 MHz. The radius of curvature of the outer and inner edges of the block is 0.1 mm. It is sharp enough for the equipment used in this work, since the expected nominal cutoff spatial frequency is 1 mm [4].

* The first experiment is designed to image surface defects (Fig. 3a).

* The second experiment is designed to image defects in the bulk. In this case the transducer is perpendicular to the surface and focused on the inner backwall (Fig. 3b). In both cases, the backwall reflections are measured along the scan. In case of a theoretical beam the reflection would have disappeared abruptly (within 0.1 mm) upon crossing the inner (or outer) edge. The actual scan output is differentiated and Fourier transformed as described above.

* The third experiment is designed to image inner defects using shear waves. In this case, the transducer is inclined (incidence angle > 0°) (Fig. 3c) and the resulting scan is zero before and after the crossing of the edge. It is only around the edge that a transient reflection appears due to the diffraction scattering from the edge. Theoretically this should be a delta function. In this particular case, the resulting scan itself represents the LSF.

* The fourth experiment was based on a 1" focused Panametrics 20 MHz (nominal frequency) transducer. It was tilted at the Rayleigh angle on an Alumina cube. In practice, the spectrum of the Rayleigh wave obtained was, in most cases, around a central frequency of 7 MHz.

The experimental setup is shown in Fig. 4:

(a) The plane of incidence is parallel to the crack. The direction of scanning is normal to this plane (and to the crack). This configuration is used to determine the Rayleigh field.

Fig. 3. Copper block showing the different positions of the transducer for the three experiments.
(b) The plane of incidence is normal to the crack. The direction of scanning is normal to this plane (and parallel to the crack). This configuration is used to determine the MTF.

RESULTS

Scans on the upper surface of the copper block (simulating the behavior when imaging surface features), are shown in Fig. 5. The two plots show Peak-to-Peak and Intensity (Energy) measurements, respectively.

Fig. 6 shows the MTF derived from the previous scans by differentiating and Fourier transforming the plots given in Fig. 5 as well as two plots which are the result of a theoretical calculation of the results obtained from an ideal transducer, without taking into account the system parameters. Three immediate conclusions are worth mentioning here:

a) There is a clear difference between Peak-to-Peak and "Energy".

b) The cutoff is between 1 and 1.5 1/mm in the experimental case.

c) The MTF obtained experimentally from the actual working system is better.

The results obtained by scanning the inner corner of the copper block (simulating the behavior when imaging the bulk features), are shown in Fig. 7. From this figure, the following observations can be made:

- The resolution of the system when imaging bulk features is much worse than the resolution when imaging surface features - under the same conditions.

![Fig. 4. Experimental settings to obtain Rayleigh Waves: a) setting to scan for Ultrasonic field; b) setting to scan for MTF.](image)

![Fig. 5. Plots of scanning of the upper surface of the block, across the edge. Peak & Intensity Detection (ESF).](image)
- The results show no difference between PTP and Energy detection methods. Clearly the beam degradation introduced by the spherical aberrations overshadows the finer differences in the detection methods.

Some practical conclusions can be drawn from the experiments made so far:
- In order to detect bulk defects with good resolution, it is necessary to use aspheric customised transducers. This is justified in case the problem is of high importance.
- The techniques presented here can be used in order to test the specifications of transducers and determine if they are adequate to perform a specified task.
- Moreover, the method can be used to test customised aspheric transducers specially ordered to carry out a particular task.

Fig. 6. Two experimental MTF plots derived from the scans on the upper surface of the copper block (imaging surface features) and two theoretical ones derived taking into account an ideal transducer only.

Fig. 7. MTF - Results obtained by scanning the inner corner of the copper block (simulating the behavior when imaging bulk features).

In Fig. 8, the LSF obtained with a tilted focused transducer is shown. The tilt angle was calculated to eliminate the longitudinal waves keeping only the shear waves.

Fig. 9 shows the MTF derived from the preceding LSF curves. The effect of the aberration due to the refraction of the ultrasonic beams when crossing the interface between solid and liquid is present here, as well. In this case too, for critical tasks, aspheric customised transducers are requested and so is the need for their test.
Figure 10 shows the Rayleigh Wave Ultrasonic field obtained with the experimental setting of Fig. 4(a) in a 3D representation and Figure 11 shows the MTF obtained from one of the scans performed with the experimental setting of Fig. 4(b). In this case the distance from the crack was 2.94 mm.

![Figure 8](image1.png)

Fig. 8. LSF - Results obtained with a tilted focused transducer.

![Figure 9](image2.png)

Fig. 9. MTF - derived from the LSF of a tilted transducer.

![Figure 10](image3.png)

Fig. 10. Rayleigh Wave Ultrasonic Field obtained with setting of Fig. 4(a) (distance from scatterer: .1 to 4 mm) - 3D representation.
CONCLUSIONS

1. The use of the MTF test method, which is standard in optical engineering, has been shown in ultrasound.
2. The difference between characterization of transducers and characterization of systems at working conditions has been emphasized.
3. A given system has been tested through three different applications, and the results have been compared with the theoretical expectations. A similar system was tested through a fourth application.
4. The decrease in the performance of transducers, when used in conditions out of their specifications, essentially, conditions producing aberrations, has been experimentally illustrated. From this, it is clear that, for important and delicate tasks, customised aspheric transducers have to be specially built.
5. It has been shown how the method can be of great help to determine whether transducers obey to their declared specifications. In particular there is a great need for such tests when expensive and/or specially customised transducers are concerned.
6. A unique method of characterizing Rayleigh Wave Field and Rayleigh Wave MTF was shown for transducers tilted at the Rayleigh Angle.

REFERENCES