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FREQUENCY ANALYSIS FOR ULTRASONIC NDT DEFECT RECOGNITION

Franco Cotana, Federico Rossi, Mirko Filipponi

Università degli Studi di Perugia, Polo Universitario di Terni
Sezione di Fisica Tecnica
Loc. Pentima Bassa, 21
05100 Terni, Italia
e-mail address of lead author: frossi@unipg.it

Abstract
Non-Destructive Testings (NDT) are used to verify products quality without modifying their characteristics and performances. At present, automatic devices are available to individuate the position of a defect inside a solid structure. However, no technique is available to determine automatically the defect type. NDT on steel samples by means of ultrasounds is here analyzed. This technique is based on the reflection of an ultrasonic signal, due to presence of a possible defect. Two kinds of defects (non-metallic inclusions and porosities) have been investigated. The signal reflected by the defect has been studied by means of frequency analysis. It has been observed that some spectra characteristics are the same for the same kind of defect. This result is not available by using only a time domain analysis. A simple mathematical model has been found by correlating experimental results. Defects dimensions have been found out to be strictly correlated with spectra (- 6dB) frequency bandwidth. Correlation depends on the kind of the investigated defect.

INTRODUCTION

The main cause of steel manufactures breaking or damage is fatigue. Fatigue strength is correlated to the number, the nature and the dimensions of defects. Non-Destructive Testing (NDT) is generally employed to individuate defects inside a DUT (Device Under Test) without modifying DUT characteristics and performances.
Ultrasounds NDT allows to determine defect characteristics such as dimensions and position; however, no technique is available to individuate the nature of defects. NDT is usually based on time domain analysis[1].
An original NDT method, based on frequency response analysis is here investigated: the ultrasonic signals reflected by two different types of defects (non-metallic inclusions [NMI] and porosities) have been analyzed by evaluating Fast Fourier Transform. Porosities and NMI equivalent diameter ranges are respectively 0.01 ÷ 24 mm and 0.002 ÷ 10mm [2]. Results have shown a strong correlation between defect dimensions and FFT (- 6dB) frequency bandwidth ($\Delta f_{-6\ dB}$). An original model has been proposed to individuate the defect type by means of frequency response and defect dimensions. A model calibration constant value has been also proposed for each type of defect.

MEASUREMENT METHOD

Experimental apparatus (see Fig. 1a) is constituted by the following devices: ultrasounds generator-receiver system Gilardoni RG 20, ultrasounds transducers, EZ-KIT Lite DSP board. Ultrasounds generator-receiver feeds the emitter transducer and acquires the reflected signal from the receiving transducer; emitter and receiver transducer is a unique probe which alternatively works as emitter and receiver. Two different probes have been employed: 4 MHz and 5 MHz [3]. A DSP board has been employed to evaluate the reflected signal FFT.

Fig. 1: a) experimental apparatus; b) porosities defects; c) non-metallic inclusion defect.

A measurement campaign has been carried out on two cube-shaped steel samples: the first one contains non-metallic inclusion (NMI) defects (see Fig. 1c), the second one contains porosity defects (see Fig. 1b). For each sample the 4 bigger defects have been taken into account. Reflected signals shape depends on: defect nature, defect distance from probe, defect dimensions [4]. Defect equivalent diameter D_{eq} has been employed to characterize defect dimensions: equivalent diameter represents the diameter of a sphere-shaped defect with the same echographic response. Defect equivalent diameter has been evaluated by employing AVG curves methodology [5].
In Tab. 1 defects characteristics are reported. FFT analysis has been carried out only on the time signal portion (voltage signal) containing the defect echo (see Fig. 2) [6].

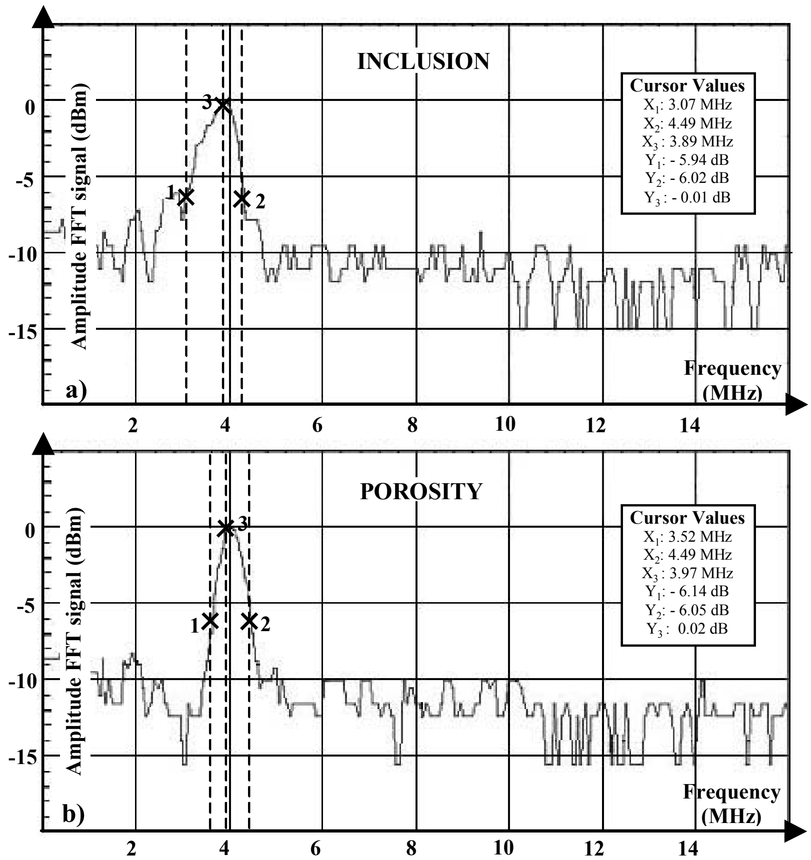

Fig. 2: Reflected signal FFT (4 MHz probe) of a) non-metallic inclusion (NMI) with D_{eq} = 1.12 mm; b) porosity with D_{eq} = 1.12 mm.

Tab. 1: Defects characteristics.

NMI	**Depth (10^{-3} m)**	**D_{eq} (10^{-3} m)**	**Porosities**	**Depth (10^{-3} m)**	**D_{eq} (10^{-3} m)**
1	82	1.50	1	70	1.12
2	92	1.00	2	49	1.68
3	123	1.19	3	101	1.00
4	114	1.12	4	60	1.42

It is assumed that defect echo frequency informations are kept into $\Delta f_{-6\ dB}$ which is the frequency interval limited by frequency values each level is 6 dB lower than the maximum one [7].

MEASUREMENT RESULTS

A measurement campaign has shown the differences between the characteristics of reflected signal due to porosities and NMI; such differences have been found into $\Delta f_{-6\ dB}$: porosities $\Delta f_{-6\ dB}$ is thinner than NMI's for each equivalent diameter both for 4 MHz probe and for 5 MHz probe.
As shown in Figs. 3 and 4, $\Delta f_{-6\ dB}$ dims as equivalent diameter D_{eq} grows.

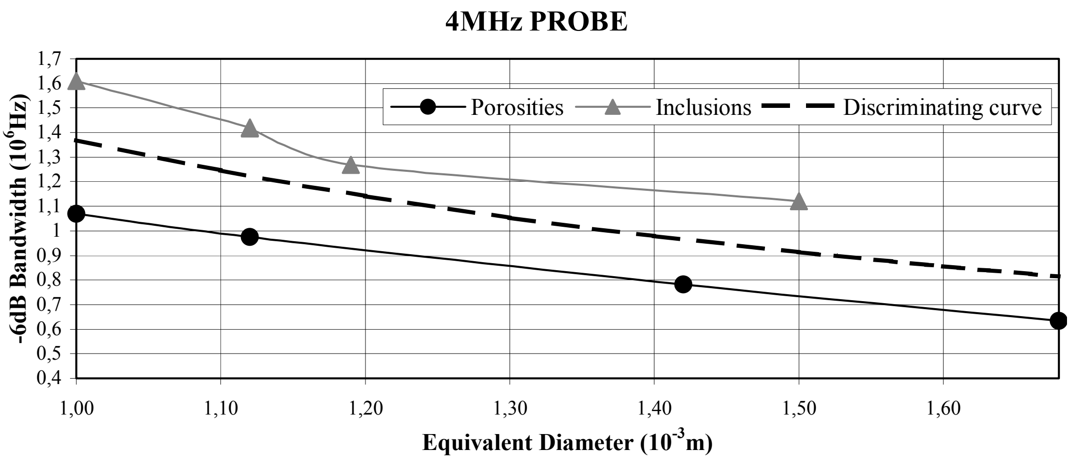

Fig. 3: $\Delta f_{-6\ dB}$ versus equivalent diameter for 4 MHz probe.

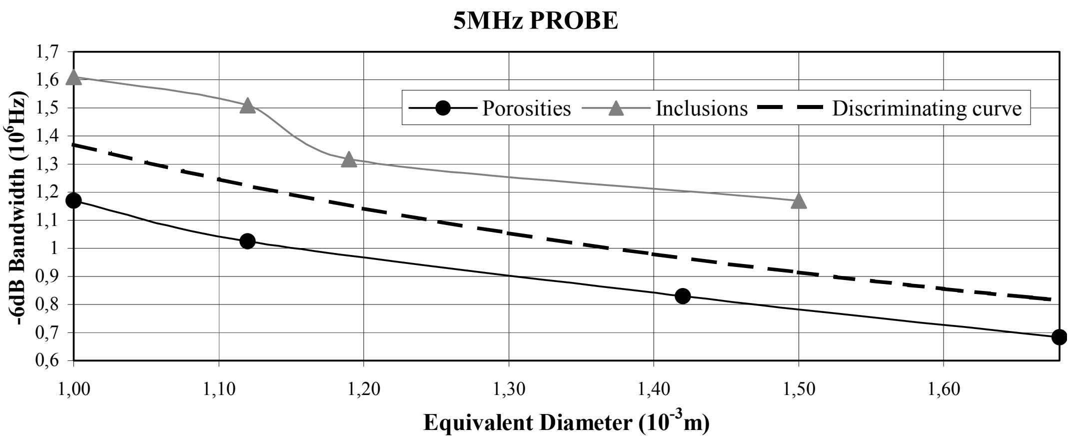

Fig. 4: $\Delta f_{-6\ dB}$ versus equivalent diameter for 5 MHz probe.

It may be also observed that porosity curve never intersects NMI one; thus a porosity locus and a NMI locus may be separated by introducing a discriminating curve both for 4 MHz probe and 5 MHz probe. The proposed discriminating curve equation is:

$$\Delta f_{-6dB} = K_{DSCR} / D_{eq} \tag{1}$$

where K_{DSCR} = 1370 is a constant [Hz·m].

THEORETICAL MODEL

A theoretical model has been proposed which introduces a mathematical relation between defect equivalent diameter and $\Delta f_{-6\ dB}$. Such a relation has been determined by analyzing the mechanism that rules reflection phenomena on defect. Both defect typologies (non-metallic inclusions, porosities) have been assumed sphere-shaped the diameter of which is D_{eq}. By observing Fig. 5, Δt is the time difference vibrations take to cover the path A with respect to path B as represented in the following relation:

$$\Delta t = C \cdot \left(D_{eq} / v \right) \tag{2}$$

where C is a constant which depends on defect nature and probe typology. The reflected signal has been supposed a unitary rectangular impulse the duration of which is Δt. Rectangular impulse signal FFT is given by:

$$S\left(f\right) = \int_{-\Delta t/2}^{\Delta t/2} e^{-j2\pi f t}\, dt = \Delta t \cdot \frac{\sin\left(2\pi f \frac{\Delta t}{2}\right)}{2\pi f \frac{\Delta t}{2}} \tag{3}$$

$S\left(f\right)$ is a cardinal sine function with maximum for $f = 0$ ($S(0) = \Delta t$) [8]. Δf_{-6dB} has been obtained by solving eq. (4) with respect to f [9].

$$S(f) = \Delta t / 2 \tag{4}$$

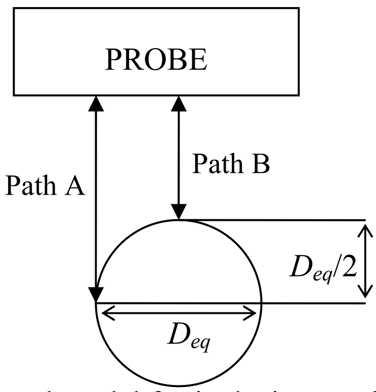

Fig. 5: Proposed model for inclusions and porosities.

Solution gives:

$$\Delta f_{-6dB} = 2 \cdot (0.6/\Delta t) \tag{5}$$

Substituting in eq. (5) the Δt value:

$$\Delta f_{-6dB} = 1.2v/CD_{eq} = K/D_{eq} \qquad \Rightarrow \qquad K = \Delta f_{-6dB} \cdot D_{eq} \tag{6}$$

Relation (6) provides a mathematical constant K which relates defects equivalent diameter D_{eq} and $\Delta f_{-6\,dB}$.

MODEL CALIBRATION

Δf_{-6dB} and D_{eq} values (see Tab. 1) may be employed together with eq. (6) to determine K. The values of K, for each defect typology, are reported in Tab. 2 and Tab. 3.

Tab. 2: Porosities K values for 5 MHz and 4 MHz probe.

Probe frequency (10^6 Hz)	**D_{eq} (10^{-3} m)**	**Experimental $\Delta f_{-6\,dB}$ (10^6 Hz)**	**K_P (Hz·m)**
4	1.00	1.07	1070
	1.12	0.97	1090
	1.42	0.78	1100
	1.68	0.63	1060
5	1.00	1.17	1170
	1.12	1.02	1150
	1.42	0.83	1180
	1.68	0.68	1140

Tab. 3: NMIs K values for 5 MHz and 4 MHz probe.

Probe frequency (10^6 Hz)	**D_{eq} (10^{-3} m)**	**Experimental $\Delta f_{-6\,dB}$ (10^6 Hz)**	**K_{NMI} (Hz·m)**
4	1.00	1.61	1610
	1.12	1.42	1590
	1.19	1.31	1560
	1.50	1.09	1630
5	1.00	1.61	1610
	1.12	1.50	1680
	1.19	1.34	1600
	1.50	1.12	1680

The following procedure may be employed to characterize the defects nature (Fig. 5):

- Evaluation of defects $\Delta f_{-6\,dB}$ by means of FFT analysis.
- Evaluation of defect equivalent diameter D_{eq} through AVG curves.
- Calculation, for each defect (porosities and NMI), of constant K by substituting $\Delta f_{-6\,dB}$ and D_{eq} values in eq. (6).

- Comparison between defects model K values and discriminating curve constant: if the defect constant K is greater than discriminating curve constant then defect is a non-metallic inclusion (NMI), else defect is a porosity.

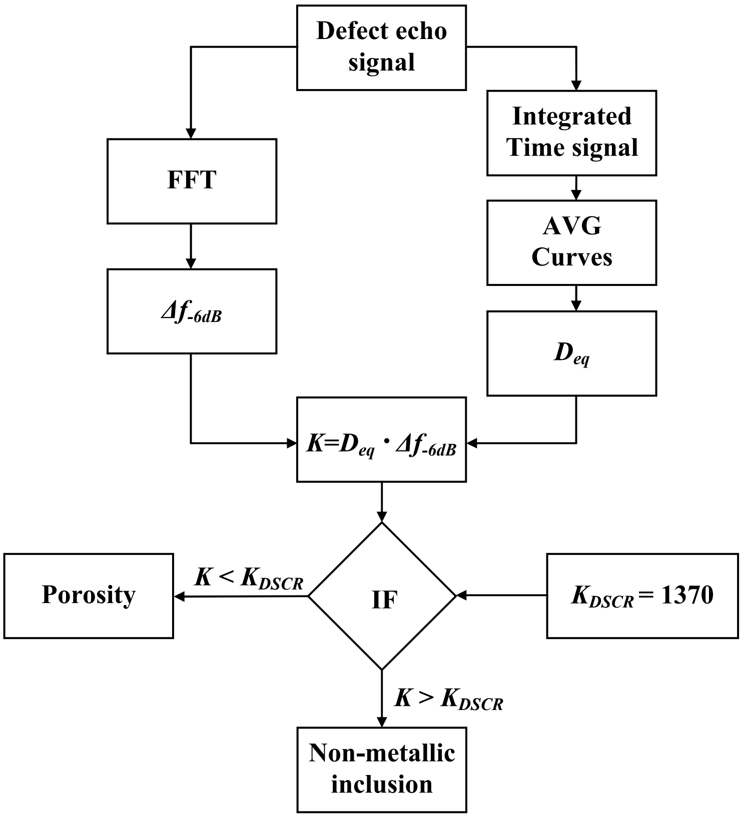

Fig. 5: Flow chart of defect objectification procedure.

CONCLUSIONS

The ultrasonic signals reflected by two types of steel manufacture defects (porosities and NMI) have been studied by evaluating Fast Fourier Transform. The FFT analysis has shown that FFT $\Delta f_{-6\,dB}$ dims as D_{eq} grows; $\Delta f_{-6\,dB}$ vs. D_{eq} diagram has been drawn and a discriminating curve has also been individuated which separates porosity locus from NMI locus both for 4 MHz probe and for 5 MHz probe: NMI locus is above the discriminating curve while porosity locus is below. An original model has been proposed which introduces a mathematical relation between $\Delta f_{-6\,dB}$ and D_{eq}. The model provides a specific constant K for each defect type. The comparison between model constants K and discriminating curve constant K_{DSCR} constitutes a discriminating criterium: results provided by the proposed relation show that when defect constant K is smaller than K_{DSCR} the defect is a porosity, else the defect is a non-metallic inclusion (NMI). It is planned to test the proposed procedure on a wider range of porosities and NMIs. Procedure is suitable to be implemented on a computer based defect objectification code.

LIST OF SYMBOLS

Symbol	Unit	Description
D_{eq}	m	Defect equivalent diameter
$\Delta f_{-6\,dB}$	Hz	FFT (- 6 dB) frequency bandwidth
K_{DSCR}	Hz·m	Discriminating curve constant
Δt	s	Defect echo time duration
C	adimensional	Proportionality constant
v	$m \cdot s^{-1}$	Sound velocity in steel (longitudinal waves)
K	Hz·m	Model calibration constant
K_P	Hz·m	Porosity model calibration constant
K_{NMI}	Hz·m	Non-metallic inclusion model calibration constant

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