

Numerical simulations for long range guided waves Nondestructive Testing by a wavelet based two port equivalent.

F. BERTONCINI, A. MUSOLINO, M. RAUGI, F. TURCU
Department of Electric Systems and Automation
University of Pisa
Via Diotisalvi 56126 Pisa,
ITALY

Abstract: - In this paper the effectiveness of a procedure that allows the detection of a defect by the analysis of parameters of a two port equivalent of a NDT ultrasound guided waves system is investigated. A wavelet expansion of the input (transmitted) and output (reflected) signals has been carried out and a constant coefficient matrix behaving as a transfer function between the input and output port has been defined. The two port equivalent representation correctly simulates the complete system under a wide range of input waveforms in the actual operating condition. The effectiveness of this method to detect and locate defects in the pipes has been investigated.

Key-Words: - Ultrasound guided waves, Two port equivalent, Wavelets

1 Introduction

In many industries pipe corrosion is one of the major problems for plant maintenance. Thus, non-destructive detection and classification of pipes integrity is of actual interest. Recently, the possibility to inspect large part of pipes from a single location by means of the so called "Lamb" guided waves has recalled interest from the potentiality of the method [1]-[3]. The Lamb guided waves are generated in the pipes via a piezoelectric or magnetostrictive transducer, called "transmitter" that is driven by proper electrical signals. Another transducer, called "receiver" is located at a proper distance from the transmitter and gives an electric signal when it detects the elastic wave that is traveling in the pipe. The defect within an incident guided wave path impacts the signature of the scattered fields by exciting all possible modes for the given frequency value. The study of the scattered field (reflected and transmitted) provides essential features for defect detection. By way of phase velocity and frequency tuning, defect detection sensitivity and location analysis can be good despite distance and environmental constraints. Techniques that are based on the Fourier Method are often used to perform the analysis of the signals involved in this procedure.

The ability to go beyond detection and location to classification and sizing, however, is very difficult. The question of which mode and frequency should be selected to impinge onto a defect and have the best chance of classifying or sizing that defect is still a challenging problem. Indeed one of the difficult problems about this kind of nondestructive test (NDT) inspection is the multi-mode coexistence. The different modes cannot be distinguished by the waveforms in the time domain. However the Fourier methods need a

large number of spatial samples of Lamb waveform. This requirement makes the Fourier methods difficult to be used in practice [4]-[6].

In this paper we have considered the transmitter and the receiver transducers respectively as the input and the output ports of the testing device. A two port representation, similar to those used to schematize electronic circuits, has been obtained for the above device. This method, not yet investigated for these kinds of applications, has been studied for detection and classification of defects.

2 Problem Formulation

Recently, Wavelet Theory [7], [8] has received a great interest in many areas of engineering. In particular Wavelet Expansion (WE) techniques have been used for the numerical solution of Multiconductor Transmission Lines [9] and have demonstrated to be a powerful tool especially in terms of simulation efficiency when fast transients are analyzed. As a matter of fact the main feature of wavelet bases is that the wavelet functions are compactly supported, hence they efficiently represent signals that are compactly supported; furthermore they self concentrate where the frequency content of the analyzed signal requires to be represented by a higher number of functions (self adaptive zooming).

In particular WE is here used as a tool through which a transfer function represented by a matrix of constant coefficients is constructed. The identification of this matrix can be obtained from data in the time of frequency domain. Let us consider a two-port system, represented by its input and output signal, respectively defined as $x(t)$ and $y(t)$.

In the frequency domain we have the transfer function relation between the x and y phasors as:

$$\dot{Y} = W(j\omega) \cdot \dot{X} \quad (1)$$

where the transfer function W is a complex number representing the relation between input and output quantities. This transfer function in the considered problems is not a priori known but it can be obtained from the time domain impulse response of the studied system obtained either experimentally or by numerical simulation.

Given a wavelet basis $d(t)=[d_1(t), d_2(t), \dots, d_n(t)]$ of dimension n with n power of two, the WE of x and y are a n -dimensional vector $y(t) = \mathbf{d}(t) \cdot \mathbf{y}$, and $x(t) = \mathbf{d}(t) \cdot \mathbf{x}$, where \mathbf{y} and \mathbf{x} are vectors of coefficients in terms of wavelet basis. The relationship between input and output quantities can be written in the wavelet domain as a matrix-vector product, as follows:

$$\mathbf{y} = \mathbf{W} \cdot \mathbf{x} \quad (2)$$

where \mathbf{W} is a matrix of constant coefficients relating WE of input and output quantities.

In applications where a mathematical model of the studied system is known the matrix \mathbf{W} is known, while in this case the matrix \mathbf{W} has to be determined. The determination of \mathbf{W} is then performed as follows: the i th column of \mathbf{W} is equal to y in the wavelet domain when $\mathbf{x} = \tilde{\mathbf{x}}_i = [0, \dots, 0_{i-1}, 1, 0_{i+1}, 0, \dots, 0]^T$. Therefore $\tilde{\mathbf{x}}_i$ is inverse transformed in the time domain obtaining $\tilde{x}_i(t)$; then its Fourier transform $X_i(j\omega)$, can be easily obtained by a FastFourierTransform and used as input for equation (1). Then, from the obtained $Y_i = W(j\omega)X_i$, $y_i(t)$ is determined by InverseFastFourierTransform and successively by WE of $y_i(t)$ we get the $\mathbf{y}_i = \mathbf{W} \cdot \tilde{\mathbf{x}}_i$ corresponding to the i -th column of the matrix \mathbf{W} . It has to be noted that the inverse transform of $\tilde{\mathbf{x}}_i$ is actually the i -th element of the chosen wavelet basis. This scheme is performed for all the columns of \mathbf{W} determining the complete representation of the two-port equivalent matrix in the wavelet domain for a given basis dimension n .

To fully determine the matrix \mathbf{W} the previous explained operations must be performed for a number of times corresponding to the value n correspondent to the n -dimension of the WE of the x and y quantities. In the author experience this usually varies among 128 and 1024 in most applications. However this number can be significantly reduced. Indeed, from the Multiresolution Analysis theory [7] the n functions $d_i(t)$ (scaling functions or wavelets) composing the basis $d(t)$ belong to different subspaces. A higher number of the above mentioned subspaces (in other words a higher dimension of the basis $d(t)$), is related to a better representation of a signal; this is referred to as

“resolution” of the basis. The basis functions $d_i(t)$ of each subspace are translated versions of a single function; hence in case of a time invariant system a single function of a subspace can be used to determine the output for all the functions of the subspace. This simple consideration allows a strong reduction of the number of simulations required for the characterization. Due to their good characteristics in terms of efficient representation of fast signals, Daubechies wavelets on the interval with $N = 6$ vanishing moments (see [7] for details about their construction) are chosen for this problem. Daubechies wavelets on the interval are characterized by having N (where N is the number of vanishing moments) functions defined on the left border and N on the right border of the interval. And this holds for each subspace of the Multiresolution Analysis. Furthermore the coarser resolution is also related to the number of vanishing moments N . In the case under analysis the lower resolution leads to 32 functions.

Higher resolutions mean higher CPU times (and in this case also an higher number of 3D simulations in order to characterize the system) but, obviously, an higher accuracy. Dimensions of the basis of $n = 128$ and $n = 256$ are a reasonable number of functions leading to low CPU times and desired accuracy. Furthermore the number of wavelet coefficients (the number of basis functions) is equal to the samples of the analyzed time domain function, hence the increase of n leads also to a better time representation of the input and output signals.

Looking at a basis of 128 functions in detail, it has been found out that it is composed by 3 subspaces, respectively characterized by 32 scaling functions at resolution 32, 32 wavelets at resolution 32 and 64 wavelets at resolution 64. Among those 128 functions the only independent ones for each subspace are the 12 functions (equal to $2N$) on the border and the central function (the one that is translated in order to form the basis). Hence referring to the basis of dimension 128 the independent functions to simulate are $N_{\text{fun}} = 3 \cdot 2N + 3 = 39$. In the same way for the basis composed by 256 functions the independent simulations to run are only $N_{\text{fun}} = 4 \cdot 2N + 4 = 52$.

3 Problem Solution

It has been evaluated the effects that different types of asymmetrical pipe defect have on the matrix \mathbf{W} . For this purpose, it has been computed the norm of \mathbf{W} corresponding to each singular defect.

Table 1 shows the parameters (characteristics of each defect) involved in simulations.

The incident wave used in the simulations is a torsional wave having the wavelength $\lambda=0.059\text{m}$. For the

evaluation it has been used the circumferential component only, as being the most representative.

Table1

| Length (mm) | Thickness (%) | Solid angle (deg.) |
|-------------|---------------|--------------------|
| 3 | 10 | 10 |
| 6 | 30 | 20 |
| 12 | 50 | 30 |
| 18 | 70 | 40 |
| 24 | 90 | - |

The norms used to evaluate the wavelet matrix are:

- Norm1(W)=max(sum(abs(W))), that is the largest column sum of W;
- Norm2(W)=sqrt(sum(diag(W'*W))), i.e. the Forbenius norm;
- Norm3(W)=max(svd(W)), i.e. the largest singular value of W.

Figures 1 to 7 illustrate the behavior of norm1 of matrix W for different sets of defects. A result to be noted is that the larger the defect volume, the higher becomes the sensitivity of the W matrix. In addition, axial dimension (i.e. length of defect), show minor influence on the norm of W matrix at small solid angle or thickness (fig.2 to 5). Higher values of solid angle and thickness (fig.1, 6, 7) also bring to a different norm trend.

Figure 8 summarizes the impact that each of the 100 types of defect has on the wavelet matrix. It confirms once again that the W matrix is more sensitive at variation of solid angle and thickness of defects.

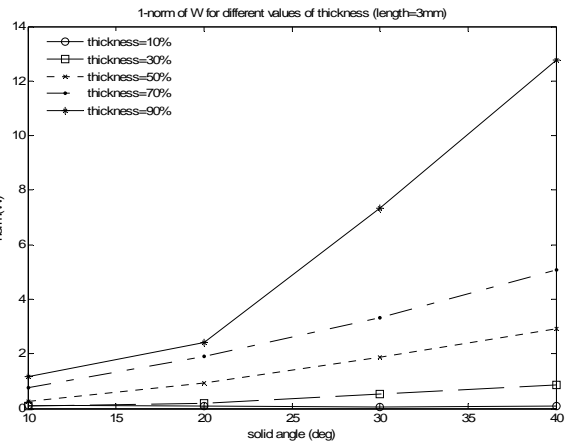


Fig.2 Behavior of W matrix at variations of solid angle and thickness of defect

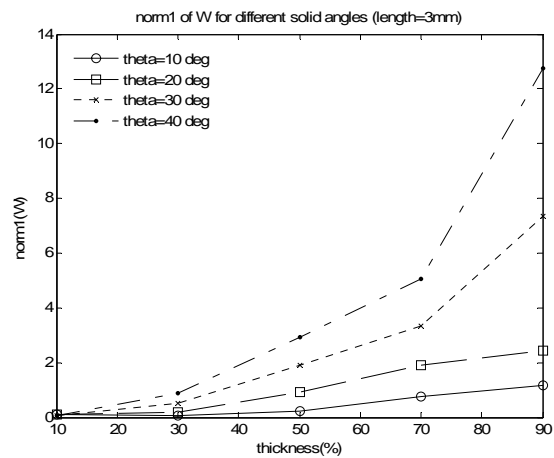


Fig.3 Behavior of W matrix at variations of thickness and solid angle of defect.

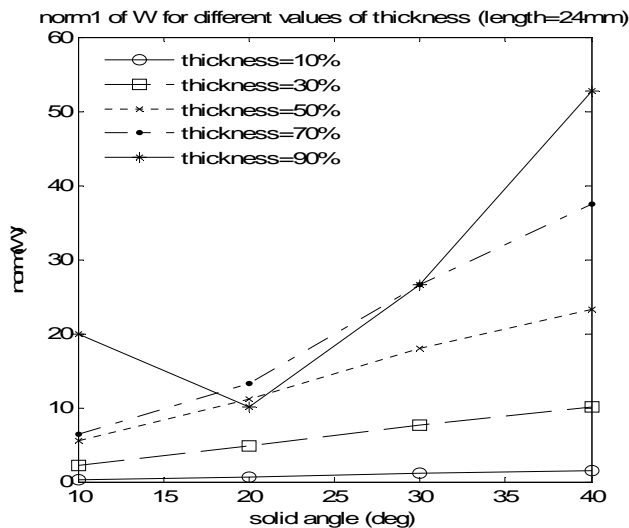


Fig.1 Behavior of W matrix at variations of length and thickness of defect

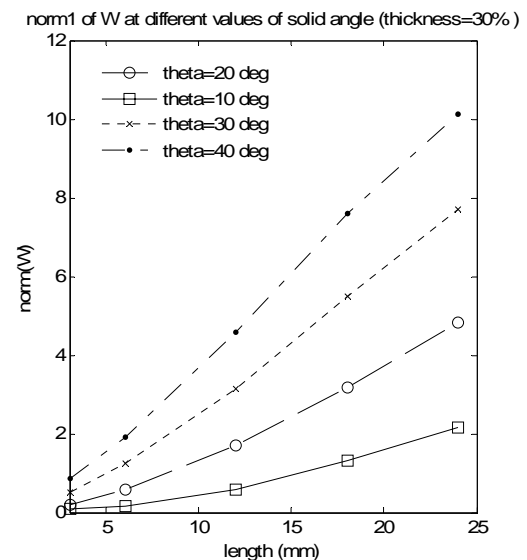


Fig.4 Behavior of W matrix at variations of length and solid angle of defect

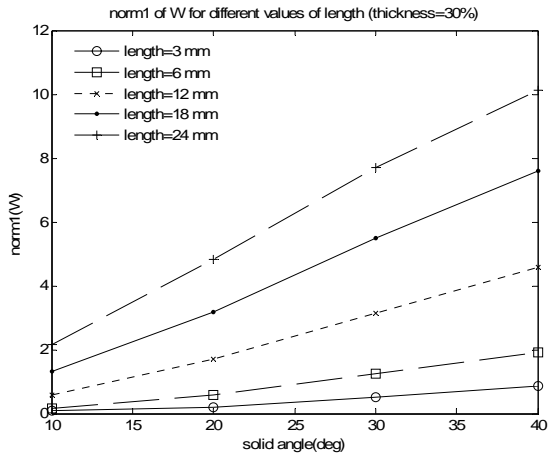


Fig.5 Behavior of W matrix at variations of solid angle and length of defect

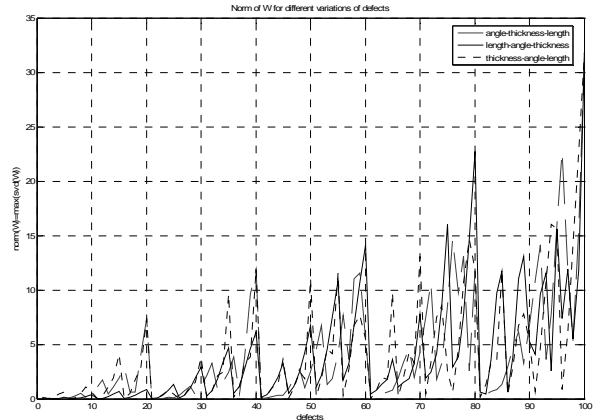


Fig.8 Behavior of W matrix at different variations of all 100 types of defect

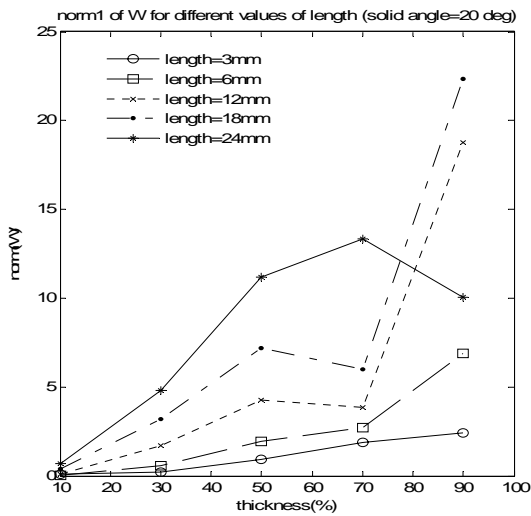


Fig.6 Behavior of W matrix at variations of thickness and length of defect

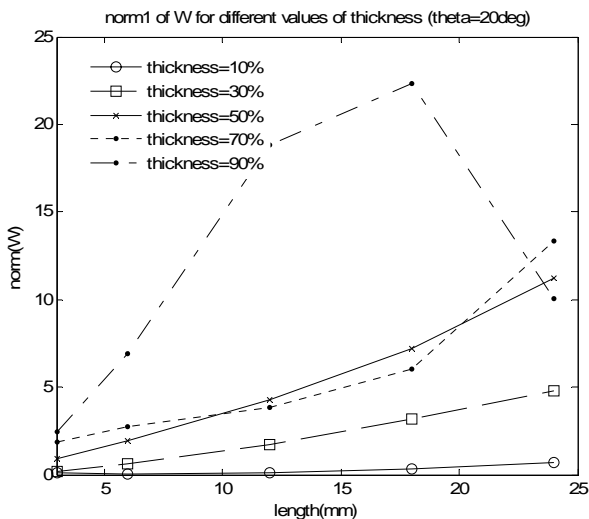


Fig.7 Behavior of W matrix at variations of length and thickness of defect

4 Conclusion

In order to classify a particular pipe defect by the means of an NDT ultrasound guided waves system, a WE of the two waves (incident and reflected) has been performed. The resulted W matrix (treated as a transfer function between input and output) behaves different for each type of defect.

The results show that W matrix can be a useful instrument in detecting the pipe defects. It can also inform about the volume of defect.

5 Acknowledgements

This work was supported in part by the Ministry of University under a Program for the Development of Research of National Interest PRIN 2003094558.

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