Model Based Microwave Non Destructive Testing of Pipes

G. ACCIANI, G.BRUNETTI, G. FORNARELLI, C. GUARAGNELLA D.E.E. – Electrics and Electronics Department – Politecnico di Bari Politecnico di Bari 4, E. Orabona, 70125 – Bari ITALY

Abstract – The problem of non destructive microwave testing of pipes has been addressed to evaluate the effectiveness of the technique based on the measurement of the scattering parameter S_{11} . An asymmetric bifilar transmission line has been used to acquire data to be used in the defect modeling, being the pipe to be tested one of the two wires in the line, and a normal copper wire the other.

The proposed data preprocessing to be used in a defect classification system is the focus of the paper. A linear time invariant convolving model of the defect is presented to take care of the experimental data acquisition setup. The assumption is that proper modeling can enhance in distinguishing different defects in the measurement system.

The technique to extract the model from the acquired data is presented, together with a few experimental results conducted on real acquired data.

Key-Words: - Microwave testing and evaluation, model, lattice filter, not accessible pipes

1. Introduction

In this work, the problem of non destructive microwave testing of pipes has been addressed to evaluate the effectiveness of the technique based on the computation of the scattering parameter S_{11} . An asymmetric bifilar transmission line has been used to acquire data to be used in the defect modeling, the pipe to be tested being one of the two wires in the line, and a normal copper wire the other, here referred as the sensor.

The used technique has been applied in several contests of NDT of metallic structures. It performs well in terms of detection rate and position estimation of the defects eventually present on the metallic structure. The possibility of extending the technique to classify also the typology of defect is addressed in this paper.

An efficient classification system should be able to distinguish defects in positions, shapes and sizes. The classification system performances are dependent on the modality used in the acquisition system (power, bandwidth, time duration of the test signals, preprocessing technique applied to acquired data) and also on the a-priori information about the physical system under test. An automatic procedure able to distinguish among several defects classes can be trained from the preprocessed data.

A second level of a classification can be achieved if a finer defect-class subclass distinction can be obtained from data. This higher classification level shifts the classification problem towards the definition of a measurement system. Of course, the possibility of defining the sub-classes of a given classification system depend on the sufficient statistics present in the acquired data. Here the problem can reveal severe. Any classification technique applied on acquired data can perform better if a suitable preprocessing step has been carried out. It is performed in order to enhance the characteristic data components of the separated classes and reducing as much as possible any misleading contributions to the acquired data (noise).

In the specific application the defect cannot be highlighted and distinguished easily, due to the low radiometric resolution of the acquired data. In this paper the defect classification issues is addressed.

To allow a higher resolution to the classification step, a model of the acquisition system has been developed, and a defect model has been assumed to take care of the experimental data acquisition setup.

The aim of the paper is to develop a defect model to enhance the defect peculiarities in the acquired data. The assumption is that the proper modeling of the data acquisition inserts in experimental data an external information (the model) that can help in distinguishing among different types of defects.

The classification algorithm can avail mainly on defect characteristics and be able to distinguish among similar defects types thus creating a sort of measurement system.

A linear convolving defect model has been used, carried out by considerations about the physical mechanism at the base of the acquisition problem, and the technique to extract the model from the acquired data is presented.

The main feature of the addressed problem lies in its general approach to system response to a known input signal, to detect anomalous behavior and classify the anomalous misbehavior. The technique can be easily applied in any other NDT signal acquisition framework.

Experimental results have been analyzed to validate the developed defect model structure. In particular, several different defects such as holes and cuts have been created on a test pipe and the acquired data used to extract the signal information. Defects have been created with different characteristics, such as the size and the depth and position with respect to the sensor used.

In Section 2 the experimental measurement setup is described. Section 3 addresses the defect model definition, while in section 4 experimental results carried out on the acquired signals are presented. Conclusions and comments close the paper.

2. Experimental data acquisition setup

The experimental measurement setup is pictorially reported in figure 1. A network analyzer has been used to measure the scattering parameter S_{11} at the input port of an asymmetric bifilar transmission line. One of the two wires in the line is the pipe under test, and the other a normal copper wire.

Measures of the scattering parameter S_{11} have been carried out on a bandwidth of about 6 GHz. The measures have been computed in the frequency domain collecting 1601 measures on the whole spanned bandwidth.



Figure 1: The used experimental setup

Such measures have been carried out both for the sound pipe and the pipe with the defect under test.

An example of acquired measures are reported in figure 2 a) and b) in the frequency domain and in the time domain (Inverse FFT signal obtained by the acquired frequencies measures).

This operating mode is not helpful in highlighting the position of the effect on the structure: in fact the position is strictly linked to the estimation of the round trip time of flight of the transmitted signal, easily achievable by the transient analysis of the system. The acquisition operating mode, making recourse on frequency measures, can be classified as a steady-state measurement system, as the acquired measures of the scattering parameter $S_{11}(f)$ are obtained as a time averaged measure of the parameter corresponding to the application of a sinusoidal signal. The evaluation is carried out by the network analyzer in an efficient way by the chirp z transform.

Due to the short pipe length and the unavoidable mismatch of the measurement system at the line gate, the impulse response of the sound system is an infinite length one. The indirect computation of the time signals by inverse Fourier transform, due to the sampling operated in the frequency domain, produces a time domain aliasing. The periodicity introduced by IFFT on the signal folds the infinite system impulse response (see fig. 3) producing several peaks in the time domain signal, thus creating ambiguities in the proper detection of the true time of flight of the received signal.

Nevertheless, prof. Celozzi has demonstrated that a fair estimation of the time of flight is possible by evaluating the peak position of the product of correlation and difference among the reference signal (sound structure) and the measured signal.

The computation of the time of flight is not addressed in this work.



b) frequency domain (GHz)

Figure 2: time and frequency domain acquired signals of the S_{11} parameter



Figure 3: Time aliasing introduced in the IFFT computation of the sampled frequency domain spectra.

3. The defect model

The defect model here used to describe the defect is reported in figure 4.

It consists of a double linear and time-invariant structure: the unknown impulse response, h(t), is introduced to describe

the defect characteristics, and is an unknown quantity.

In the assumed model, when $h(t) = \delta(t)$, the returning signal is totally reflected by the defect discontinuity section, while the transmitted signal is null. On the opposite case, if h(t)=0, no defect is present on the generic section and all the signal is transmitted at the right output port. Any other possibility can be accomplished by the proposed defect model.

The doubled structure is required to take care of the physical system behavior: if a signal is propagating from the right end side toward the generator, it gets across the defect, so that the received signal at the generator section of the structure reveals the defect filtered signal.



Figure 4: The assumed convolution defect model.

The model here introduced is used to take care of the defect behavior in the pipe. To well compare situation of sound pipes and pipes with defects, a model of the data acquisition system for the case of the sound pipe case is also introduced. The physical analysis of the acquisition system can easily convince to be in presence of an IIR (infinite impulse response) filter. In absence of any defect, because of the presence of a discontinuity at the measurement side of the structure and of the finite length of the pipe to be measured, the impulse response is the result of several delayed pulses, so that the used system to model the sound structure has been chosen as a lattice terminated on a short circuit (total reflection hypothesis).

The used structure is presented in figure 5.

The k coefficient takes care of the obvious presence of a mismatch between the measurement system at the leftmost position in the line and the pipe under test. For k=0 there is no mismatch and the received signal is a single pulse, delayed by the two ways path time of flight.

When a discontinuity is present in the pipe at section "s", the acquisition structure changes slightly: due to the presence of the defect at the generic position that can be represented by the two ways time of flight T_1 , the complete structure results the one reported in figure 6: the whole structure at the right of section s_2 can be used to model the defect as it contains the whole information about the defect: the delay T_1 (position of the defect on the structure) and convolving model, h(t).

The defect model thus results in a transfer function $H_{in}(f)$ terminating the pipe at the section s_2 .

$$\begin{bmatrix} X_1(f) \\ Y_1(f) \end{bmatrix} = \frac{X_3(f)}{1 - H(f)} \begin{bmatrix} 1 & -k \cdot e^{-j\omega T_1} \\ k & e^{-j\omega T_1} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ H_{in}(f) \end{bmatrix}$$
(2)

The acquired signals used to test the pipe are the sampled sequence for the typical sound pipe (the reference signal) and the acquired signal of the structure with the given defect. The compared measures refer to the two described measure signals, for several types of defects.

The two acquired signals to be used in the experiments are



Figure 5: The lattice structure of the transmission line terminated on a short circuit (line end). T_0 is the delay introduced in the two ways path of an hypothetic pulse applied as a test signal.

 $y_{1}(t)$ and $y_{1d}(t)$ where the former refers to the sound structure and the latter to the structure with the defect. For the sound structure equations (1) simplify to:

$$\begin{bmatrix} X_1(f) \\ Y_1(f) \end{bmatrix} = X_3(f) \cdot \begin{bmatrix} 1 & -k \\ k & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ e^{-j\omega T_0} \end{bmatrix}$$
(3)

Stated $H_o(f)$ the ratio between the observation of the defect and the sound structure, and combining (2) and (3) to exploit $H_{in}(f)$ it can be obtained:

$$H_{in}(f) = \frac{H_o(f) - k}{1 + k \cdot H_o(f)} \cdot e^{j\omega T_1}$$

$$\tag{4}$$

Equation (4) well candidates to describe the defect model.

As the goal of the paper is to distinguish among different typologies of defects, the exponential term in (4) is neglected: it contains only the information about the position of the defect on the system under test, here not addressed.

 $H_o(f)$ is easily computable in the frequency domain as the ratio between Fourier Transforms of the signal of the structure with the defect and the sound one.

The coefficient k takes care of the mismatch of the measurement acquisition system with the structure under



Figure 6: The complete model used to describe the experimental acquisition system. In the scheme, $T_1 + T_2 = T_0$ of fig.5

test. If k=0 there is no particular difficulty in computing $H_{in}(f)$, as it equals $H_o(f)$, but for the delay.

When a mismatch is present, instead, the transfer function naturally involves terms due to reflections of the test signal on the discontinuities present in the pipe, both for the sound and defect cases.

As the first impulse response of the defect is much higher then the others, the response of the sound structure to the input can be subtracted to highlight the differences among several defects.

This is due to three causes:

- 1. the mismatch between the instrumentation and the system under test is normally very low, so that after the first reflection, the amplitude of the other echoes of the defects are much lower at the measurement section s1;
- 2. the system under test is a dispersive system, so that the reflected pulse is much widened and thus reduced in power;
- 3. the system is also highly dissipative, so that losses reduce very much the amplitude of the received signal.

Definitely, the used defect model here introduced is:

$$H_{in}(f) = \left[\frac{H_o(f) - k}{1 + k \cdot H_o(f)} - \frac{1 - k}{1 + k}\right]$$
(5)

The reported experimental results refer to (5).

4. Experimental results

Data have been acquired with the instrumentation reported in table 1. The acquired measures refer to the Scattering parameter at section s1. Such measures have been acquired roughly on a bandwidth of 6 GHz and organized over a vector of 1601 frequency bins.

The experimental setup refers to section s1 as the reference point for the acquisition of the scattering parameter S_{11} . All the presented results have been obtained using an hypothesized mismatch parameter k=0.1, anyway results don't differ too much with other values of the mismatch parameter.

Table 1	
Vector network analyzer	HP8753E
Test measurements	S ₁₁
Frequency span (Span)	[3,747,657
	5,999,998,857] (Hz)
	~ 6 GHz
Acquired measurement	N = 1601;
points (Frequency domain)	
IF-BW	300 Hz
Sampling time units (IFFT	~ 12 ps
transformed), T _{samp}	
Two ways Light Speed in	$1.11 \times 10^5 \text{ m/s}$
the line (speed)	
Observed line length	2.131 m
(speed \times N \times Tsamp)	(> measured line length)

Experimental data acquisition system parameters

Several kind of defects have been tested: every defect is located at a given distance from the sensor and in a different position with respect to the sensor position.

Defects are shortly described hereafter:

- 1. Vertical circular hole located on the pipe under the sensor (three types: 3 mm wide and 1 mm deep; 3 mm wide passing; 5 mm wide passing);
- 2. Vertical circular hole located on the pipe at 90 degrees of rotation with respect to the sensor position (three types: 3 mm wide and 1 mm deep; 3 mm wide passing; 5 mm wide passing);
- 3. Cut orthogonal with respect to the pipe axis at 90 degrees of rotation with respect to the sensor position (three types: 10 mm x 1 mm and 1 mm deep; 20 mm x 1 mm and 2 mm deep; 20 mm x 1 mm passing);
- 4. Cut orthogonal with respect to the pipe axis at 180 degrees of rotation with respect to the sensor position (three types: 10 mm x 1 mm and 1 mm deep; 20 mm x 1 mm and 2 mm deep; 20 mm x 1 mm passing);
- 5. Cut parallel with respect to the pipe axis (three types: 15 mm x 1 mm and 1 mm deep; 25 mm x 1 mm and 2 mm deep; 25 mm x 1 mm passing).



Figure 7: The obtained signals plotted together correspond to different sizes of defects of the same typology.

Figure 7 reports for each defect type the obtained signals both in the frequency and in the time domain, by applying the proposed model. For these defects, three curves are shown demonstrating somehow a quantitative capacity of the model to distinguish among defects of the same typology, and also from defects of different typologies.

5. Discussion and conclusions

The proposed technique has been developed for the non destructive testing and evaluation of not accessible pipes by a microwave based measurement system. The acquired measures refer to the scattering parameter S_{11} data of a asymmetric bifilar transmission line in which the pipe to be tested represents one of the two wires in the line (a normal copper wire is used as the sensor).

To enhance the defect peculiarities and allow the defects distinction, classification and eventually measurement, a priori information about the physical system is introduced. A novel convolving defect model is presented.

Preliminary qualitative results seem to indicate that a moderate capability in distinguishing among defects of the same kind and on different kind of defects, can be obtained.

The use of microwave signals seems the highest limitation of the proposed technique: obtained measures should be almost independent on the conditions the pipe is working (soil characteristics if grounded, atmospheric parameters, and also surrounding objects).

The experience about this work is that due to the high frequencies used, several parameters concur to deviate the acquired signal.

The proposed procedure is, anyway, general and almost independent on the type of acquired signals; next step will address the application the proposed technique to ultrasonic nondestructive inspection techniques.

The final goal to be pursued is a neural network based automatic measurement system for on site non destructive pipe inspection.

Acknowledgments

The present work has been developed in the framework of the Italian 2004 PRIN project "Studio e Sperimentazione di diagnostiche non distruttive per tratti non accessibili di condutture", national coordinator prof. Marco Raugi.

Experimental results refer to the data acquired by prof. Salvatore Celozzi.

References

- C. Buccella, M. Feliziani, G. Manzi, Accurate Detection of Low Entity Cable Faults by Wavelet Transform, International Symposium on Electromagnetic Compatibility, 2004, EMC 2004, v l. 3, Aug. 2004, pp. 936-941
- [2] S. Corsi, A. Massa, M. Pastorino, A. Randazzo, Electromagnetic Detection of Dielectric Scatteres using Phaseless Synthetic and Real Dataand the Memetic Algorithm, TECHNICAL Report, DIT-04-066
- [3] W. H. Weedon, W.C. Chew, P.E. Mayes, A Step Frequency Radar Imaging System for Nondestructive Evaluation, PIER 2000, 28, pp. 121-146
- [4] G. L. Plett, T. Doi, D. Torrieri, Mine Detection Usng Scattering Parameters and Artificial Neural Network, IEEE Trans. On Neural Networks, 8, NO. 6, Nov. 1997
- [5] M. Pastorino, S. Caorsi, A. Massa, A Global Optimization Technique for Microwave Nondestructive Evaluation, IEEE Trans. Instrumentation and Measurement, Vol. 51, No. 4, Aug. 2002
- [6] S. Caorsi, A. Massa, M. Pastorino, M. Donelli, Improved Microwave Imaging Procedure for Nondestructive Evaluations of Two-Dimensional Structures, IEEE Trans. Antennas and Propagation, Vol. 52, No. 6, June 2004
- [7] R. Zoughi, Microwave Non Destructive Testing and Evaluation Principles, Kluver Academic Publisher, 2000