Development of a hybrid finite element/finite integration model for the UK's National Physical Laboratory acoustic emission reference facility

P. N. Gélat, National Physical Laboratory, Queens Road, Teddington, Middlesex TW11 0LW, United Kingdom
P. D. Theobald, National Physical Laboratory, Queens Road, Teddington, Middlesex TW11 0LW, United Kingdom
F. Schubert, Fraunhofer-Institute for Nondestructive Testing (IZFP), Branch Lab EADQ, Kruegerstrasse 22, D-01326 Dresden, Germany

ABSTRACT

Recent advances in computing power and signal processing techniques have highlighted the need for a greater understanding of acoustic emission (AE) wave propagation and the interactions with the sensor being used. Complex structures often lead to numerous wave modes being generated which arrive at a surface mounted sensor from different angles of incidence and in different planes. To fully understand the signals produced by the sensor, one requires intimate knowledge of the elastic wave propagation through the structure and understanding of the sensors response to the propagating elastic wave.

This paper proposes a hybrid method for modelling acoustic emission reference systems in both the electrical and acoustical domain using the finite element (FE) method and the elastodynamic finite integration technique (EFIT). The method for validation of the FE and EFIT methods is detailed and the hybrid method has been tested using inputs to the EFIT code generated in a FE model of a conical piezoelectric transducer excited with an electric charge function. The agreement for both axial and radial displacement components at the opposite sensor loaded surface has been shown to be excellent and only shows small discrepancies after several reflections.

The hybrid method shows excellent potential for modelling more complex acoustic emission structures in the future by combining the FE capabilities of modelling piezoelectric material in the electro-mechanical domain and the EFIT capabilities for rapid solutions to large scale linear and non-linear propagation problems.

Keywords
Finite element, finite integration, acoustic emission, conical transducer

1 INTRODUCTION

AE events in complex structures lead to the generation of numerous modes of propagation which can arrive at a surface mounted sensor from different angles of incidence and thus generate different displacement vectors across the sensor. Although a sensor calibration provides the sensor's electrical response to a given displacement event, to fully understand the electrical signals generated by the sensor, one requires intimate knowledge of the elastic wave propagation through the structure and an understanding of the sensor's interaction with the propagating elastic wave incident at the surface/sensor boundary. Many acoustic emission measurements are performed without this prior knowledge and the sensors are often only calibrated for a particular wave mode under controlled conditions making the interpretation of measured signals difficult.

The UK's National Physical Laboratory (NPL) is currently developing a method for modelling stress wave generation using a point contact transducer and the interaction of the stress waves with a coupled piezoelectric receiver using a reference propagation medium. Ultimately the method is being developed for the modelling of the NPL AE reference facility used for the out-of-plane displacement calibration of acoustic emission sensors [1][2] and will implement a full FE/EFIT hybrid configuration with the potential to model larger and more complex structure in the future. The overall aim of the work is to provide a greater understanding of how an AE sensor interacts with incident stress waves and thus improve measurement confidence based on the interpretation of electrical signals generated by an AE sensor.

This paper presents the results of an initial comparison of the NPL finite element (FE) model with results of an EFIT method produced by the Fraunhofer Institute’s EADQ Laboratory [3][4][5]. Further comparison results are presented for each development stage of the hybrid method, including a conical PZT transducer as a transmitter, a cylindrical glass block and a coupled AE sensor, to test the validity of the hybrid approach.

2 FINITE ELEMENT AND FINITE INTEGRATION HYBRID MODEL

In order to model a complete reference system, consisting of a piezoelectric transmitter with an electrical transient excitation, a BK7 glass propagation medium and a coupled piezoelectric AE sensor. It is not practical to use the NPL FE code alone due to the computational times involved when solving problems with non-axisymmetric geometries at ultrasonic frequencies. The NPL FE code uses the PAFEC Vibroacoustics package developed by PACSYS Ltd. which employs an implicit numerical method to solve arbitrary Partial Differential Equations (PDE’s). The Vibroacoustics package allows coupling between electrical and acoustic elements. This is extremely advantageous as it allows modelling of piezoelectric sensors in both the electrical and mechanical domain, providing electrical impedance and response for a mechanical/acoustical excitation and vice versa. However, the implicit nature of the FE code makes it very processor-intensive for transient analysis, requiring a solution for the whole mesh for each time step. For this reason, it was decided to use a hybrid approach which employed the PAFEC FE code for the modelling of the piezoelectric transmitter and sensor, with the glass propagation medium modelled using an elastodynamic finite integration technique by the Fraunhofer Institute’s EADQ Laboratory. The EFIT is an explicit numerical time-domain scheme to model elastic wave propagation in isotropic and anisotropic, homogeneous and heterogeneous as well as non-dissipative elastic media [7] and allows rapid solutions to be obtained for two-dimensional and three-dimensional stress wave propagation media. The hybrid method should allow the coupling of the advantages of the FE modelling transmitter/receiver electro-acoustical properties with the high speed EFIT for modelling propagation in larger complex structures.

3 TESTING METHOD AND COMPARISON RESULTS

This paper aims to validate the use of the hybrid modelling method by comparison of the hybrid results against a complete PAFEC FE model for a reduced scale model in two stages. Predicting the output of the coupled sensor was beyond the scope of this paper.

3.1 Point source excitation of FE and EFIT models

The first stage compared the outputs from the FE and the EFIT code for a point excitation on a small scale cylindrical BK7 glass block. The glass block measured 90 mm in length with a 30 mm radius such that it could be solved as a two-dimensional axisymmetric model. The material properties used for the glass block were: Young's modulus, $E = 61$ GPa; Poisson's ratio, $v = 0.25$ and density, $\rho = 2224$ kg m^{-3}. In both cases, a transient force was exerted in the axial direction at $r = 0$ and $z = 0$ on the cylinder shown in Figure 1. The time history of the force $f(t)$ is described by:

$$f(t) = \sin(2\pi f t)\sin(\pi f t) \qquad \text{for } t \leq 0.5\times10^{5}\text{ s} \qquad (1a)$$

and

$$f(t) = 0 \qquad \text{for } t > 0.5\times10^{5}\text{ s} \qquad (1b)$$

where a force magnitude of 1 N was applied, f is the frequency (100 kHz and 200 kHz were used) and t is the time.

An eight-noded isoparametric curvilinear quadrilateral element was used to provide a flat element which carries loads in its own plane only for the NPL's FE model. This type of element has two degrees of freedom (u_x, u_y) in its own plane at each node, where the x and y coordinate refer to the z and r axis shown in Figure 1 respectively. The stiffness, mass and loading matrices are all calculated by transforming the curved shape to a square using the isoparametric method. The FE calculations were performed using both three and then six elements per structural wavelength with excellent agreement between the two. The time-steps used to calculate the solutions were 0.1 µs and 0.05 µs for 100 kHz and 200 kHz respectively. The wave speed used for this criterion was that of shear waves in glass, i.e. 3312 m s^{-1} where the smallest structural wavelength was based on a maximum excitation frequency component of 2 MHz. This was considered sufficient following spectral analysis of the source function, $f(t)$ shown in equation (1) for $f = 200$ kHz.

A fine 191×573 numerical grid was employed by EADQ for the EFIT model selected to provide an accurate solution to over 2 MHz in addition to a 100×300 grid which showed negligible deviation from the fine mesh solution.

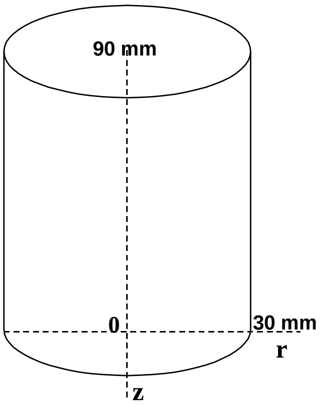

Figure 1. Coordinate system used for model of glass cylinder.

The FE and EFIT results were compared for both 100 kHz and 200 kHz source functions described in equations (1a) and (1b) at a number of locations on the surface of the glass cylinder. Figure 2 shows a comparison at 200 kHz for both axial and radial displacement components for the FE solution using 3 elements per wavelength and the EFIT using the fine 191×573 numerical grid at position $r = 15$ mm, $z = 0$ mm. In this case, the comparison point is on the same surface as the point force excitation so the first arrival observed represents the Rayleigh wave travelling along the surface. The agreement is excellent over the complete 0.06 ms period shown.

Figure 2 also shows the result from the same comparison at position $r = 0$ mm, $z = 90$ mm which is on the central axis directly opposite the source excitation. In this case, only the axial displacement is shown as the radial components cancel out along the central axis in this particular case. The small first arrival observed at around 0.15 ms is the direct longitudinal wave with larger arrivals occurring after this due to reflections and mode conversion from the external boundary at $r = 30$ mm.

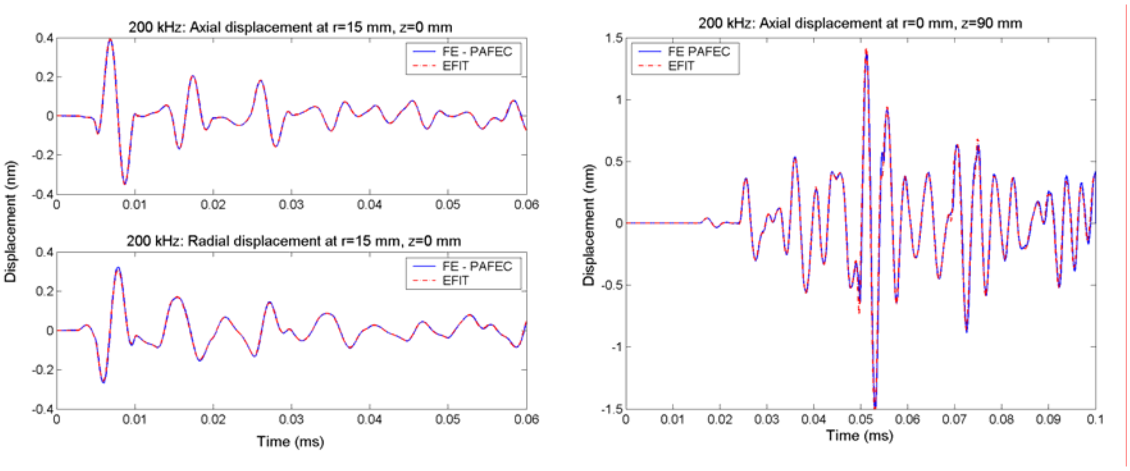

Figure 2. Displacement component comparison of NPL FE and EFIT model for a point force excitation.

Again, the agreement obtained between the two models in Figure 3 is excellent. The propagation volume was completely enclosed by boundaries and the duration of the calculated signal was relatively long so that there were many different wave modes and mode converted reflections within the given time window. Thus any small inaccuracies due to the finite grid would have had enough time to accumulate and produce discrepancies between the results. The agreement at other locations on the surface of the glass cylinder was also excellent.

3.2 Hybrid comparison for piezoelectric transmitter

The hybrid method requires outputs from the FE PAFEC code to be entered as inputs to the EFIT code at the transmitter phase with suitable boundary conditions and outputs from the EFIT code to be entered as inputs to the FE PAFEC code for the sensor phase, again with suitable boundary conditions. This paper only considers the transmitter phase where the transmitter modelled was a conical transducer [1] consisting of a conical piezoelectric (PZT-5A) element with a top diameter of 10 mm and a contact diameter of 1 mm with a central thickness of 3 mm. The piezoelectric element was mass loaded with a 14 mm layer of tungsten-loaded epoxy and a 14 mm layer of pure epoxy backing layer with a 20 mm diameter.

The first step was to obtain suitable outputs from the FE model of the conical transducer to feed into the glass cylinder coded in the EFIT model. The conical transducer was modelled using a combination of the elements described in section 3.1 for all non-piezoelectric material together with axisymmetric piezoelectric elements for the PZT-5A. This was a curvilinear eight-noded quadrilateral element, used for modelling the generator plane of an axisymmetric piezoelectric structure and 2D plane stress piezoelectric structures. The elements have four degrees of freedom; u_x, u_y, u_z and Φ_z at each node, where u_x, u_y and u_z are the displacements and Φ_z is the electric potential. The material properties used for the transducer FE model are given in Table 1.

Table 1

Material	***E*** **(GPa)**	**ρ (kg m^{-3})**	**ν**	**tan δ (viscous damping)**
Tungsten Epoxy	2.215	6932	0.35	$4.77\ 10^{-7}$
Pure Epoxy	6.215	1148	0.30	$2.39\ 10^{-7}$
PZT-5A	N/A	7750	N/A	$1.18\ 10^{-8}$

A zero potential was applied to the PZT-5A surface in contact with the glass block, effectively modelling the earth electrode. The following charge time history, *q(t)*, was applied to each node on the live electrode:

$$q(t) = -\sin(2\pi \times f \times t) \qquad \text{for } t \leq 0.5\ 10^{5}\ \text{s} \tag{2a}$$

and

$$q(t) = 0 \qquad \text{for } t > 0.5\ 10^{5}\ \text{s} \tag{2b}$$

where the excitation frequency, *f*, was 100 kHz.

In order to obtain the axial and radial displacements at the transducer/glass block interface to be used as input data for the EFIT code, it was necessary to produce waveforms that were free from reflections within the block. To minimise the interference of reflections with the displacements at the transducer/glass block interface, a glass block measuring 180 mm in length with a 60 mm radius was used with an L-shaped region within the block starting at $z = 135$ mm and $r = 45$ mm was generated, which had the same properties as glass but a damping factor of 5×10^{-7}, hence approximating an anechoic termination. The mesh for this FE axisymmetric model is shown in Figure 3. For the 100 kHz case, an FE mesh equivalent to 6 elements per wavelength were used.

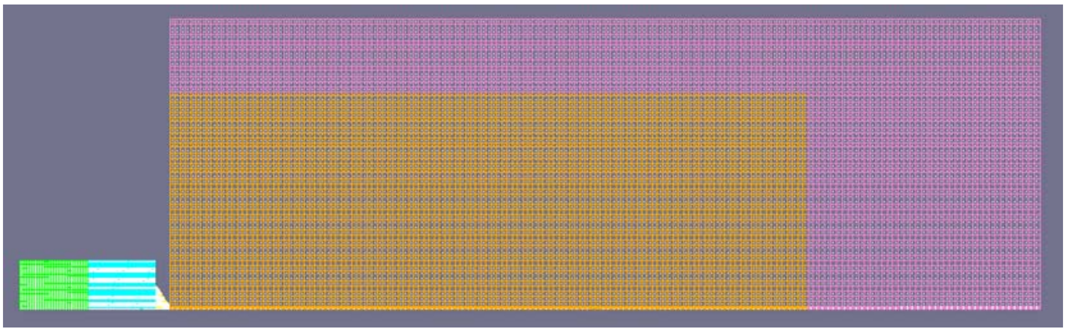

Figure 3. PAFEC FE mesh used for anechoic block.

The output axial and radial displacements were extracted from the FE model for each node along the transducer/glass block interface. The axial displacement at $r = 0$ mm (centre of the transducer contact point) is shown in Figure 4 as well as the axial and radial displacements at $r = 0.25$ mm (halfway between the contact centre and the contact edge). These results show both that the transducer response is heavily damped and that any reflections present within the time window from the boundaries of the block are negligible. The apparent large displacements of several metres are due to the large unity charge applied to the piezoelectric element. Although this leads to unreasonably large displacements in the model, the model is in fact linear so the displacements can easily be scaled to the expected nanometer region without any loss of accuracy in the model.

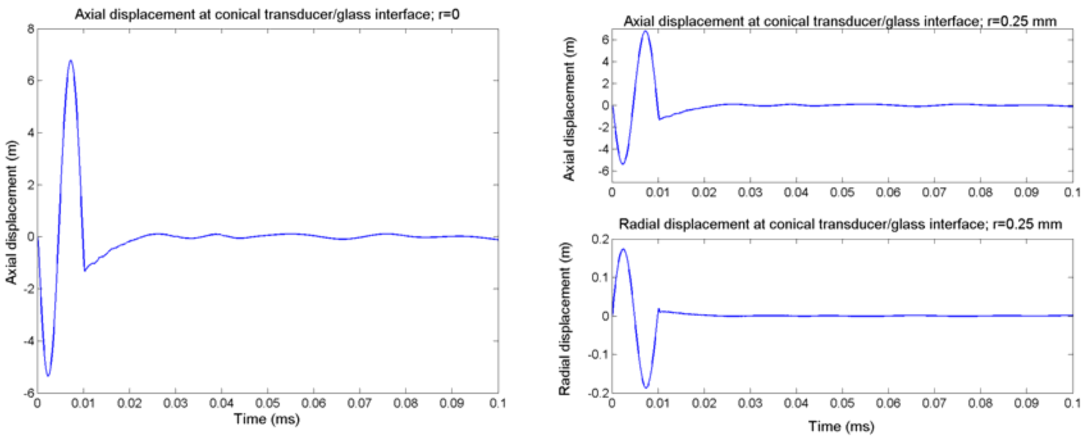

Figure 4. 100 kHz anechoic displacement generated in PAFEC at transmitter/glass block interface.

The displacements calculated for each node at the transducer/glass block interface were used as source function inputs to the EFIT model of the original glass block measuring 90 mm in length with a 30 mm radius. A time integral was performed on the data as the EFIT code required velocity and stress tensor components. It was also necessary to interpolate the EFIT mesh in space and time due to the different grid spacing and time step.

To compare the displacements calculated by the EFIT code at the opposite side of the cylinder, a complete FE model was constructed using the same conical transducer model coupled to the original 90 mm glass cylinder. A coupled sensor was also added to the FE model. The sensor was modelled on a 20 mm diameter brass transducer with a brass contact wear plate, with Perspex spacers holding the air backed PZT-5A disc in place. The top of the brass case was sealed with silicon rubber. The properties of the non-piezoelectric materials in the sensor are given in Table 2, where the PZT-5A material properties are given in Table 1.

Table 2

Material	***E*** **(GPa)**	ρ **(kg m^{-3})**	ν
Brass	101	8500	0.25
Silicon	107	1190	0.32
Perspex	5.05	1190	0.36

The complete axisymmetric FE mesh is shown in Figure 5 with the transducer, glass block and sensor, where the mesh is based on 3 elements per wavelength for the 100 kHz case. The same sensor structure was also added to the EFIT model of the glass block so the displacements at the glass block/sensor interface could be compared under the same loading conditions. Since the present axisymmetric EFIT code cannot model piezoelectric or orthotropic materials, equivalent values for Young’s modulus and Poisson’s ratio were used to describe the PZT-5A crystal, which were 61.0 GPa and 0.35 respectively.

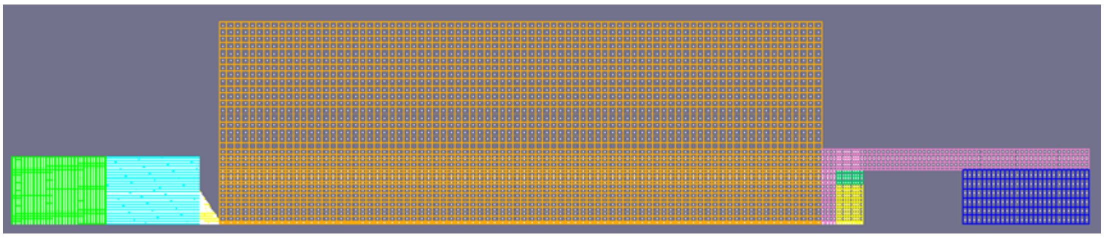

Figure 5. PAFEC FE mesh used for complete system.

Following the input of the source function obtained from the FE conical transducer model, the displacements at the glass block/sensor interface for the EFIT model were compared with those obtained using the complete FE-PAFEC model with the original glass block shown in Figure 5 at each node along the interface. The axial displacements calculated for *r* = 0 mm (centre of the sensor) are shown in Figure 6 as well as both the axial and radial displacement components calculated at *r* = 5 mm (half way between the centre and edge of the sensor).

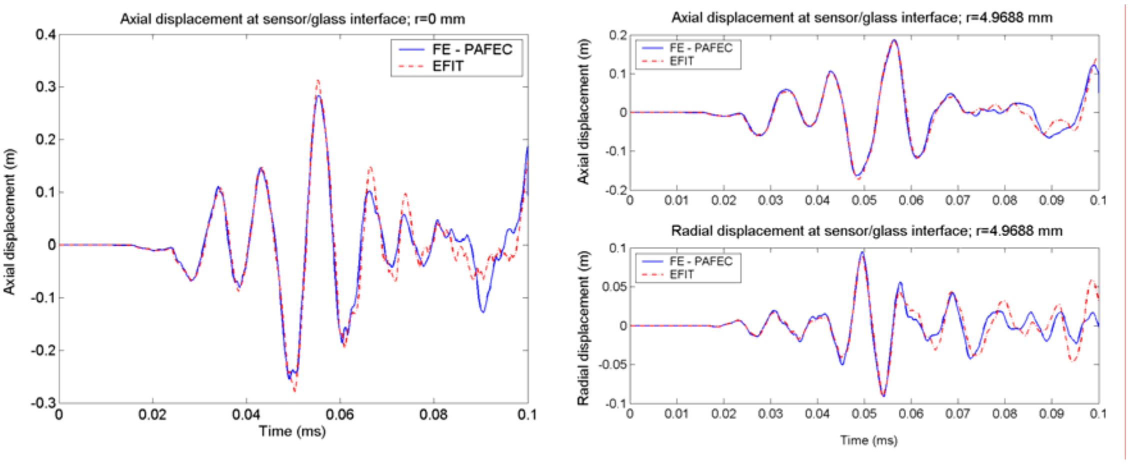

Figure 6. 100 kHz comparison of sensor loaded displacements at the glass block/sensor interface.

The initial agreement is excellent and only starts to deviate after the arrival of several reflections. As stated earlier any small inaccuracies due to the finite grid would accumulate and produce discrepancies between the results following several reflections and a large time window. It was thought that some small reflections present in the ‘anechoic block’ used to generate the free-field source function for the EFIT model could introduce such discrepancies. However, the agreement is still excellent and shows that the hybrid method could provide a viable option for modelling larger and more complex structure using the EFIT code coupled with the FE capabilities of modelling the electro-mechanical properties of piezoelectric transducers. The hybrid approach could also be coupled with different source functions to simulate other transient type events such as a pencil lead break or fracture event.

The next stage of the work is to use the EFIT output functions as inputs into the FE sensor model using appropriate boundary conditions and establish the electrical transfer function of the system and study the ways in which the sensor responds to the stress wave arrivals at the glass block/sensor interface. The current model was limited in scale and frequency due mostly to the speed limitation of modelling the complete system in PAFEC, which was required to perform the validation. Future work based on the hybrid approach would also aim to increase the size or complexity of the propagation medium and increase the frequency range possible.

4 CONCLUSIONS

A hybrid method for modelling acoustic emission reference systems in both the electrical and acoustical domain has been proposed using the FE method and the EFIT. Initial calculations showed excellent agreement between the two techniques for a point source excitation on a finite cylindrical glass block. The hybrid method was then tested using inputs to the EFIT code generated in an FE model of a conical piezoelectric transducer excited with an electric charge function. The agreement for both axial and radial displacement components at the opposite sensor loaded surface was excellent and only showed small discrepancies after several reflections.

The hybrid method shows excellent potential for modelling more complex AE structures in the future by combining the FE capabilities of modelling piezoelectric material in the electro-mechanical domain and the EFIT capabilities for rapid solutions to large scale linear and non-linear propagation problems. Moreover, more advanced EFIT codes for piezoelectric and anisotropic media could lead to further improved AE reference models [3][8].

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support of the UK Department of Trade & Industry (National Measurement System Directorate).

REFERENCES

[1] T. J. Esward, P. D. Theobald, S. P. Dowson and R. C. Preston, *An investigation into the establishment and assessment of a test facility for the calibration of acoustic emission sensors*, NPL Report CMAM 82, 2002.

[2] P. D. Theobald, T. J. Esward, S. P. Dowson, *Towards traceable calibration of AE transducers: a new development at the UK's NPL*, Proceedings of the 25th European Conference on Acoustic Emission Testing, Vol. II, pp. 211-218, 2002.

[3] R. Marklein, R. Baermann, K-J. Langenberg, *The ultrasonic modelling code EFIT as applied to inhomogeneous, dissipative isotropic and anisotropic media*, in: Rev. Prog. Quant. Nondestr. Eval. (QNDE), Vol. 14, Plenum Press, New York, pp. 251-258, 1995.

[4] F. Schubert, A. Peiffer, B. Koehler and T. Sanderson, *The elastodynamic finite integration technique for waves in cylindrical geometries*, J. Acoust. Soc. Am., Vol. 104, No. 5, pp. 2604-2614, 1998.

[5] F. Schubert, O. Sacharova and B. Koehler, in: Rev. Prog. Quant. Nondestr. Eval. (QNDE), Vol. 18B, Plenum Press, New York, 1999.

[6] P. Fellinger, R. Marklein, K. J. Langenberg and S. Klaholz, *Numerical modeling of elastic wave propagation and scattering with EFIT - Elastodynamic finite integration technique*, Wave Motion Vol. 21 pp. 47-66, 1995.

[7] F. Schubert, *Numerical time-domain modeling of linear and nonlinear ultrasonic wave propagation using finite integration techniques – theory and applications*, Ultrasonics, Vol. 42, pp. 221-229, 2004.

[8] R. Marklein, O. Glitza, T. Kaczorowski, and K. J. Langenberg, *Numerical time domain modelling of piezoelectric transducers/sensors and ultrasonic wave phenomena with the piezoelectric finite integration technique (PFIT)*, in: Rev. Progr. Quant. Nondestr. Eval., Vol. 18, Plenum Press, New York, pp. 1053-1069, 1998.