Model Based Design and Acoustic NDE of Surface Cracks

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Abstract

Modeling and simulation are rapidly becoming an integral part of the design and optimization process in all fields of engineering. Model Based Design (MBD) uses finite element analysis (FEA) as one of the most powerful tools for acoustic phenomena modeling in real structures design. MBD of acoustic NDE of surface cracks in structural materials gives a new opportunity to predict wave propagation through surface cracks for different structural materials and optimize NDE technology for cracking evaluation. There is also an opportunity to optimize testing algorithms by choosing a specific combination of acoustic methods. It is necessary to point out that different construction materials have different physical characteristics of cracking and disintegration. MBD built on a unique multiphysics-modeling foundation with FEA interfaces, like ANSYS and COMSOL, lets us to solve complex technical problems of acoustic tests of hidden and surface cracks. Modeling of acoustic wave propagation in complex structural materials with analysis of wave propagation through surface notches using FEA is presented in this work.

Keywords: model based design, cracks, notches, finite element analysis, acoustic wave propagation.

1. Computational environment

Meaningful simulations of today’s complex systems require arbitrary couplings between different physics phenomena in one and the same model–multiphysics. Choice is COMSOL pillar in the design philosophy with carefully implemented best-in-class solvers. Its speed and accuracy stand out as superior in independent benchmark studies. With advanced solver techniques and multicore parallel solvers, COMSOL Multiphysics optimizes computationally intensive routines for maximum performance with respect to solution times and memory consumption. ACOUSTICS@MBD CONSULTANTS has performed modeling and simulation of acoustic wave propagation using Dell System T3500 Precision WorkStation T3500 x64-based PC Processor Intel(R) Xeon(R) CPU with W3520 @ 2.67GHz, 2666 MHz, 4 Core(s), 8 Logical
Processor(s). Operating memory was increased up to 25 GB. Wide screen display allowed using multi-window information from MATLAB, SOLID WORKS and COMSOL.

2. Acoustic source modeling

In the scattered-field formulation, the total acoustic pressure, $p_t$, is written as the sum of a known incident field, $p_i$, and an unknown scattered field, $p_s$. Inserting this sum in the standard acoustic wave equation and assuming that the incident field by itself is a solution to the source-free equation, it follows that $p_s$—which is what $p$ refers to in this formulation—satisfies the source-free. We could set the expression for the incident wave, $p_i$, in the application scalar variables dialog box. The default expression is a Gaussian pulse $p_s$ of width discrete time $t_i$ traveling in the $x$ direction:

$$p_s = p_0 \exp \left[ -\frac{(t-b)^2}{2c^2} \right]$$

(1)

Where $p_0$ - incident pressure and $b, c$ - form's coefficients.

Using Fourier transformation for spectrum analysis

$$s(\omega) = \int_{-\infty}^{\infty} p(r, t) * \exp(-i\omega t) \, dt$$

(2)

we could analyze acoustic pulses in time and frequency domain simultaneously like approximated expression of spectrum

$$s(\omega) = 2A_\omega \frac{\sqrt{\pi}}{\omega_0} \exp \left[ -\frac{\omega^2}{\omega_0^2} - i\omega t \right]$$

(3)

Where $\omega_0$ - cutoff angular frequency of magnitude $A_\omega$ with energy of signal contained in frequency bend $-2\omega_0 < \omega < 2\omega_0$.

Gaussian pulse is presented in Figures 1-2 as pressure amplitude $p(r, t)$ and its frequency spectrum $s(f)$.

Original pressure amplitude of Gaussian pulse is shown in Figure 1:
Figure 1. Pressure amplitude of Gaussian pulse with central frequency \( f=5 \) kHz and its spectrum is shown in Figure 2:

![Figure 1. Pressure amplitude of Gaussian pulse with central frequency \( f=5 \) kHz](image1)

![Figure 2. Spectrum of Gaussian pulse with central frequency \( f=5 \) kHz](image2)

Figure 2. Spectrum of Gaussian pulse with central frequency \( f=5 \) kHz.

Different pulses could be used for modeling and simulation as well as for design of new NDE equipment. Some examples of them are presented in Figures 3-6 below:
Figure 3. Amplitude of Gaussian pulse with central frequency $f=10$ kHz.

Figure 4. Spectrum of Gaussian pulse with central frequency $f=10$ kHz.
3. Models with surface notch

Models were prepared in 2D for easier and faster modeling and simulation of acoustic wave propagation and scattering on the surface notch. The model presents twin-media imitation of two beams: one of them contains surface notch. Schematic of batch model is presented in Figure 7:

Figure 7. Schematic of the model: one beam without a notch (upper part) and the other beam with a notch (lower part).
Optimal meshing of the model is given in Figure 8:

Figure 8. Optimal meshing of the model

Acoustic wave propagation and scattering was modeled regarding acoustic pressure distribution in the beams. A snap of pressure distribution is presented in Figure 9:

Figure 9. Pressure distribution

Different phases of wave propagation and scattering through the model are presented in Figures 10-14:
Figure 10. Acoustic wave generated by Gaussian pulse.

Figure 11. Wave propagation before notch.

Figure 12. Wave scattering on the notch.
Acoustic source oscillation generated by Gaussian pulse looks similar to mechanical impact (knocking) and is shown in Figure 15:
The charts below show the difference between pulses on surfaces with and without notch:

<table>
<thead>
<tr>
<th>Without notch</th>
<th>With notch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delay, sec</strong></td>
<td><strong>Delay, sec</strong></td>
</tr>
<tr>
<td>0.35e-3</td>
<td>0.4e-3</td>
</tr>
<tr>
<td>0.9e9</td>
<td>0.7e7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Without notch</th>
<th>With notch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplitude, Pa</strong></td>
<td><strong>Amplitude, Pa</strong></td>
</tr>
<tr>
<td>0.5e-3</td>
<td>0.55e-3</td>
</tr>
<tr>
<td>0.7e9</td>
<td>0.6e8</td>
</tr>
</tbody>
</table>

Time delay and amplitude of pulses are presented in Table 1:

**Table 1**

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Figures 16-29 compare acoustic pulses showing their differences between parts with and without notch.

MATLAB was used for implementation of digital signal processing (DSP) of arriving pulses. Several techniques were applied: spectral analysis, phase analysis, time delay and spectrograms. It is clearly visible that pulses at control point 1 after notch have amplitude and arriving time different from upper and lower parts of the built model as shown in Figure 16:
Figure 16. Amplitude and arriving time difference between pulses in part with notch and without notch.

Amplitude spectrums graph is presented in Figure 17:

Figure 17. Amplitude spectrum differences between pulses in parts with and without notch.

Spectrograms of arriving pulses in parts with and without notch are demonstrated in Figures 18-19:
Similar analysis was performed for pulses arriving at points 2-4 and presented in Figures 20-25 below:
Figure 20. Amplitude spectrum.

Figure 21. Spectrogram of part without notch.
Figure 22. Spectrogram of part with notch.

Figure 23. Amplitude spectrum.
4. Ongoing modeling and future plans

At present time some models are “on the way” and will be presented in further works. The following additions to the presented model for surface crack investigation will be provided [8]:

- standard types transducers;
- non-contact air-coupling transducers;
- beam concentrating acoustic transducers;
- dry point contact (DPC) transducers;
- MEMS based transducers.
Conclusions

Modeling and simulation are rapidly becoming an integral part of the design and optimization process in all fields of engineering. Model Based Design (MBD) uses finite element analysis (FEA) as one of the most powerful tools for acoustic phenomena modeling in real structures design. MBD of acoustic NDE of surface cracks in structural materials gives a new opportunity to predict wave propagation through surface cracks for different structural materials and optimize NDE technology for cracking evaluation. There is also an opportunity to optimize testing algorithms by choosing a specific combination of acoustic methods. MBD of acoustic NDE presents an advantage to analyze acoustic effects on surface cracks and then build new or modify existing equipment for real physical testing. Data and graphs received as a result modelling and simulation using COMSOL show that acoustic waves have a strong diffraction and refraction on notches (surface cracks) and produce different patterns in time or frequency domains. These acoustic effects could be successfully applied to NDE monitoring and implemented to architecture of new design of control systems. But it is necessity to point out that model meshing and optimization of solvers could affect results. MBD of acoustic NDE of surface cracks would also need to integrate advanced DSP, optimal algorithms of acoustical parameters measuring, design of transducers and post-processing of data flow.

References

   Edited by: Giuseppe Petrone and Giuliano Cammarata, Publisher: InTech Education and Publishing , Publication date: June 2008;
3. Integrated Modeling using MatLab, Simulink and COMSOL: with heat, air and moisture applications for building physics and systems (Paperback), by Jos van Schijndel , Eindhoven University of Technology 2008;
8. Link to ACOUSTICS@MBD CONSULTANTS: www.mbd-acoustics.com