Enhancement of the POD of Flaws in the Bulk of Highly Attenuating Structural Materials by Using SAFT Processed Ultrasonic Inspection Data

Martin SPIES, Hans RIEDER, Fraunhofer ITWM, Kaiserslautern, Germany

Abstract. The determination of the size of flaws in the bulk of Duplex stainless steels and the determination of the Probability of Detection (POD) from ultrasonic data is addressed. The ferritic-austenitic mixed microstructure of these steels causes a strong attenuation of the ultrasonic waves. Therefore, the Synthetic Aperture Focusing Technique SAFT has been applied which leads to a reduction of the microstructural noise signals and thus to an improvement of defect detection. Based on the ultrasonic rf-data acquired on a test block with model defects an ã versus a-approach has been performed to determine the POD for the inspected Duplex specimen according to MIL-HDBK-1823. It is shown that SAFT-processing of the ultrasonic data leads to a remarkable improvement of defect detectability.

1. Introduction

The determination of defects in materials and components using nondestructive testing and evaluation techniques is widely applied in many industrial areas. The safe operation of transportation vehicles such as airplanes, trains and ferries requires permanent inspection of relevant parts and components. Depending on the size of flaws to be detected and depending on the material to be inspected the choice of the proper nondestructive method is made. Generally, the capability of the chosen nondestructive evaluation (NDE) system has to be assessed, especially in safety-relevant areas such as those named above.

In this contribution the determination of the size of flaws in the bulk of Duplex stainless steels and the determination of the Probability of Detection (POD) from ultrasonic data is addressed. Duplex steels are increasingly used as structural materials because of their favorable strength and toughness properties as well as their corrosion resistance. Due to the large thicknesses of the relevant components the NDE method of choice is usually ultrasonic inspection. However, the ferritic-austenitic microstructure of these steels causes a strong attenuation of the ultrasonic waves. Thus, ultrasonic inspection has to be optimized in order to improve its performance in view of the least detectable defect sizes. Refering to ship propulsion components as an example, the critical, i.e. the smallest tolerable defect sizes can inferred from hydrodynamic load calculations and fracture mechanical considerations [1].

To improve the performance of ultrasonic testing we have applied the Synthetic Aperture Focusing Technique (SAFT) which leads to a reduction of the microstructural noise signals and thus to an improvement of the signal-to-noise ratio of the defect echoes.
Based on the ultrasonic rf-data acquired on a test block which has been supplied with model defects of various dimensions and depths, we have applied an $a$ versus $a$-approach to determine the POD for the inspected Duplex specimen. Following the Department of Defense Handbook ‘Nondestructive Evaluation System Reliability Assessment’ in its updated version of 2007 [3], we have determined POD-curves applying both the raw and the SAFT-processed ultrasonic data. The latter has lead to a remarkable improvement of defect detectability which encourages a standard application of ultrasonic inspection to ensure the integrity and to increase the reliability of Duplex components, such as ship propellers.

2. Synthetic Aperture Focusing Technique SAFT

When it comes to ultrasonic inspection of structural materials, wave attenuation cannot be neglected. While the sound attenuating character of carbon-fiber reinforced composite materials is due to the viscoelasticity of the polymer matrix as well as to the wave scattering at the fibers, the attenuation effect in polycrystalline materials, such as cast stainless steels under investigation in this study, is mainly due to microstructural features, such as grain scattering and/or scattering at second phases. For such materials the heuristically derived SAFT-algorithm [4] has been proven to be beneficial in view of improving the defect detection [3, 5]. In principle the SAFT-algorithm processes ultrasonic rf-datasets acquired in mechanized scan procedures in the following way: (i) the region of interest is divided into small volume elements (voxels); (ii) the transducer movement along line scan paths is simulated in the computer and the received experimental echo signals are added and stored in those voxels within the transducer beam field where they might have originated according to the respective times-of-flight. Since the phase information of the signals is exploited, this procedure provides an image with large amplitude due to constructive interference at those positions where defects and the component’s boundaries are present, and with low amplitude due to destructive interference elsewhere. The increasing wave attenuation leads to a 'shrinkage' of the transducer beam field which has to be accounted for by respectively reducing the reconstruction volume at each scan position [6]. Beam field simulation techniques are correspondingly applied to evaluate the changes in the beam field divergence angle, which is generally used to characterize the SAFT reconstruction volume [7]. A second modification of the algorithm affects the inversion of wave attenuation when backpropagating the detected rf-signals. Using experimentally determined attenuation coefficients, this inversion is performed in a respective pre-processing of the rf-data prior to SAFT-processing [1, 6].

3. Probability of Detection POD

The Probability of Detection concept represents an important part of the examination and the evaluation of the integrity of a component (see e.g. [3, 8, 9]). The POD designates the probability to detect a flaw which is present in the component, and will here be determined as a function of flaw size $a$. The resulting POD-curve in combination with the imposed confidence bounds provides the flaw size, which can be detected with a reasonable probability given a required range of confidence. This flaw size is then compared with the requirements imposed on the total component integrity. In the case of ship propellers, which is of particular interest to the authors, this integrity is evaluated from hydrodynamic calculations for the propeller load states and the critical flaw sizes, which are determined from the fracture mechanical material characteristics [1].
The POD-concept has originally been developed for the US Air Force focusing on turbine engine inspection [10], but is applicable to other areas of NDE as well. The principal shape of a POD-curve shows that with increasing flaw size the probability of detection increases accordingly. At size $a_{90/95}$ the lower 95% confidence bound hits the 90% POD-level. This size is usually regarded to represent the flaw size to be surely detected. To experimentally determine POD-curves, well-defined inspections have to be performed on proper specimens. The principal procedure to establish a POD using the $\hat{a}$ versus $a$-approach is as follows. A defect of size $a$ generates a signal of amplitude $\hat{a}$. According to the inspection instructions usually a threshold value $\hat{a}_{th}$ is defined, which corresponds to the smallest value of the signal amplitude that the NDE system records, i.e. the value below which the signal is indistinguishable from noise. The second threshold that is defined is the decision threshold $\hat{a}_{dec}$, which is the value above which the signal is interpreted as a hit, and below which the signal is interpreted as a miss. The inspection threshold $\hat{a}_{th}$ is always less than or equal to the decision threshold $\hat{a}_{dec}$. Assuming that the signal amplitudes exhibit a statistical normal distribution the $\hat{a}$ versus $a$-diagram can be transferred into a POD-curve. A detailed mathematical description of this procedure can be found in [3, Appendix G].

4. Experimental

4.1 Duplex Stainless Steel Test Specimen

Since it is very difficult to obtain proper specimens with well-defined ‘natural’ flaws, ultrasonic data are usually acquired on test specimens with artificial ‘model’ defects. For this study a test block of 50 mm thickness has been fabricated from cast Duplex material. Its surfaces have been ground in order to ensure proper coupling conditions for the ultrasonic transducers. The specimen has been supplied with a number of flat-bottomed holes (FBHs) of various diameters and depths at various distances, as sketched in Figure 1. Emphasis will be on the detection of the FBHs of 3 mm, 5 mm and 7 mm diameter, respectively, all being in the same depth of 45 mm from the top surface.

![Fig. 1 Schematic sketch (left) of the arrangement of the FBHs; the cross-like FBHs (right, red box) are not included in the POD assessment, since these are in a depth of 40 mm from the surface.](image-url)
4.2 Ultrasonic RF-Data and SAFT-Processed Data

The measurements have been performed using commercial single-element transducers of 9.5 mm diameter, operating at center frequencies of 1 MHz, 2.25 MHz, 3.5 MHz and 5 MHz, respectively. Attenuation values ranging between 0.9 dB/cm and 1.2 dB/cm have been measured for longitudinal waves at 2.25 MHz, a frequency of 1 MHz has thus been considered to be the best choice. However, due to this probe’s characteristics (bandwidth), the FBH signals could not be separated from the backwall echoes. Therefore, ultrasonic rf-data have been acquired at the higher frequencies. Further evaluation has been performed for 2 MHz, applying a respective filter with its 3dB-bandwidth as indicated in Table 1, which shows the acquired datasets and the ones selected for POD-determination. For further discussion, we refer to the datasets DPX002 and DPX003. Figure 2 displays the B-scan images for the inspection line centered across the sequence of 3 mm FBHs, separated by decreasing distances (Fig. 2a), as well as the inspection line which is centered across the three FBHs of 3 mm, 5 mm and 7 mm, respectively (Fig. 2b). It can be recognized that the signal of some of the 3 mm FBHs can hardly be distinguished from the signals which are generated by reflection and scattering at the grain boundaries (‘microstructural noise’). From the representative A-scans also shown in Fig. 2 it can be recognized that the noise signals are, as expected, lower in the 2MHz-filtered dataset. Applying the SAFT-algorithm, the FBH signals are enhanced while at the same time the noise is minimized. Figure 3 displays the SAFT-result obtained from DPX002 at a selected amplitude level; all 3 mm FBHs are visualized, even those which could not be detected from the ‘raw’ A-scan data.

The efficiency of the SAFT-procedure can be seen from the direct comparison of amplitudes of the reconstructed data and the rf-data. Table 2 shows the amplitude values obtained with both types of evaluation. In case of the conventional procedure two of the 3 mm FBHs could not be interpreted as a hit, while SAFT allows the detection of all FBHs. However, the two 3 mm FBHs very close to each other are not resolved as separate defects and therefore not included in the POD-assessment. Especially remarkable is the increase in the signal-to-noise ratio, which is roughly 9 dB on average (Tab. 2). The improvement obtained using the SAFT-algorithm will also be evident from the POD-curves calculated using datasets DPX002, DPX005 and DPX007.

<table>
<thead>
<tr>
<th>Measurements Filename</th>
<th>Probe frequency [MHz]</th>
<th>Filter frequency [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPX001</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>DPX002</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>DPX003</td>
<td>5</td>
<td>broadband</td>
</tr>
<tr>
<td>DPX004</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>DPX005</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>DPX006</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td>DPX007</td>
<td>2.25</td>
<td>2</td>
</tr>
<tr>
<td>DPX008</td>
<td>2.25</td>
<td>broadband</td>
</tr>
<tr>
<td>DPX009</td>
<td>2.25</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1 Acquired rf-datasets with respective probe frequencies; the filtered datasets used for further evaluation are indicated.

2 MHz Filter:
3 dB bandwidth
=> [1.3,2.7] MHz
Fig. 2a) B-scan with echoes from backwall, the 3 mm FBH sequence and noise signals, obtained for 5MHz frequency with broadband filtering (DPX003, left) and with the 2 MHz filter (DPX002, right).

Fig. 2b) B-scan with echoes from backwall, the 3 mm, 5 mm and 7 mm FBHs and noise signals, obtained for 5MHz frequency with broadband filtering (DPX003, left) and with the 2 MHz filter (DPX002, right).

Fig. 3 SAFT-imaging (projected top view) of the various FBHs; the two FHBs within the ellipse (right arrow) are too close together and therefore appear as one indication; the FBH marked by the left arrow is shaded by a natural defect near the upper (scan) surface; a second natural defect is seen within the white box.
5. POD Calculation

The selected datasets have been analyzed using the mh1823 POD-software (Version 2.5) relating to the 2007 update of MIL-HDBK-1823. The latest version of the mh1823 POD-software can be downloaded from the Statistical Engineering website [11]. In applying the software, the following limitations have to be obeyed:

1. the NDE system must produce output that can be reduced to either a quantitative signal, \( \hat{a} \), or a binary hit/miss response;
2. the specimens must have targets with measurable characteristics, like e.g. size or chemical composition;
3. the mh1823 POD-software assumes that the input data are correct; that means, if the size is \( X \), then that is the true size; if the response is \( Y \), then that is the true response; situations were these conditions can not be ensured (e.g. where target size is only approximate) will necessarily provide only approximate results.

The limitation on the targets to be addressed when acquiring ultrasonic inspection data for POD-calculation is particularly important. It has been the main reason to rely on the flat-bottomed holes supplied to the test specimen in establishing POD-curves for the Duplex material under investigation. The three limitations listed above are obeyed in our case, if it is assumed that the fabrication of the FBHs has been performed correctly, i.e. these have the indicated size and a horizontal, smooth circular surface.

The ultrasonic data obtained for the model defects are evaluated using \( \hat{a} \) versus \( a \)-analysis, while a hit/miss-evaluation has not been considered. Both the amplitude values obtained from the A-scan data and the SAFT-processed data have been used for evaluation, which are exemplarily shown in Table 2 for dataset DPX002 (similar values have been obtained for DPX005 and DPX007).

All \( \hat{a} \) versus \( a \)-systems have two censoring values. A target’s signal that is indistinguishable from the background noise is left censored. The right censoring value corresponds to the maximum possible signal (e.g. full screen height). These censoring values usually follow directly from the experimental data (see Tab. 2), accordingly we have set the left censoring value \( \hat{a}_{\text{th}} \) to noise level (0 dB) and the decision threshold \( \hat{a}_{\text{dec}} \) to the 6 dB above noise level.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise level</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>FBH 7 mm</td>
<td>8.1</td>
<td>18.2</td>
<td>20.0</td>
<td>26.0</td>
<td>9.8</td>
</tr>
<tr>
<td>FBH 5 mm</td>
<td>4.1</td>
<td>12.3</td>
<td>12.6</td>
<td>22.0</td>
<td>9.7</td>
</tr>
<tr>
<td>FBH 3 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>1.0</td>
<td>0.0</td>
<td>4.5</td>
<td>13.1</td>
<td>13.1</td>
</tr>
<tr>
<td>No. 2</td>
<td>1.8</td>
<td>5.1</td>
<td>4.5</td>
<td>13.1</td>
<td>8.0</td>
</tr>
<tr>
<td>No. 3</td>
<td>5.4</td>
<td>14.6</td>
<td>14.1</td>
<td>23.0</td>
<td>8.4</td>
</tr>
<tr>
<td>No. 4</td>
<td>5.6</td>
<td>15.0</td>
<td>7.1</td>
<td>17.0</td>
<td>2.0</td>
</tr>
<tr>
<td>No. 5</td>
<td>2.4</td>
<td>7.6</td>
<td>7.1</td>
<td>17.0</td>
<td>9.4</td>
</tr>
<tr>
<td>No. 6</td>
<td>4.3</td>
<td>12.7</td>
<td>7.9</td>
<td>18.0</td>
<td>5.3</td>
</tr>
<tr>
<td>No. 7</td>
<td>not resolved</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>No. 8</td>
<td>not resolved</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Signal amplitudes obtained in detecting the FBHs using conventional A-scan evaluation and evaluation of the SAFT-processed data, respectively.
Representing the data in $\hat{\alpha}$ vs $a$, $\hat{\alpha}$ vs $\log(a)$, $\log(\hat{\alpha})$ vs $a$, and $\log(\hat{\alpha})$ vs $\log(a)$-plots is the first step in the analysis, where the best model to fit the data to linear behavior is selected. The mh1823 POD-software shows the linear approximations of the data with the 95 % confidence bounds and the 95 % prediction bounds [3]. The regression parameters are placed on the summary plot, with the standard deviation and the probability that the value occurred by chance. The resulting POD-curves are plotted with the important features of the applied model. These include the parameters of the model and their covariance matrix, the flaw sizes $a_{50}$, the size having 50 % POD, $a_{90}$, the size with 90 % POD, and $a_{90/95}$, the 95 % confidence bound on the $a_{90}$-estimate; the equation for the POD-model is also given.

It has become common practice to assume a $\log(\hat{\alpha})$ vs $\log(a)$-relationship for describing NDE data, but in some cases the $\log(\hat{\alpha})$ vs $a$ may be a similarly good or even better model for the data analyzed. Here, we have selected the $\log(\hat{\alpha})$ vs $\log(a)$-model. The resulting POD-curves for the A-scan and SAFT-processed data, respectively, are shown in Figure 4. It can be seen that using the SAFT-algorithm has lead to far better results, which can be recognized in the improved POD-curve as well. For the $\log(\hat{\alpha})$ vs $\log(a)$-evaluation, the size $a_{90/95}$, which is regarded as the flaw size to be surely detected, is approximately 4.4 mm for the evaluation based on the A-scan data, while it has dropped to about 3.2 mm using the SAFT-processed data.
6. Summary

The determination of the Probability of Detection has been addressed for UT inspection procedures applied to structural materials with high sound attenuation. The preliminary measurements presented in [2] have already shown the potential of the Synthetic Aperture Focusing Technique for improving ultrasonic NDE of such materials. The efficiency of SAFT in combination with defined mechanized scanning procedures has been illustrated by the results presented here for a Duplex stainless steel specimen with model defects. The considerable reduction of $a_{90/95}$ which has been obtained by SAFT-processing of the acquired ultrasonic data verifies the algorithm’s benefits also quantitatively.

Although evident it should be noted that the efficiency of SAFT in view of the least detectable flaw size is closely related to the proper consideration of the material properties. Thus, inspection parameters like probe diameter, frequency and bandwidth on one hand as well as scan line separation and discretization of A-scan acquisition on the other hand have to be properly selected. This is an important aspect, since the goal e.g. in production ultrasonic inspection is the maximization of the inspection throughput. This is, however, usually gained at the expense of reducing the number of scan indices, directly affecting the inspection’s POD performance [12].

Acknowledgment

Charles Annis, Statistical Engineering, provided prompt information and advice concerning background and details of the mh1823 POD-software, which is gratefully acknowledged.

References