Weld Inspection

Objectives

The purpose of this exercise is to design an inspection for a particular task, and then demonstrate its performance on data acquired from a test sample in a blind trial.

Summary

The integrity of welds in nuclear reactor coolant water lines is critical to their safe operation. It is necessary to develop an inspection for the axial and circumferential welds in the piping of the main feedwater lines in a boiling water reactor. The geometry is shown in Fig. 1. The inspection will be performed using an ultrasonic array in direct contact with the external pipe surface. The external diameter of the pipe is 860 mm, and the curvature of the surface can be ignored for the purposes of the ultrasonic inspection. Longitudinal waves must be used for the inspection and the bulk longitudinal wave speed in the pipe material has been measured as 6020.0 ms^{-1}. The array must be positioned on the smooth surface of the parent material adjacent to a weld rather than directly over a weld because the caps of the welds are not dressed (i.e. the weld has a rough surface not suitable for coupling ultrasound into the part). Modelling suggests that if defects exist, they will be cracks on the fusion faces between the weld and the parent material of the pipe. The weld fusion faces are inclined at 45° to the normal of the pipe surface. Due to the heterogeneous and anisotropic nature of the weld material, it is only possible to reliably detect defects on the fusion face nearest to the array. For this reason, the actual inspection will use a pair of identical arrays on either side of the weld cap as shown in Fig. 1, which will be scanned along the length of each weld using a robotic manipulator. To minimise the time taken to perform the inspection, the pair of arrays will only be scanned in the along-weld direction; they will not be scanned transverse to the weld, hence the distance from each array to the edge of the weld is fixed and needs to be determined as part of the inspection design. The arrays can be assumed to have identical performance and will be synchronised to operate independently. Therefore, the requirement for the qualification of the inspection is to prove that one array can detect and characterise any potential defects on the weld fusion face that is closest to it. The data acquisition from both arrays will be performed using a single Peak NDT Micropulse FMC array controller[i] with 128 independent channels. Hence, the maximum number of elements in each array is 64. Irrespective of frequency, number of elements, pitch and element width, the size of the array elements in the direction parallel to the weld is a constant 15mm. The key inspection design decisions that need to be made are:

- the array properties (centre frequency, number of elements, element pitch and element width);
- the position of the array relative to the edge of the weld cap (defined by position of first element in Fig. 1);
- the imaging algorithm to be used;
- the defect detection protocol;
- the defect characterisation method.

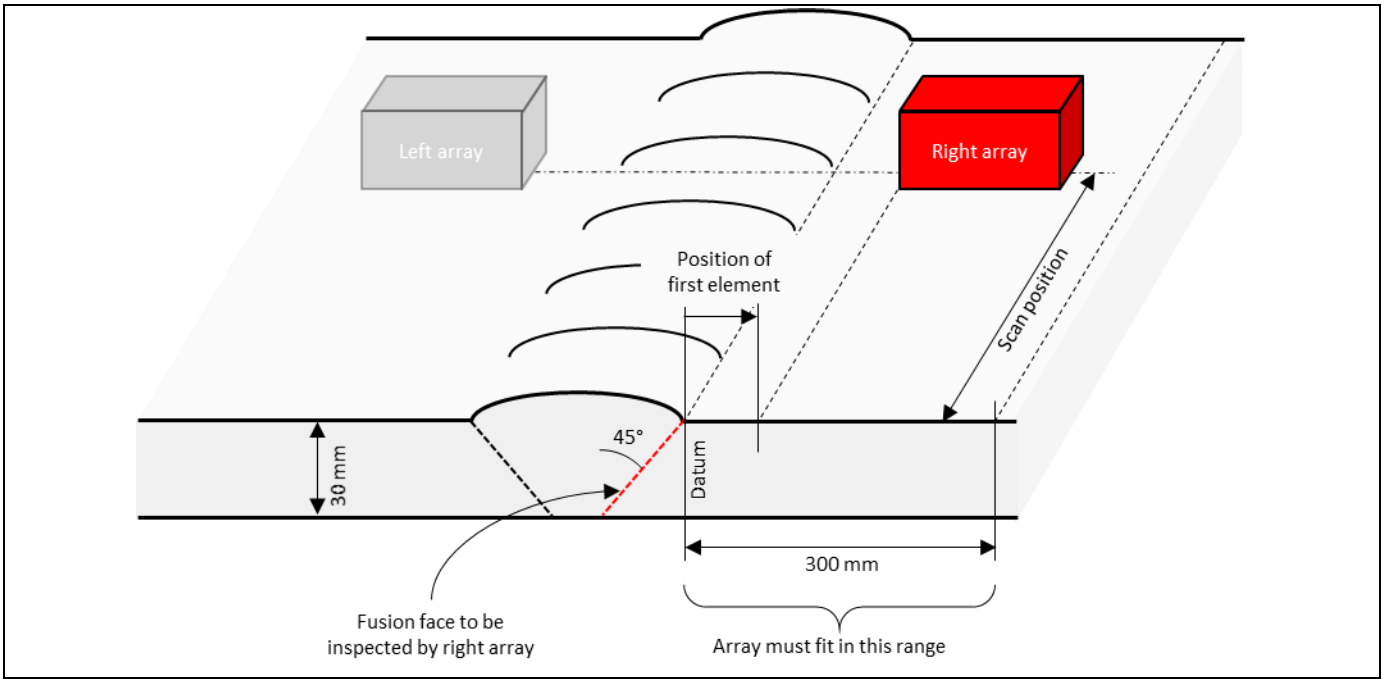

Fig. 1 Inspection geometry (not to scale).

Further Details

If using Matlab, download the simulation function `fn_simulate_data_weld_v5.p` from Blackboard; if using Python the function is already include in the `NDE_functions.py` module. As in the previous formative exercise, this function is used to simulate FMC ultrasonic array data based on the parameters provided for the configuration shown in Fig. 1 (data is only simulated for the red array on the right hand side of the weld). Your task is to determine (1) the parameters to use for the inspection, (2) a method of processing the FMC data to form images, (3) a protocol for detecting defects, and (4) a method for sizing defects that are detected. The simulation function has various test modes that you can use to develop your inspection on pristine samples and samples containing known defects. The simulation can also generate data from an array that is scanned parallel to the weld in a sample for a blind trial that contains a number of unknown defects at various positions along the length of the weld. The final stage of the assignment is to identify the positions and sizes of the defects present in the blind trial sample.

How to use simulation function, `fn_simulate_data_weld_v5`

The simulation tool is the function

```
fn_simulate_data_weld_v5(mode, scan_position, no_elements, element_pitch,
element_width, first_element_position, centre_freq)
```

which returns:

`time`, `time_data`, and `element_position`.

The inputs are as follows:

- `mode` – string that specifies the mode of operation of the simulation function (see below);
- `scan_position` – position of the array along the length of the weld when simulating data on the trial sample (units: metres), must be in the range 0 to 0.3;
- `no_elements` – number of elements in array, must be in range 1 to 64;
- `element_pitch` – pitch of array elements (units: metres);
- `element_width` – width of array elements (units: metres), must be greater than 0.1×10^{-3} m and less that both 4.0×10^{-3} m and (`element_pitch` minus 0.05×10^{-3} m) to ensure a minimum gap between elements of 0.05 mm;
- `first_element_position` – position of the first element of the array (i.e. the nearest element to the weld) relative to the datum position at the edge of the weld cap shown in Fig. 1 (units: metres), must be greater than 0.0 and such that the last element in the array (i.e. the element furthest from the weld) is not more than 0.3 from the edge of the weld cap;
- `centre_freq` – centre frequency of array (units: Hertz), must be greater than 1×10^{6} and less than 10×10^{6}.

The outputs are:

- `time` – m-element vector of time (units: seconds);
- `time_data` – an $n \times n \times m$ array (Python) or $m \times n \times n$ matrix (Matlab) of time-traces for every transmitter–receiver combination in array where $n =$ `no_elements`;
- `element_position` – n-element vector of array element positions relative to the datum position shown in Fig. 1 (units: metres).

The –40 dB bandwidth of the array in the simulation is 112% (i.e. the spectral amplitude is within 40 dB of its peak value at the array centre frequency, f_c, between $0.44 f_c$ and $1.56 f_c$).

Simulation mode parameter, `mode`

The following strings for the `mode` parameter enable data to be simulated from test samples containing known defects:

- `'_PRISTINE'` – no reflectors within sample (only reflections from sample walls present);
- `'_POINTS'` – 5 equi-spaced point targets along the fusion face;
- `'_CRACK_TOP'` – 5 mm long crack at the top of the fusion face (i.e. closest to the outer surface of the pipe);
- `'_CRACK_MIDDLE'` – 5 mm long crack at the centre of the fusion face;
- `'_CRACK_BOTTOM'` – 5 mm long crack at the bottom of the fusion face (i.e. closest to the inner surface of the pipe).

All the above may be suffixed with `'_NO_NOISE'` (e.g. `'_POINTS_NO_NOISE'`) to generate the same result but without noise. Note that in these test cases the `scan_position` parameter is ignored.

To return a frame of date from the blind trial sample, set the `mode` parameter equal to your University of Bristol username (e.g. `'ab12345'` and **state the exact string used in your report**). For the blind trial sample, the `scan_position` parameter determines the position of the array along the length of the weld and you will eventually need to generate data from positions along the whole 300 mm length of the sample in order to detect and characterise all defects present. Note that for the blind trial sample, noise is always present and cannot be turned off.

How the simulation function works and its limitations

In order to be fast, the simulation function uses a ray-based approach and a Kirchhoff-like[ii] approximation for defect scattering. Only one mode of ultrasonic waves (longitudinal) is included in the simulation, and a maximum of one reflection off the back wall of the sample is considered on both the ray path from transmitting element to the defect and the ray path from defect to the receiving element (i.e. the following ray paths are simulated: transmitter-defect-receiver, transmitter-backwall-defect-receiver, transmitter-defect-backwall-receiver, transmitter-backwall-defect-backwall-receiver). You will not be able to use signals from other ray-paths for imaging (e.g. those involving mode-conversions of waves or transmit/receive ray paths involving more than one reflection off the boundary of the component); these signals are not simulated and will not exist in the data.

Random noise is added to the data to represent material backscatter. It is therefore coherent noise and will be identical if you repeat a simulation (the simulation function resets the seed of the random number generator to the same value each time it is executed). Therefore, averaging the results of multiple simulations from the same sample will not reduce noise.

SUGGESTED APPROACH

There are 6 parameters that need to be selected for the simulation function, so the number of possibilities is huge. The time taken to simulate a frame of FMC data varies from a few seconds to a few minutes (depending on how many elements are in the array, how many defects are present and how fast your computer is). To simulate and process data for a complete scan along the weld in the blind trial sample will take an hour or more. Therefore, it is not going to be feasible to try every combination so you should use some basic physical reasoning and simpler modelling tools first to narrow down the selection. For example:

- Use basic physical reasoning: What is the optimal direction to 'hit' potential defects from with ultrasound? where should the array be placed to achieve this? How big does the array need to be?
- Use a simple model (e.g. Huygens): Given array position and size, how is focusing at potential defect locations affected by frequency, number of elements, element pitch and element width?
- Use simulation tool on test samples (you need to write a suitable imaging algorithm to convert the raw FMC data from the simulator into an image of the region of interest): Can your array image point targets along the fusion face in the relevant test sample in the absence of noise? Does the presence of noise in the data affect the choice of parameters? Can crack-like defects at the top, middle and bottom of the fusion face be detected in the relevant test samples? How do you set your detection threshold? Can you determine the size of the known defects from the image?
- Use simulation tool on blind trial data (you will need to simulate date and generate images at incremental positions along the weld in the blind trial sample): What defects have you detected in the blind trial sample? What are their positions and sizes?

Your report should contain a convincing and logical technical justification for the approach used. This may include a combination of physical reasoning, basic calculations, references to the literature, simulations using simplified models, results from simulations on test samples with known defects etc. Once you have decided on an approach, you should apply it to the blind trial sample and report the results you obtain. Your conclusion should summarise your assessment of the overall effectiveness of the inspection and any recommendations for improvement to the inspection.

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[i] Peak NDT Ltd., https://www.peakndt.com/product-range/full-matrix-capture/, accessed 6/11/20.
[ii] L. W. Schmerr, *Fundamentals of Ultrasonic Non-Destructive Evaluation, A Modelling Approach*, Plenum Press, 1998.