UOIT – Shahram Shahbazpanahi CRD

CRD Title: Advancement of Sensor Array Processing and MIMO Signal Processing for Non-destructive Testing

Overview

In this NSERC Collaborative Research and Development Grant proposal, we propose to study the applications of sensor array processing and multiple input multiple output (MIMO) imaging to ultrasonic non-destructive testing (NDT) in nuclear power plants. NDT is a type of analysis performed on a completed product to detect fatigue effects and structural imperfections. Such processes utilize ultrasound, infrared radiation, x-ray, or other testing techniques, to ensure that products are not damaged or destroyed during the testing process, thereby providing a balance between quality control and cost effectiveness. Additionally, NDT can be used to ensure safety and quality, to increase production and serviceability, and to extend the life of equipment and systems' components. As one of the significant breakthroughs in wireless communications, MIMO signal processing has been widely investigated as a means used to increase reliability and data throughput in the area of wireless connectivity. In MIMO communication schemes, the transmitter and the receiver are equipped with multiple antennas, thereby providing more reliable communication and/or higher data rates as compared to traditional single antenna transmission-reception schemes. More recently, MIMO techniques have found their applications in radar systems. Known as MIMO radars, these systems employ multiple antennas to transmit temporally short but high-frequency electromagnetic bursts toward targets (reflectors) that are under surveillance. Once these bursts are reflected back towards the radar, they are recorded using multiple antennas and processed afterward to extract the information of interest about the targets and obtain an *image* of the environment under surveillance. Similar techniques are used in sonar systems where the localization of moving objects (such as ships and submarines) in the seawater is of particular interest. In NDT imaging applications, MIMO signal processing involves two tasks: i) designing the signals that are to be transmitted on multiple transmitters, and ii) processing the signals received by multiple receivers in order to ensure that the most accurate images are obtained. The objective of the project is to apply MIMO imaging and sensor array signal processing techniques to the development of new design tools for the ultrasonic non-destructive testing of nuclear power plants and systems therein. In nuclear power plants, certain surfaces and materials require proper maintenance and inspection as they are critical to the safe operation of the plant. As compared to current methods, this project will provide OPG inspection operators with superior ability to detect cracks and thinning in these surfaces. Based on the recent breakthroughs in the areas of array signal processing, our objective is to develop and apply novel techniques for NDT in the nuclear industry. The project will investigate MIMO signal processing methods for imaging, array calibration techniques, wideband and vector sensor processing tools as well as high-resolution and distributed source (reflector) localization approaches.

After imaging the structural imperfections, it is time to build an optimal image processing chain including: noise filtering, region of interest (ROI) extraction, and measuring the dimensions of the extracted regions. Proposing this chain brings the following two benefits for the current research project:

1) Introducing an objective assessment method to compare proposed variant imaging algorithms - By utilizing benchmark imaging, we will be able to conduct a numerical comparison instead of subjective visual assessment. These kind of comparative studies help to improve the proposed imaging methods.
2) Providing detailed information about the structural flaws – Extracting ROI and measuring the required dimensions provide more detailed information about the ***severity*** of the flaws; which are essential factors to make any further decision about the product under non-destructive testing.

In order to obtain the required image processing chain, the image processing modules, their optimal arrangement and also corresponding control parameters will be determined using an optimization method. A mathematical morphology (MM) chain - built using dilation, erosion, opening, and closing operations with optimal structuring elements (SE.s) - will be utilized. The performance of the proposed algorithms will be examined using a comprehensive suite of benchmark images.

Progress made towards the objectives of the projects

PI and his research team have disclosed the following four inventions to UOIT and to the industry partners:

- Ultrasonic Imaging for Non-Destructive Testing Using Correlation Receiver
- Ultrasonic Imaging for Non-Destructive Testing using Distributed reflector Modelling
- Ultrasonic Imaging for Non-Destructive Testing using MUSIC and Capon Techniques
- Ultrasonic Imaging for Non-Destructive Testing using Beamforming and Phase Shift Migration

Moreover, Dr. Rahnamayan has been conducting research on proposing optimal image processing chain using mathematical morphology (MM) techniques and hybrid genetic computation.

<u>Outcomes of Each Invention Resulting from this Work</u>

- Ultrasonic Imaging for Non-Destructive Testing Using Correlation Receiver

Using an ultrasonic transduce array, we have developed a method to extract, from the array signals, the location and shape of the upper surface of a test sample which has been immersed in water. The location and shape of this surface is crucial in imaging the inside of the sample. Our method is based on correlating the signal received by each element with the signal transmitted by that very same element. This transmitted signal is extracted from a few hundred samples of the signal received by one of the transducers adjacent to the transmitting transducer. We have tested this method on the measurement data to extract the location and shape of the upper surface. The proposed correlation-based surface imaging method performs well in our experiments.

- Ultrasonic Imaging for Non-Destructive Testing using Distributed reflector Modelling

In most signal processing literature, it is usually assumed that sources or reflectors are point sources or reflectors located at far field from the sensors. However, in most application such as radar, sonar, wireless communication and non-destructive testing (NDT), sources or reflectors are distributed in space. Especially in immersed ultrasonic test considering the upper surface of the material under test as a point reflector will cause a major error in localization of the crack inside the material under test. This surface not only produces a strong interference on the received signal by reflecting the probing signal, but also has an effect on the signature of all the points inside the material under test. Therefore, a precise model for this surface will result in a precise localization of the cracks inside the material under test. In this work, we model the reflectors as spatially distributed reflectors. That is, we model the reflectors as distributed reflectors consisting of infinite number of point reflectors.

In order to localize the reflectors, we consider a shape for the reflector and try to estimate the parameters of this shape using a covariance fitting approach. To do so, we assume that the reflectors have random reflection coefficients. In practice, the reflectors are partially correlated. It means that signals arriving from different part of the source or reflector are partially correlated. These kinds of signals can be localized using the Incoherently Distributed (ID) sources modeling. We assume that reflectors are incoherently distributed reflectors, then we conduct the experiment a sufficient number of times and we calculate the covariance matrix of the received vector. In the Covariance Fitting Approach, assuming a known shape for the reflector, we estimate the parameters of the reflector which result in a covariance matrix which has the minimum difference with the covariance matrix obtained from our measurements. This results in solving a least-square (LS) estimation problem. Computer simulation has been used to show the performance of this approach. The simulation shows the accuracy of the approach. The model has a low computational complexity. The code can be run for a few minutes for a good grid search.

- Ultrasonic Imaging for Non-Destructive Testing using MUSIC and Capon Techniques

Previous studies in non-destructive testing (NDT) mostly focus on applying the traditional delay and- sum (DAS) technique for imaging defects in solid materials. However, the DAS-based approaches are independent of the second order statistics of the data, therefore, they provide lower resolution and have inferior interference suppression capabilities, as compared to high-resolution techniques such as the well-celebrated multiple signal classification (MUSIC) and Capon techniques. In this work, we apply MUSIC and Capon methods to NDT applications, thereby exploiting the second order statistics (SOS) of the data. Different from traditional MUSIC and Capon approaches, we take the mode conversion phenomenon into account and develop MUSIC- and Capon-based imaging techniques which exploit the additional information that are present in all propagating modes to the advantage of imaging procedure- a problem not previously addressed in the context of NDT applications. We exploit the dominant modes in acoustic propagation (e.g., longitudinal and shear modes) in the data and propose mode conversion based MUSIC (MC-MUSIC) and mode conversion based Capon (MC-Capon) imaging methods. Both the numerical simulations as well as data validation show that our proposed SOS-based approaches perform better compared to the DAS-based imaging algorithms in terms of root mean square error (RMSE) and also provide higher resolution, and better side-lobe suppression capabilities. In addition, the proposed MC-MUSIC and MC-Capon methods provide higher resolution images as compared to their standard mode-neglecting counterparts.

- Ultrasonic Imaging for Non-Destructive Testing using Beamforming and Phase Shift Migration

Ultrasonic imaging is a technique to provide an image from an object using ultrasounds. Frequencies which are being used range from 2MHz to 18MHz. In this method a probe containing multiple acoustic transducers is used to send pulses of sound into a material. Whenever a sound encounters a material with a different density (acoustical impedance), part of the sound wave is reflected back to the probe and is detected as an echo. This reflected signal is then used to obtain an image of the material under test.

In this work, we are dealing with immersed objects in water. This case is different from the contact situation, where there is no gap between transducers and the object to be imaged. When we are imaging objects immersed in water, the difficulty that arises is that the speed of wave in passing through different layers changes. In such scenarios, traditional algorithms developed for contact cases cannot be applied directly.

We have developed a method based on phase shift migration and delay and sum beamforming. In phase shift migration, we compensate for different velocities that wave experiences while passing through different layers. This algorithm has been implemented in frequency domain. The delay and sum beamforming algorithm is the second method that we have applied it to multilayer case. In this approach different time-of-flights from each transducer element to each point in the region of interest are compensated and then a summation is performed on all the aligned observations to form the image. However, as we mentioned before in multilayer imaging scenarios, these delays cannot be calculated easily. The way we tackle this problem, is by introducing a root-mean-square (RMS) velocity and replacing our multilayer situation with just one layer where the speed of wave in this layer is RMS speed. This algorithm has been implemented in time-domain.

- Proposing Optimal Image Processing Chain Using Mathematical Morphology (MM) Techniques and Hybrid Genetic Computation

In order to propose an optimal image processing chain, MM-based image processing techniques have been studied, including: dilation, erosion, closing, opening, hit-or-miss and pruning transforms, morphological skeleton, filtering by reconstruction, and granulometry. The optimal arrangement of operations and designed structuring elements should be determined to achieve a desirable performance. In a two-level hybrid optimization, a genetic programming (GP) will be utilized to find the optimal arrangement of MM operations; and genetic algorithm (GA) will optimize the numerical parameters, including structuring elements. The designed hybrid algorithm will employ synthesis ground-truth images for training of the chain. Currently, we are working on designing of a hybrid GP+GA algorithm.

<u>Research Team and HQP</u>

During this reporting period, the research team consists of the following personnel.

1. Prof. Shahram ShahbazPanahi, Principal Investigator
2. Prof. Shahryar Rahnamayan, Co-Investigator
3. Dr. Foroohar Foroozan: Joined the team as a Postdoctoral Fellow in January 2011 and left the team in March 2012, she has been working on the following topics:

- Time Reversal Bayesian Ultrasonic Array Imaging for Non-destructive Testing.
- Adaptive Beamformers for Multi-Modal Ultrasonic Array Imaging.
- Applying Adaptive Imaging (Capon, MUSIC) to Simulated and Measurement Data.

4. Ms. Nasim Moallemi: She joined the team in January 2011 as a PhD student and is currently working on:

   - Active Array Parametric Localization of Distributed Reflectors for Near-Field NDT Applications.

5. Mr. Yaser Matar: He started as a Master student in September 2011 and is currently taking his course load while studying about the fundamentals of non-destructive testing. He was working on considering multipath in layered media with the aim of improving the quality of the image in such media. He quit his MASc. studies in summer 2012.

6. Mr. Aras Azimipanah: He started as a Master student in September 2011 and is currently taking his course load while studying about the fundamentals of non-destructive testing. He helped Dr. Foroozan with measurement data. He is currently working towards the application of compressive sensing for NDT imaging.

7. Mr. Shaho S. Panahi: He joined the team as a Research Associate (now a Master student) and is currently taking his course load and studying about state-of-the-art image processing techniques for NDT applications. He is working under the supervision of Dr. Rahnamayan.

8. Mr. Shahrokh Hamidi: He joined the research team in September 2012 and is working on Ultrasonic Imaging for Non-Destructive Testing using Beamforming and Phase Shift Migration.

9. Dr. Soheil Salari: He worked with the research team for four months and performed simulations to assess the performance of MUSIC and Capon methods applied to imaging for NDT.

The research teams benefited from the following industry representatives of the Technical Advisory Committee (TAC):

1. Mr. Shaddy Shokralla, OPG
2. Mr. Stuart Craig, AECL-CRL
3. Mr. Andrew Glovers, Bruce Power

So far, the research team had four meetings with the industry representative on a quarterly basis. During these meetings, members of the team have presented the results of their latest achievements. The feedbacks received from the industry representatives were very helpful in properly positioning the research into the context of the available technology.