Additive Manufacturing of Sensors and Components for Non-Destructive Evaluation Applications

*Real-Time Characterization of VTR Coolant Variables by High Resolution
Distributed Sensing*

Nuclear Science and Engineering Division

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Additively manufactured machine components were designed for use in non-destructive evaluations. Additive manufacturing (3D printing) enables rapid production of simple or complex objects at a low cost for use in many fields of research and industry. 3D printed components were used to optimize an eddy current array probe to inspect various **complex** shaped objects, such as gears. Preliminary eddy current inspections were conducted to test the functionality and compatibility of the 3D printed components to the array probe and existing system. These were done by wrapping replica 3D printed gears with aluminum foil. The results were as expected, rough, uneven surface of the aluminum foil. Calibration scans were also executed to enable proper measurement of defect size in metal structures. For use in waveguide-based distributive sensing technologies, additively manufactured custom waveguides were designed for use in liquid environments to collect pressure and flow data. Waveguides were designed with membranes, thin sections of the walls, which would be pressed inward due to fluid pressure. Waveguide models continue to be developed and revised for most functional utility in liquid environments.

I. INTRODUCTION

The field of non-destructive evaluation of material structures frequently requires adapting sensing probes to the specific geometry of complex shape structures. This makes it difficult to reuse sensors and components on different objects and surfaces. Several different components are produced to inspect various objects which is often an expensive procedure since a custom part has to be industrially produced for each evaluated structure. Additive manufacturing offers similar benefits as industrial production at a lower price and in a shorter amount of time.

Additive Manufacturing (3D printing) is a low-cost technology that enables the possibility to design numerous uncommonly shaped objects or originally designed components that are more intricate than what can be produced industrially but still maintain reasonable accuracy. 3D printed models can be made from various materials depending on project needs, including nylon, metals, ceramics, etc, but mainly thermoplastics.

A common type of non-destructive evaluation is eddy current testing. Eddy current testing is an electromagnetic testing method based on electromagnetic induction. It consists of a probe with an alternating current flowing through a wire coil which when brought near a conductive object, induces an eddy current in the material. A defect is detected when the eddy current is disturbed which can be analyzed by measuring the coil impedance variation. This method can be used to measure the width and depth of a fracture in a structure. The frequency of the alternating current affects the depth at which the eddy current probe can inspect for defects. Frequencies used for eddy current testing

ranges from² 100 Hz to 10 MHz, where lower frequencies are used to scan deeper and higher frequencies for surface defects. Multiple coils can be used together to examine an object more accurately and more quickly. To optimize a recently acquired eddy current array probe with a 128 coil film strip for various surfaces, multiple probe designs were needed to inspect gears and other uneven surfaces. 3D printing was used to produce multiple probe mount designs to fit the geometry of gears.

3D printing is also useful in quickly producing components that closely match industrially made parts or custom prototypes which can be used for preliminary testing. To create a distributed pressure sensor capable of taking measurements in liquid environments, unique microwave waveguide models were designed to assess the value of waveguide-based distributed pressure sensing. A waveguide is a hollow rectangular metal tube used to direct electromagnetic waves with minimal loss of energy. Distributed Sensing, unlike conventional point sensing, monitors a large region of liquid which provides comprehensive measurement of fluid temperature, pressure, and flow rate. Waveguide-based pressure sensing requires measurements of waveguide wall membrane displacement due to fluid pressure. Displacement of the membrane wall causes propagating microwaves to be reflected and the amplitude of the reflected waves are used to calculate pressure and flow rate. Multiple models were created to test 3D printed waveguides for wave reflection losses compared to industrially made microwave waveguides.

II. METHODOLOGY

The 3D printed components were all originally designed in Blender, the open-source 3D creation software.

The eddy current array probe component models

^{a)} Additive Manufacturing Advisor

were printed with polyethylene terephthalate glycol-modified (PET-G) filament on a Series 1 Pro 3D printer, a fused deposition modeling (FDM) type printer which extrudes thermoplastic filament. The waveguide models were printed with polymethyl methacrylate (PMMA) on a Form 2 3D printer, a stereolithography (SLA) type printer which solidifies liquid resin with a UV laser across the print area.

Eddy current tests were conducted using Zetec Velocity Data Acquisition software and test data was acquired with a Zetec MIZ-200 instrument.

III. RESULTS

A. Optimization of Eddy Current Array Probe

Eddy current testing often requires probes that match the tested surface to accurately examine the material, therefore, many probes are dedicated to inspecting a certain shape. Eddy current probes need to match an object's distinct surface curvature and geometry to keep a small and constant lift-off, the distance between the surface and wire coil, while scanning the structure to obtain valid data, otherwise, a defect could potentially be incorrectly detected.

The previous working automated system of scanning gear components consisted of a mechanism that held and rotated the gear along with an extended portion containing a metal mass standard with drilled holes used for calibration and an apparatus on which an eddy current pencil probe was mounted and scanned the gear by moving laterally along each gear tooth. To optimize the system for an eddy current array probe with a film of 128 wire coils that is capable of scanning for flaws much quicker than a pencil probe, new components were needed, specifically for inspecting two different sized gears, the large gear with a radius of 14.29 cm and the small gear with a radius of 12.34 cm. The system is set up with 3D printed duplicate gears since the real metal gears are currently in use.

1. Eddy Current Array Probe for Large Gear

Multiple models for the large gear were created before the first version was printed and tested for compatibility with the wire coil film and the automated gear scanning system. The first design was modeled to inspect one side of each gear tooth at a time, therefore, the gear needed to be reversed for the other side of each tooth to be inspected, similar to the way the pencil probe worked. This design made it possible to also scan flat surfaces as well, but for the specific use with gear inspection, the design did not optimize the array probe for minimum scan time. The model was then modified to scan a whole tooth at a time, since the coil film had the length and enough wire coils to cover the surface area, thus reducing scan time by half and eliminating the need to reverse the gear. It consisted of the same top portion with two protruding sections instead of one to reach between gear teeth.

FIG. 1. Automated eddy current testing scanning system with probe scanning stage and gear holder.

FIG. 2. (Left) Array probe mount model designed to scan half a gear tooth at a time. (Right) Design of mount for a whole gear tooth and first 3D printed version of the array probe mount.

The whole tooth design was the first 3D printed version of the array probe mount. The overall shape was compatible with the gear, probe connector, and wire coil film, but not with the apparatus that holds the gear in place and the calibration standard container. Since it was initially designed for use with pencil probes only, the larger design of the array probe did not fit dimensions of the machine, thus the whole gear was unable to be inspected with that setup. About 2.25 cm of the gear was unreachable due to the base of probe mount colliding with the gear rotating machine during a scan.

To solve the issue of scanning limits, the array probe mount was modified so that the base width was reduced, thus allowing the probe to inspect the previously unreachable area of the gear tooth. Further slight changes were made such as enlarging the protruding areas of the mount to cover more surface area at the base of the gear teeth and rounding off edges to reduce the chances for printing failures. Figure 3 shows the printed version attached to the array probe connector with the film wrapped around the bottom area of the probe mount.

The previous calibration standard holder was only compatible with pencil probes, therefore also needed to be redesigned. Since there was a limit to the range of movement of the stage that holds the eddy current

FIG. 3. Eddy current array probe mount design for inspection of large gear connected to eddy current array probe.

probe, extending the gear holder to include a section for the calibration standard could not be done without a new apparatus with a larger movement range. A design for the calibration standard container was modeled to be placed over the gear teeth, thus resolving the problem of the system's movement limits. Figure 4 shows a simple box model with a concavity that was fitted to be securely placed over the gear which was sufficient for this system. This way the movement of the automated system would not need any drastic adjustments, simply minor setting changes for array probes.

FIG. 4. Final design of calibration standard container made to be placed over the gear teeth.

Sample tests were conducted with the large gear array probe mount by wrapping the large gear replica with aluminum foil. A gear tooth was manually scanned with the probe at 500 kHz to test the functionality and compatibility of the 3D printed mount with the array probe and constancy of lift-off from the gear surface. Only half of the film coils were functional due to some issues in the probe connector, thus, the film was adjusted accordingly.

FIG. 5. Manual test scan results of eddy current array probe on aluminum foil covered large gear tooth A. Orange and blue areas describe bulges and depressions of the foil lined gear complete with heights and depths.

Data expectedly shows a rough surface of the aluminum foil. Irregularities are indicated by color depending on the rotation of the data, in this case, bluer represents indentations and redder represents protuberances. Figure 5 displays a selected region of the sample data with a relatively large bulge.

The test was redone using the automated system. New system settings were applied to the probe stage and gear holder for the array probe. Data for this test is more relevant since the probe mount was designed to work with the scanning stage. Figure 6 displays the surface features of the aluminum foil with a median filter, which accounts for major differences in lift-off.

FIG. 6. Test scan of aluminum covered large gear tooth A with eddy current array probe on automated system.

The data presents the rugged, uneven surface of the aluminum foil. Differences in lift-off were more noticeable with this method due to inaccuracies in the design of the probe mount which was an issue for future inspections. The requirement for the accuracy of surface geometry match is less than 1 mm of lift-off. A proposed solution was that the probe mount is printed with thermoplastic polyurethane (TPU), which is a flexible filament. With this, the mount could be made more exact and adjust to the surface if needed.

The test data isn't particularly meaningful since the gear was simply covered with aluminum foil and no data on an actual gear was taken. Determining whether the array probe functioned properly while maintaining reasonably constant lift-off during the test was more important. The working portion of the array probe showed expected results, thus, indicating that the array probe was operable with gear scanning.

Knowing that the array probe operated properly, a scan of the calibration standard was conducted to correctly interpret the sizes of surface flaws of future inspections. Since the shape of the calibration standard is rectangular, with the gear probe mount only 1-3 coils can scan it at a time. Figure 7 shows the data acquired in the scan of the calibration standard.

Data obtained by the array probe was examined and relevant information from the three coils was isolated for analysis. The holes in the calibration standard, in-

dicated in blue in Figure 7, are clearly visible, therefore, there is penetration data. The holes evidently are similar in size and are evenly spaced apart. The only inconsistency is that since the array probe scans the calibration standard horizontally by moving through each height layer twice, towards and away from the operator, the data should show exactly the same results in both directions, but the graphs disagree with the expected outcome. Figure 7 shows the scan towards the operator has more irregularities than away. During analysis, the information on the scan towards the operator was discarded since it contradicted the expected results and away scan.

FIG. 7. Array probe scan results of the calibration standard. Left visual representation displays the scan area with depths indicated by color, and right graphs display measured depths with respect to position.

The results were analyzed on the Velocity software so future data can be correctly interpreted since the sizes of the holes in the calibration standard are known. It was previously unknown whether the coil film could be calibrated with only one coil in contact with the material, but determining which coils were receiving data allowed for the array probe to calibrate based on those coils, thus, solving the issue of incapability of scanning the calibration standard with the entire film coil.

2. Eddy Current Array Probe for Small Gear

To be used for the small gear, new probe mounts needed to be designed specifically for the array probe as well. The shape and size of the gear teeth were distinct such that the models for the large gear were incompatible with the small gear. The same overall shape of the large gear probe and calibration standard holder was used to create models for the small gear.

Similar to the large gear array probe mount, the design for the small gear probe mount has two protruding sections on the bottom. A potential issue with this probe design is that since the gear teeth are relatively small, the wire coils in the film could be too large to wrap properly around that portion without bending.

The calibration standard holder design is a box model with concavities to securely attach to the gear. Since its shape has little effect the workings of the system other than its placement on the gears, it was designed to be nearly identical to the one for the large gear.

FIG. 8. Eddy current array probe mount and calibration standard container for small gear.

3. General Surface Eddy Current Array Probe

Gears are not the only objects sent to the lab for inspection. Other various parts with different geometries are expected to be examined. Most often, new array probe designs are needed for more uniquely shaped objects, but for surfaces that have relatively lower curvature, a versatile probe would be beneficial.

A model for a "general use" eddy current array probe mount was drafted to be used for objects other than gears. The design is modeled such that the coils on the film strip are aligned on a curved portion, similar to several pencil probes lined up. This way, fewer probe mounts would need to be produced to inspect other objects. The mount is expected to be printed with TPU filament as well.

FIG. 9. Eddy current array probe mount design to align wire coils on film for inspection of various objects.

The issue with this model is that the coil film is required to bend in two directions which is nearly impossible without creasing the film with its short length. Because the coils run parallel to the length of the film strip, to create a mount that aligns them with this type of array probe is a difficult task. A proposed solution is purchasing a custom array coil film with the coils orthogonal to the length of the strip. This prevents any creasing of the film strip and simplifies the mount design.

B. Production of Waveguide Prototypes for Distributed Pressure Sensors in Liquid Environments

To create custom components for a waveguide-based distributed pressure sensor, waveguide models were designed and printed for wave-reflection tests in fluids. The first models of straight rectangular waveguide

guides were created with membranes, thin sections of the waveguide wall, which deformed when exposed to fluid pressures. Figure 10 displays the first prototype with membranes of different thicknesses, ranging from 0.5 mm to 0.9 mm.

FIG. 10. Waveguide with membranes of difference thickness to allow for pressures to be measured from changes in displacement of waveguide wall.

The prototype was successful in that it was accurate enough for the purpose of aligning with the sensor system. The downside to printing waveguides with thermoplastics is that microwaves are not transmitted as well as in metal waveguides. A proposed temporary solution was to coat the waveguide with conductive nickel spray paint, which decreased wave losses, but not nearly comparable to pure metal. Another idea was to create the waveguide with resin mixed with copper particles while still in liquid form. This would give it semi-metallic properties. Issues with this technique include printing issues due to the opacity of copper. The printer used uses a UV laser to harden resin. Since copper is not transparent, the laser has difficulty printing a higher number of layers. The technique is continuing to be developed.

Variations to the waveguide with membranes were created. Figure 11 shows a waveguide designed to attach to pipe walls to measure fluid pressure and flow in pipes. A sensor designed as such reduces alterations to fluid flow properties while still collecting extensive data.

FIG. 11. Curved waveguide design with membranes on bottom wall to attach to pipe structures to measure fluid pressure and flow.

Further developments to the waveguide model continue to be added. Waveguide resonators models are being drafted to increase the sensitivity of the waveguide to external pressures and flow changes.

IV. CONCLUSION

Additively manufacturing probe components for eddy current testing proved to be the most efficient and productive technique. Since eddy current testing requires probes that match the shape of the objects scanned, complexly shaped probes were needed to accurately inspect each object. The attempts at designing models that fit the shape of the gear were reasonably accurate. Depending on the printer and filament types, sufficient accuracy could be achieved with this technique. With the 3D printed components optimized for an eddy current array probe, expected scan times for gear inspection have significantly decreased. The preliminary inspections generated satisfactory results which correctly depict the expected outcomes of the scans of the aluminum foil and the calibration standard. Future directions tend toward producing a semi-flexible probe usable for many different structures. 3D printing prototype custom waveguides rapidly and inexpensively enable quicker development of waveguide models. Since models can be produced almost immediately compared to ordering an industrially made custom waveguide, trials were conducted to test the functionality and limits of thermoplastic waveguides. It was concluded that they were not ideal transmitters. The proposed solutions were coating the waveguide with a conductive nickel spray paint and mixing the liquid resin used to make the waveguide with copper particles to give it semi-metallic properties. The paint coating decreased wave losses but still does not nearly as well as pure metal. Copper particle filled thermoplastic waveguides proved to be a difficulty printing a full working model due to the opacity of copper. Future developments to waveguide models continue to be made as more experiments are performed.

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