CON-9309199--3
SAND--93-18900

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NOV 17
1993

Multi-axis seam tracking using a noncontact capacitive sensor

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ABSTRACT

This paper describes the development and use of the Multi-Axis Seam Tracking (MAST) sensor for tracking seams or other features in real-time. Four independent, spatially-distributed electric fields are used to sense changes in the relative position of the sensor and the workpiece. The MAST sensor is very inexpensive compared with commercially available seam tracking sensors. It can be used in systems to perform cost-effective small-lot manufacturing operations in a faster, more consistent manner. The MAST sensor is used in an automated system for dispensing braze paste during a rocket nozzle fabrication process.

1. INTRODUCTION

Large classes of manufacturing operations require the precise tracking of a gap or seam between mating parts. Seam tracking sensors provide error signals that the manipulator can use to accurately follow the desired seam in real-time, as the parts are being processed. These data are fed back to the controller which can modify the nominal trajectory to compensate for mismatch in the joint, misalignment of the fixture, and process-induced distortions of a workpiece. A wide variety of "disturbances" can thus be rejected by the control system, resulting in a useful processed part. This type of system permits the application of automation and robotics to small-lot manufacturing operations in a cost-effective manner.

Sandia and Rocketdyne, a Division of Rockwell International, have entered into a collaborative research and development agreement (CRADA) to solve a particularly difficult seam tracking problem during the manufacture of rocket booster thrust chambers¹. These large, bell-shaped thrust chambers consist of many individual tubes furnace brazed together to form a structural unit. To manufacture a chamber, loose tubes are first assembled into the final shape. The interstices or gaps between the tubes are then manually filled with nickel powder and silver-palladium alloy paste and subsequently furnace brazed to form a complete structure.

The manual application of nickel powder and braze alloy is a tedious, time-consuming task that is subject to inconsistencies. Deviations in the material flow or the motion of the dispensing nozzle with respect to the gaps between the tubes can result in imperfections in the braze quality. Excess material can be applied to prevent thin spots, but this increases costs. This operation cannot be automated by using preprogrammed dispensing paths, i.e., taught points, because of the size and mechanical flexibility of the unbrazed thrust chambers. Rocketdyne has had some success in locating the gaps on a nozzle using a contacting probe; commercially available seam tracking sensors did not meet the project's requirements for cost, complexity, and maintainability.

This report focuses on the development of the noncontact Multi-Axis Seam Tracking (MAST) sensor for use in an automated system for the manufacture of these rocket engine components. The MAST sensor is simple, low-cost, requires little maintenance, and can be readily applied to a variety of automated seam or feature tracking problems^{1,2}. Because it does not contact the nozzle, the sensor can locate tube gaps more quickly, reducing the processing time required. Information from the MAST sensor is used by the robot system to locate and track the tube interstices. Because of the use of sensor feedback, variations in the position of the chamber with respect to the robot are compensated for in the control system. The team expects that the use of a capacitive seam tracking sensor described below will result in faster, more consistent processing of nozzles without costly fixturing.

MASTER

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2. MAST SENSOR PRINCIPLE OF OPERATION

Sandia has developed a unique sensor capability utilizing capacitance to locate and measure objects without contact. The MAST sensor uses capacitance variations to permit the measurement and control of sensor position and orientation with respect to the seams on a workpiece. The sensor consists of a specially designed arrangement of capacitor electrodes that are connected to appropriate signal conditioning electronics. The first version of this sensor has four output signals that can be combined to provide tracking in the Δy and Δz positions as shown in Figure 1.

Figure 1. Diagram of the Multi-Axis Seam Tracking (MAST) sensor. The MAST sensor is a printed circuit board with precisely patterned electrodes at the tip. The geometry and spacing of the electrodes determine the performance characteristics of the sensor.

The MAST sensor is an inexpensive five layer PC board with one integrated circuit for buffering (Figure 1). The sensing elements comprise four rectangular electrodes (numbered 1, 2, 3, 4) with one pair on each flat face of the printed circuit board (PCB). A more detailed description of the capacitive principles involved is given in Reference 3. Power and output signals are carried by a ribbon connector at the opposite end of the PCB to the signal conditioning electronics. Two SMB connectors are used to provide a coaxial connection for the input oscillators. The entire system, including sensor and signal conditioning electronics, has an estimated component cost of \$500.

The MAST sensor generates four electric fields that are perturbed by changes in sensor position relative to a workpiece. Three of these sensing fields are indicated in Figure 2. Changes in the electric field between the electrode plates are detected as capacitance variations. The shape and extent of the electric sensing fields are functions of the position and size of the electrodes. By varying the geometry of the electrode pairs, the field can be optimized for a particular application. For the seam tracking

perpendicularly to the bundle surface in the y axis (across the gaps) for 1 and 2 mm heights (above the surface). Data from the DL sensors are plotted (as symbols) versus distance from the tube gap for two different nominal heights (in z) above the nozzle bundle in Figure 4. The minimum and maximum values of the experimental data have been linearly scaled to match the simulated values. Notice that the model accurately predicts the shape of the response curves throughout the nonlinear profile. Because the electric fields extend primarily along the z-axis, the DL sensors exhibit a greater sensitivity to changes in this distance than the SL sensors. This is noticeable in Figure 4 where the dynamic range of the signal at 2 mm above the surface is significantly smaller than that for a 1 mm distance. These DL sensors are primarily used to control the motion of the robot toward the inner chamber surface.

Figure 3. Scan directions for MAST sensor experiments. The flat assembly of tubes was used to simulate the structure of a thrust chamber.

Figure 4. Comparison of simulated and experimental output of DL sensors.

application, the size and placement of the electrodes has been optimized for locating and tracking the interstices associated with the typical rocket nozzle tubes or similar structures.

A top view of the MAST sensor positioned over a tube interstice is given in Figure 2a. The sensing fields between electrodes 3-4 and 1-2 extend primarily outward in the +y and -y directions, respectively, although they will extend some distance along the z axis. These sensors are termed "side-looking" (SL) sensors. A different pairwise combination of these electrodes provides additional sensors. The fields between electrodes 1-3 and 4-2 extend primarily downward in the +z direction (Figure 2b). These will be referred to as the "down-looking" (DL) sensors. The rear DL sensing field lies directly behind the forward DL sensing field and is not visible in Figure 2b.

Figure 2. The MAST sensor principle of operation. The electric fields generated by the MAST sensor have been designed to take advantage of the geometry of the thrust chambers of rocket engines. a) Top view of the MAST sensor illustrating the "side-looking" (SL) sensing fields. b) Side view illustrating the "down-looking" (DL) sensors.

During a seam tracking operation, the difference between signals from the two SL sensors is used as an error signal that compensates for inaccuracies in tracking the seam in the y direction. The sum of the signals from the DL sensors is used to control the height of the sensor along the z axis. Furthermore, the difference between the forward and rear DL sensors can be used to sense the orientation about the y axis. This orientation sensing is not used for the present application, since sufficiently accurate sensor orientation can be achieved with apriori motion programming.

3. SENSOR EXPERIMENTS

The DL MAST sensors were simulated in 2D using the Electro[®] boundary element software package. The simulated sensor was "moved" across a surface similar to that in Figure 3 representing the cross section of a series of 9.5 mm OD tubes. The mutual capacitance between the DL electrodes was calculated for different sensor distances from the gap between the tubes. The data are plotted as solid lines in Figure 4. As expected, the signals are at a maximum when the sensor was directly over the gap since the shielding effect of the tubes on the sensor electric fields is at a minimum at this position. As the sensor is moved further from the gap toward the top surface of a tube (distance = 4.25 mm), the signals reach a minimum value of capacitance as the shielding effect increases.

The MAST sensor was experimentally tested using a fixture consisting of a flat bundle of 9.5 mm in OD tubes. The sensor tip was oriented parallel to the interstice axis as indicated in Figure 3. Data values were collected as the sensor was moved

Figure 5 shows a plot of the two SL sensor signals, their difference, and a DL sensor output as the sensor was scanned along the y axis of the tube bundle at a distance 1 mm above the surface. Notice the phase differences between the signals. The DL sensor signals are in phase with the gap, rising to a maximum at the gap location. The value of the difference signal goes to zero at both the centers of the interstices and at the tops of the tubes due to the symmetrical geometry at both locations. Plots of the sum of SL sensor signals ([SL1-2 plus SL3-4], not shown) exhibit positive peaks at locations over the tops of tubes and negative peaks at interstices. Thus, the difference signal identifies the locations of symmetry, while the sum of the sensor signals identifies whether the location is a tube top or an interstice. This sensor information is used to precisely locate an interstice by directing the robot to move the sensor tip to zero the SL difference signal (i.e., balance the readings of the SL sensors) while maintaining a minimum value for the common-mode SL sensor signal.

Figure 5. Comparison of phase differences between DL and SL sensors for a distance of 1 mm above the simulated nozzle surface.

4. APPLICATION TO MANUFACTURING PROCESS

The MAST sensor was mounted on a Fanuc Robotics S-700 robot and the sensor output signals were connected to the controller A/D inputs. The data from the previous section were analyzed to extract calibration parameters for the y and z perturbations. These parameters allow the robot motion control program to interpret the MAST sensor data and formulate the appropriate movement of the robot arm in order to bring the sensor to the desired position. The sensor signals were incorporated into robot control software to locate the surface and track the interstices in y and z of the simulated chamber surface.

The process starts by using a surface locating algorithm to locate the inner chamber surface. Only one taught point is required – a starting location approximately 0.5" from the inner nozzle surface. The robot moves the sensor to this nominal position and then uses feedback from the DL sensors to move the tip to the desired distance from the surface. Next, the sensor is scanned perpendicularly across the surface while distance values are collected again using DL sensors. The collected data are sorted to find the maximum distance value, thus obtaining the approximate location of the reference (first) interstice. This step is required since differential tracking using the two SL sensors requires the MAST sensor to be over an interstice, and not a tube top. Then the sensor is moved under servo control that minimizes the difference signal between the SL sensors to provide an accurate location of the first interstice. Adjacent interstices are located by offsetting the tip position by the nominal width of a tube and repeating the process. Evaluation of this software has shown that the robot/MAST sensor system can locate the inner surface of the nozzle and the initial seam to within 0.002" in about 3 s, significantly faster than contacting probe methods.

5. SUMMARY

A Multi-Axis Seam Tracking (MAST) sensor has been developed for use in tracking seams or other features in real-time. This capacitance-based device consists of four independent, spatially-distributed electric fields which sense changes in the relative position of the sensor and the workpiece. The MAST sensor is very inexpensive compared with commercially available seam tracking sensors. It can be used in systems to perform cost-effective small-lot manufacturing operations in a faster, more consistent manner.

6. ACKNOWLEDGEMENTS

This work was performed at Sandia National Laboratories supported by the United States Department of Energy under contract number DE-AC04-76DP00789.

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