An Undergraduate Research Effort into Non-contact Motion Tracking

B. L. Newberry, H. Collins, and I. Lockwood

Oklahoma Christian University

I. Introduction

Cable structures are used in many engineering applications for their ratio of high axial strength to negligible lateral stiffness. This advantageous property, however, can give rise to nonlinear oscillations that impair performance. Newberry¹ and Newberry & Perkins² analytically demonstrated that nonlinear modal coupling may occur between lateral and axial modes of certain cable suspensions producing premature cable failure. This coupling is most severe in submerged structures subject to fluid/cable interaction.

A prototype non-contacting sensor array, capable of submerged operation, is herein presented to allow future experimental verification of the analytical findings of Newberry and Perkins. The prototype array uses Hall sensors to track the position of a magnetic target, attached to the structure, by sensing magnetic field variations caused by motion. A properly configured array will allow motion to be accurately determined without physically touching, and thereby altering, the dynamics of the system. A prototype sensor array developed by undergraduate students at Oklahoma Christian University is presented. This prototype array is currently only a bench tool for experimentation, but provides proof-of-concept for eventual implementation in submerged service. Preliminary results for the constructed array are discussed.

II. Non-contact Sensor Array Theory and Calibration

The proposed array consists of three Hall sensors arranged in a triangular pattern around a moving structure equipped with a small magnetic target, as shown in Figure 1. The prototype array discussed in this report will be a bench-top adaptation of this concept. The motion of the structure is determined within the plane defined by the sensor array by triangulating the location of the target using the Hall sensor signals. The Hall sensors (named for their use of the effect discovered in 1879 by Edwin Hall) produce a voltage proportional to the perpendicular magnetic flux striking the element³. The magnetic field strength is related to the separation distance between the sensor and the magnetic target. Melexis Hall elements (Digi-Key Part # MLX90215LVA-LC03-ND) were used in constructing the prototype array.

Figure 1: Sensor Concept Sketch

Sensor Calibration

Each Melexis Hall sensor was individually calibrated by placing a movable magnetic target a known distance from the element. The Hall voltage was then collected, using a National Instruments data acquisition board and the Labview software package. The process was repeated with the magnetic target positioned at different known locations to produce a plot of separation distance versus Hall Voltage. A Neodymium permanent magnet, shown with the calibration stand in Figure 2, was used as the target during calibration and testing.

Figure 2: Photos of the calibration stand and magnetic target used in testing.

Typical calibration results are shown in Figure 3. Curve fitting was used to determine an empirical relation for separation distance as a function of the Hall voltage. An “average” logarithmic fit was selected for the calibration equation as it accurately matched the test results for separation distances greater than one inch. . The logarithmic curve fails to capture the asymptotic nature of the test results for small separation distances. This limitation, though recognized, was not considered problematic as the target will never be allowed to near impact with a sensor. The lower portion of Figure 3 shows a plot of distance verses Hall signal for the calibration curve and the equation for the fit.

Figure 3: Raw calibration data and curve fits are shown in the upper plot for the individual Hall sensors. The logarithmic fit, though it fails to predict the asymptotic nature of the response as the distance approached zero, was selected. The lower plot is the “average” fit, based upon combined data sets from all sensors.

Prototype Array Assembly

Upon completing the calibration, three sensors were assembled into an “L” shaped array. The sides of the pattern measure six inches (the nominal calibration limit during this prototype stage). Figure 4 provides a photo of the assembly.

Using the calibration curve previously discussed and the individual signals from the Hall sensors, the distances separating the target from each sensor were determined. Three techniques were developed to triangulate the location of the target using the Hall voltages (see Figure 5). The first method examined the intersection of three circles defined using the separation distances as radii. This method proved to be overly sensitive to error as a single incorrect radius results in multiple intersection points. The second method utilized the Law of Cosines to determine the angles between the sides of the sensor array and the position vectors connecting the Hall elements and the magnetic target. Once these angles are known, simple trigonometric relations are used to determine the coordinates of the target. The third and final method used the Pythagorean Theorem to derive two equations, one governing X and one governing Y, based upon the Hall voltages. The latter two triangulation methods were primarily used.

Figure 4: Photo of the prototype sensor array. This prototype consists of three Hall sensors positioned in an “L” pattern. The three sensors allow the location of the magnetic target to be triangulated using the Hall voltages from the array.

“Circle Method”

The target is located by mathematically determining the intersection of the circles defined by the separation distances from the sensors to the magnetic target.

“Trigonometric Method”

The target is located by determining the angles α_1 , α_2 , β_1 , and β_2 that satisfy the figure to the left. Once the angles are known, the position of the magnetic target is determined via trigonometry.

“Distance Method”

The target is located by determining the X and Y values that satisfy the right triangles for the figure to the left. The Pythagorean Theorem is all that is required.

Figure 5: Post-processing strategies for the Prototype Sensor Array

IV. Prototype Qualitative Testing

With the prototype array constructed, several tests were performed to assess the accuracy of position detection. The primary method used for these tests consisted of placing the magnetic target on a vertical stand made of a ballpoint pen (reference Figure 3). This allowed the “actual” image traced by the pen to be compared to the “acquired” image (recorded via the National Instruments data acquisition system) to allow qualitative assessment.

Figure 6 demonstrates one example test of the prototype array. A “heart” shaped figure was drawn using the magnetic target stand while collecting the Hall voltage from each sensor in the array. As seen in the figure, significant high frequency noise was measured in the array output. This noise is believed to be the result of unanticipated fluctuations in the array’s supply current. While plans exist to eliminate this noise in future arrays using filtering, during this proof-of-concept phase the noise was mathematically handled using averaging (smoothing) of the results.

Figure 6: A sample test of the prototype array. This chart shows the raw sensor voltage data collected during movement of the target in a “heart” shape within the working plane of the array. The high frequency oscillations are believed to be linked to noise in the supply current to the array elements.

Using the “Distance Method” to triangulate the target position, the original “heart” figure was approximately recreated as shown in Figure 7. Note that the sensed image is distorted from the original image. The most likely reason for this distortion is actual motion differences between the top of the target stand (the location of the magnet) and the pen tip at the base of the stand associated with tipping of the stand during movement. Steps are underway to produce a more precise test fixture for the next phase of the project.

Figure 7: A sample test of the prototype array. This chart shows the sensed and actual target motions for a single test. A packet size of 200 has been applied to the Hall voltage signals to smooth the noise in the resulting shape. Note the array qualitatively reproduces the target shape, but quantitatively shows some distortion.

V. Conclusions and Summary

The proposed concept of tracking target motion by detecting magnetic field changes has been proven. The qualitative success of the sensor has been repeatedly demonstrated via multiple tests reproducing geometric shapes. Limited tests have been performed to crudely assess the quantitative accuracy of the sensor array. Further assessment of the quantitative accuracy will require improving the driver circuitry for the sensor array to eliminate signal noise. The prototype array, built and tested by two senior mechanical engineering students at Oklahoma Christian University, serves as a successful example of meaningful research and development being performed at the undergraduate level. The project is continuing at an increased effort, still utilizing undergraduates, to improve the electronics driving the sensor array and to precisely quantify the performance.

VI. Bibliography

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VII. Biographical Information

BYRON L. NEWBERRY

Dr. Byron L. Newberry is an Assistant Professor of Mechanical Engineering at Oklahoma Christian University. He holds B.S., M.S., and Ph.D. degrees in Mechanical Engineering (advanced degrees from the University of Michigan). His areas of interest include structural analysis, thermal stress, linear and nonlinear oscillations, and engineering design.

HANNAH COLLINS

Hannah Collins is a recent graduate from Oklahoma Christian University with her degree in Mechanical Engineering. She is most interested in the area of machine design and is currently pursuing a career in research and development.

IRA LOCKWOOD

Ira Lockwood is a senior at Oklahoma Christian University majoring in Mechanical Engineering and Bible and Ministry. He is interested in designing products for the automotive or aerospace industry, especially in areas of vibration analysis or aerodynamic design.