OMNI-DIRECTIONAL VELOCITY SENSING WHISKER

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ABSTRACT

This paper presents the development of a whisker sensor capable of force and momentum measurements. This type of sensor is useful in exploratory space applications involving fluids and atmospheres. It can be used to determine velocity, acceleration and fluid properties including density and viscosity which are derived from the force exerted on the whip. A single whip sensor is capable of sensing two dimensions of force through the use of beam elements and piezoceramic strain gauges to achieve superior sensitivity. The whip and beam elements are dimensioned specifically for its intended application based on expected acceleration and/or drag force. Experiments were done using a simple wire type and piezo type strain gauge. The wire type strain gauge produced force reading results with as little as 1% error whereas the piezo force readings were subject to accumulated error and require further refinement in data acquisition and filtering. The refinement is a worthy undertaking because the piezoceramic strain gauge is approximately 50 times as sensitive as the wire strain gauge.

INTRODUCTION

In space and underwater, vehicle position and orientation must be tracked accurately to accomplish their respective missions. The task of position monitoring can be solved by taking accurate velocity readings and accounting for relative position by the use of two whip sensors that read two directions of velocity each. In a space application the velocity can be determined in a fluid or non-fluid environment. In such a case the deflection of the whip would be due to acceleration. In the presence of a fluid and combined with other velocity sensors it can be used to determine the velocity, density, or viscosity of an unknown fluid for exploratory and navigational use.

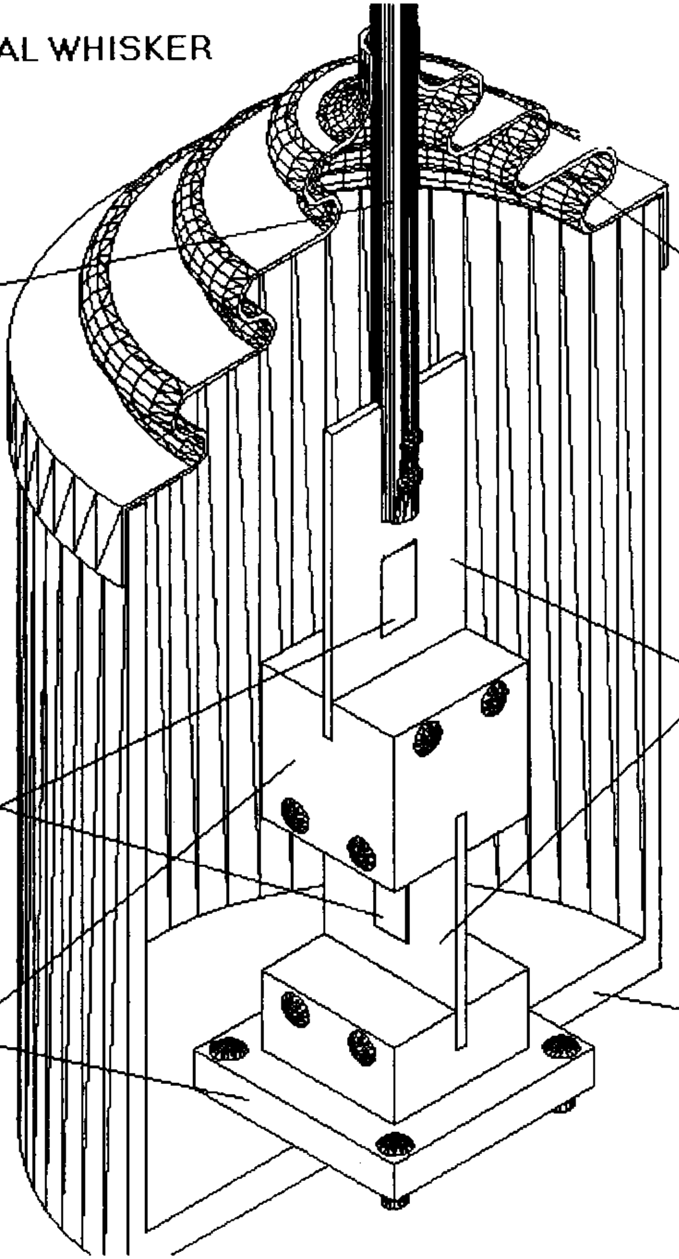
DESCRIPTION OF APPARATUS

The use of two whip sensors allows one direction to be read twice. This particular set of sensors was fitted for the use on an underwater vehicle called SAUVIM (Semi-Autonomous Underwater Vehicle for Intervention Missions). In this case the vehicle required velocity to be calculated in three directions x, y, z(horizontal forward, horizontal sideways and vertical) and rotation in one direction(yaw). By mounting sensor #1 on top of the vehicle on axis with the center of rotation it will read x and y velocity. Sensor #2 will be mounted 90^0 on either side of the vehicle, inline with the center of rotation and will read x and z velocity. This configuration allows all three velocities to be read from the sensors and the rotation of the vehicle to be calculated from the difference in the two x velocity readings.

The transducer was configured as shown in Figure 1: Omni-Directional Whisker Velocimeter. The whip protrudes into the fluid and as the vehicle moves the whip experiences a

FIGURE 1: OMNI-DIRECTIONAL WHISKER VELOCIMETER

(Cut-away view)



force on it. This force and subsequent moment are transmitted through the grip blocks and to the beam element. The aluminum beam element deflects and is strained. A strain gauge is mounted to the aluminum beam element, which provides an analog signal that can be manipulated. The strain gauges used in this design were of two different types. The first type tested was a variable resistance wire strain gauge and the second was a piezoelectric ceramic element.

MATERIALS

The material for the structural components of the sensor was chosen as 6061 T6 aluminum stock, for its machinability, corrosion resistance, and relatively low cost. Stainless steel fasteners were chosen for their corrosion resistance, relatively low cost and high availability. Piezoceramic materials produce a charge and voltage when a stress is applied to them. Alternatively, the piezoceramic acts as an actuator when a voltage is applied to it. The piezoceramic element material chosen was PSI-5A for its temperature insensitivity and relatively high voltage output. A dual layer element offers a higher output voltage and allows more configurations than the single layer. The brass shim was chosen over the stainless steel shim because of its considerably lower cost. Since the unit will be operated in an oil filled canister, seawater will not be in contact with the piezo element making the brass suitable. Although there are ready mount bolt-on piezo configurations available, the more basic piezo unit with the piezoceramic material, brass shim and nickel coating was chosen and decidedly offered a better performance to price ratio. In addition a procedure for the mounting and wiring was developed.

CALCULATIONS

Drag force calculations were based on fluid dynamics. Due to the high stiffness of the whip and beam element there is a negligible amount of deflection. The force on the whip is proportional to the square of the velocity of the fluid from the fluid dynamic's Equation (1), where C_D is a drag coefficient for a smooth circular cylinder based on the Reynolds Number, ρ is the mass density of the fluid, V is the velocity and A is the projected area of the cylinder. Reynolds Number is found from Equation (2), where μ is the dynamic viscosity.

$$Force = \frac{1}{2} C_D \rho V^2 A \qquad \textbf{(1)}$$

$$\mathrm{Re} = \frac{\rho V D}{\mu} \qquad \textbf{(2)}$$

Design of beam element was done using statics and mechanics of solids beam theory. The resultant force and moment calculations determined the deflection of the whip and beam elements and maximum strain on the beam. The design criterion was the maximum allowable strain of the piezoelectric element, which was 0.0005 in/in. The necessary clearances were calculated and final dimensions determined.

FABRICATION

The Mechanical Engineering Department's Machine Shop was used for fabrication of the prototype whisker assembly, according to design. A Bridgeport end mill was used to machine the grip-blocks and beam elements to the specified dimensions. A drill press was used to create the necessary fastener holes and selected taps were used to create the required threading for the fastener hardware.

The wire strain gauge mounting & wiring procedure is described next. Two wire type strain gauges were mounted to the beam element using "superglue." One strain gauge was mounted to each side of the beam and wired into a wheatstone bridge. This type of double bridge configuration allowed for automatic cancellation of varying thermal effects and does require a DC voltage source between 1 to 5 V to power the wheatstone bridge.

The piezo strain gauge soldering procedure started with a small 30-gauge wire soldered to the nickel-plated piezo element. The nickel plating required the use of flux to achieve a good solder joint. The flat piezo element was sandwiched between two flat heat sinks to reduce the heat-affected zone of the element. High temperature in the soldering range can cause depoling of the piezoceramic material altering the voltage and charge output drastically and cause nonuniformity. Each side of the dual element required the attachment of a wire lead, so the element was no longer flat. A dish-like groove was milled out of the aluminum beam element so that the piezo element could lay flat as shown in Figure 2: Beam Element with Dish-like Groove Removed. This prevented the soldered joint from coming into contact with the aluminum and creating an electrical conduction.

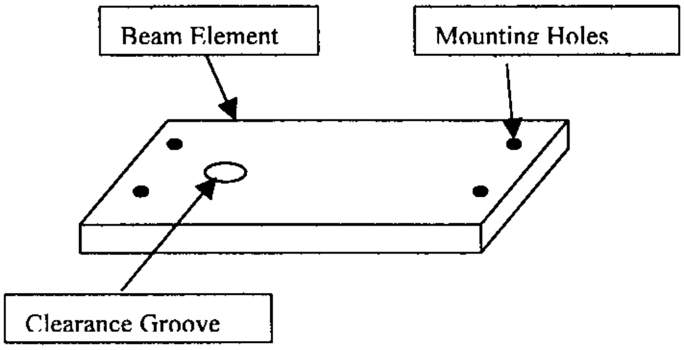


Figure 2: Beam Element with Dish-like Groove Removed

The piezo strain gauge mounting procedure required that the aluminum beam element be prepared for the piezo element. This included first sanding the area to which the element would be mounted. Second, the area was cleaned with acetone to remove all particles of material and contaminants. Third, a thin coat of cyanoacrylate "superglue" was applied to serve as an electrical insulator. The piezo element was then mounted to the aluminum beam element. It was lightly coated on the underside with "superglue" and pressed firmly down in place to end up with a thin film of adhesive between the beam and piezo element. The adhesive was allowed to cure fully and a voltmeter was used to check to see if electrical insulation from the aluminum beam element was achieved.

To access the center brass shim of the piezo element an area of the nickel coating and ceramic material had to be removed from one end. Using a precision 5/64" mill bit, 8 thousandths of material was removed until a clean surface of brass was reached. An area of 3/16" X 3/16" was removed to provide a surface suitable for soldering. The center shim lead was soldered in place.

DATA ANALYSIS

LabView vi readings and Excel calculations were done with the aid of a 16 bit Texas Instruments analog to digital converter, combined with a Macintosh computer to achieve a digital signal and exportable spreadsheet file. As shown in Figure 3: LabView Panel the readings are displayed in voltage versus time. The voltage is directly proportional to the force exerted on the whip for the variable resistance wire strain gauge. The piezoelectric strain gauge required further calculations on Excel to sum the voltage output. The resolution that LABVIEW offers meets the requirements of voltage continuity thereby eliminating errors due to loss of data caused by too few data points. Microsoft Excel was used to determine the force exerted on the whip based on accumulated charge and voltage produced by the piezoelectric element.

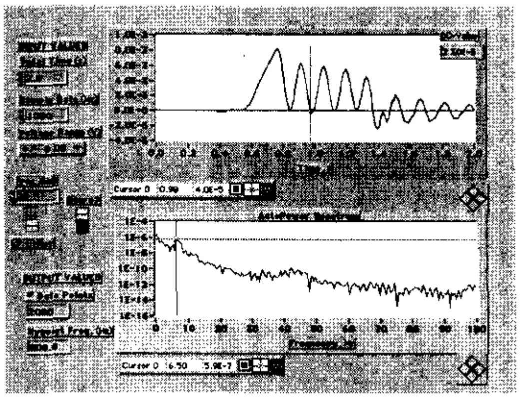


Figure 3: LabView Panel Used for Analysis

EXPERIMENTAL RESULTS

The bench tests of the transducer with the resistance strain gauge showed an overall accuracy of 0.995% when tested within the force calibration range. The bench test of the piezoelectric element showed extremely sensitivity to vibration and force that the resistance strain gauge gave no reading for. Maximum instantaneous voltage output of the piezo was ±0.800 mV. The natural frequency of the system calculated from a step input was approximately 12 Hz.

DISCUSSION

The piezoelectric element creates a charge and an associated voltage due to the mechanical strain input. The total amount of charge produced by the piezo theoretically determines the current status of the element. The piezoceramic material experiences a complete voltage/charge leakage in less than 0.1 second. Therefore, the voltage across the piezo must be recorded continuously and summed to determine the status of the element. The LABVIEW and A/D board combined to introduce an error of ±0.01 mV. The maximum values produced by the piezo element were of the order of ±0.8 mV, which corresponds to 1.25% error. To account for the piezo voltage continuously a sampling rate between 1000 – 4000 Hz was used. Summation of 1.25% error 4000 times per second resulted in unusable readings.

CONCLUSION

The wire type strain gauge offers very good results for accurate force-velocity readings. The piezoelectric strain gauge offers superior sensitivity, approximately 50 times, but the problem of voltage leakage and the inaccuracies of the analyzing equipment proved to offer a formidable challenge. The piezoelectric element demonstrated the greatest ability to sense the smallest changes in force and hence the potential for a superior sensor but the accumulation of error still needs to be resolved.

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REFERENCES

Chaudhry, Z. and C. A. Rogers, 1993. "Enhancing Induced Strain Actuator Authority Through Discrete Attachment to Structural Elements," *AIAA Journal*, Vol. 31, No. 7, July 1993, pp. 1287-1292.

Fox Robert W., and McDonald Alan T. (1999) *Introduction to Fluid Mechanics*, 5th edition, John Wiley & Sons, Inc., New York.

Gere James M. and Timoshenko Stephen P. (1997) *Mechanics of Materials*, 4th edition, PWS Publishing Company, Boston.

Riley, William F., and Sturges Leroy D. (1996) *Engineering Mechanics: Statics*, 2nd edition, John Wiley & Sons, Inc., New York.