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Deep Ocean Applications of Rotational Position Sensors

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The successful conquest of the ocean depths requires technological advances in many areas, that can not be achieved without the adaptation of proven state-of-the-art technologies and mechanisms to developmental systems. One such area of concern is rotary position sensing in components such as manipulators, rotational thrusters, TV pan and tilt mechanisms, etc. The most common sensor used has been a potentiometer, however, the state-of-the-art has advanced considerably in this area. With the increased use of robotic systems in this country and throughout the world, newer and more accurate rotary position sensors are being developed. Therefore, the question facing the engineer is whether or not these sensors can be adapted to the high pressure, oil-filled environment required for operation in the deep ocean. In order to answer this question, position sensors representing the different types available such as optical encoders, synchros, potentiometers, etc., were acquired and tested to 10,000 psi operating pressure while in an oil environment. This paper presents a brief description and comparison of these position sensors, the test results, conclusions and recommendations.

INTRODUCTION

The United States Navy has spearheaded a pioneering effort in the development of undersea systems. This is quite evident at the Naval Ocean Systems Center (NOSC) where the development and testing of manned and unmanned undersea vehicles has been continuing for the last two decades. These vehicles range from very small inspection systems which are no more than a "flying eyeball" up to complex, multi-manipulator work vehicles as shown in Figure 1. When the complexity of the system increases, the reliability often goes down. Therefore, it is mandatory to choose the most reliable components available within the state-of-the-art, assuming all other criteria in the tradeoff are equal.

The future development of advanced undersea vehicles and work systems will draw heavily upon computer technology. Under computer control, great strides can be taken in the area of optimizing undersea work system design. For example, tool exchanges can be performed automatically, the manipulator can be directed to follow a critical path, and the TV camera pan and tilt mechanism can be programmed to automatically follow the manipulator. However, the computer will be totally useless unless the position input to it is accurate. The primary method of providing this position feedback is by detecting a relative rotational position between components. In the past, this position sensing was usually provided through the application of potentiometers. The determination of whether this is still the best approach for deep ocean position sensing is the goal of this test series.

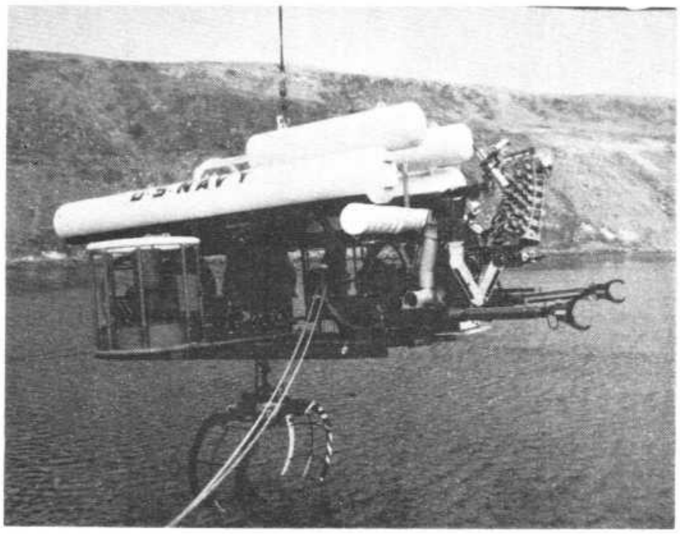

Fig. 1. Work Systems Package Mounted on Pontoon Implacement Vehicle

Although a search of literature and manufacturer's data has provided the information on the principle of operation of various types of sensors and relative advantages and disadvantages, it revealed relatively no information concerning the pressure tolerance of these sensors. In order to determine their adaptability to high pressure (10,000 psi), a series of tests was performed on several sensors to determine their survivability and performance under simulated deep ocean conditions.

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ROTATIONAL POSITION SENSORS IN UNDERWATER SYSTEMS

The Need for Rotational Sensors

The design of advanced work systems, as currently envisioned, will incorporate a microprocessor based position control system for the manipulators and TV pan and tilt systems. Such a system requires feedback of accurate position data to the computer. A feedback control system is one in which the actual system response is compared with the desired response, or command, and appropriate control action is taken (Figure 2). An output signal is subtracted from the command signal, generating an error signal. The compensation system uses the error signal to generate a command to an effector. The effector then modifies the system output (1).

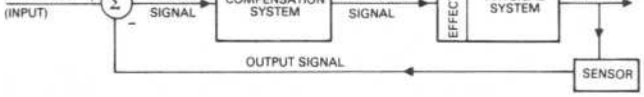

Fig. 2. Feedback Control System

The object of the manipulator or camera pan and tilt feedback system is to control the spatial and/or rotational position of the working member (i.e., the claw or camera). Any sensor system which accurately determines these parameters could be used to produce the feedback signal. Sensing the rotational position of each joint of the manipulator and applying suitable coordinate transformations produces the required position information. An example of such a system would be the camera pan control system. The system consists of a hydraulic actuator to rotate the camera (effector), a rotational position sensor (generating the output feedback signal), the microprocessor (the compensation system), and a joystick (for command input).

While sensing rotational joint position is not the only means of providing position feedback, it has been used extensively in the past in manipulator systems and appears to offer the simplest means of fulfilling the requirements imposed by such a system.

Environmental and Resolution Requirements

The overriding constraint on any system designed for a deep ocean application is the need to survive extremely high pressures in an oil filled environment. A system lacking this pressure tolerance must be housed in a heavy, thick-walled, vessel to maintain atmospheric pressure. Size and weight restrictions usually preclude the use of such pressure housings for rotational position sensors. Therefore, pressure tolerant systems have been developed which are subjected to the ambient pressure while separated from the seawater by an oil environment. This environment can be provided by placing the sensor inside an oil filled system or enclosing it separately in its own housing. However, due to the compressibility of the oil, the oil-filled housing must be attached to its own reservoir which can compensate for the oil volume change with increasing pressure. This can be performed by providing pressure compensators designed specifically for this purpose or by attaching to the hydraulic system's low pressure return line which has its own compensation system.

Angular resolution tolerance for rotational sensors is dictated by the spatial resolution tolerance placed on the manipulator at full extension. Quarter inch spatial resolution of a 6-1/2 foot arm requires approximately .08 degree angular resolution.

There are several other criteria, not rigidly defined, to be traded off before final selection is made. Among these are:

Package - A relatively large diameter, thin sensor package that could be mounted inside the manipulator housing, might be preferable to a smaller volume package that had to be mounted externally. The preferred configuration will depend on the overall manipulator design. Weight is also an important criterion. Since the sensors will be mounted along the manipulator arm, this weight will generate proportionately larger moments when the arm is fully extended.

Signal Noise Tolerance - The ambient electro-magnetic (E/M) noise environment seen by sensors and their data lines depends on the final configuration of the manipulator arm but will include lines carrying command signals to hydraulic actuator valving in the arm. Sensor data lines must be protected from both induced noise from the environment and cross talk among data lines. Various sensor signals have differing noise susceptibility characteristics and thus differing requirements for shielding and/or isolation.

Mechanical Ruggedness - The sensor must be able to withstand mechanical shock, vibration, and shaft loading induced through vehicle handling and manipulator operation. This is a function of both the inherent toughness of the sensor and the method of mounting.

Electrical Lead Requirements - Electrical leads to the sensors, whether power, ground or data, will require slip rings or flexible connectors at each articulated joint. Thus, minimizing the number of leads required simplifies the mechanical design. Also, a sensor that requires electrical leads to only one side of the component reduces by one the number of joints that must be crossed by the leads.

TYPES OF ROTATIONAL POSITION SENSORS

Rotational position sensors can be broken down into two broad categories: incremental and absolute. Incremental sensors detect reference points on a rotating member moving past the sensor which is mounted on the stationary member. Absolute sensors operate on a variety of principles.

Incremental Sensors

Incremental sensors require a counter and a method for establishing a zero or reference position to count from. If interfacing with a digital system, signals from incremental sensors are readily handled by a microprocessor with little additional hardware; interface with an analog system requires additional counting and Analog-to-Digital (A/D) hardware. Most of these sensors require zeroing each time data is lost (through power down, signal loss, etc.); however, once zeroed, they need no further calibration since the ratio of reference points to angular position increments is fixed by the geometry of the system. Incremental sensors also require a method of debouncing the signal, i.e., rejecting spurious counts caused when a reference point spends a finite amount of time near the sensors detection limit.

Proximity Switch

A proximity switch can be used to detect gear teeth passing the face of the sensor. In general, proximity switches operate by detecting changes in a Radio/Frequency (R/F) or magnetic field caused by the approach of a conductive or ferromagnetic material. Some sensor packages include a solid state R/F oscillator which generates the required field while others need a magnet or other external field source. Most sensor packages include a Schmitt trigger or similar circuit to debounce the signal.

A typical commercially available proximity switch has a detection range of approximately .1 in. which produces a resolution of .2 in. for a complete on-off cycle. If the targets being detected are teeth on a revolving gear, the angular resolution can be readily calculated. For example, a 3 in. diameter gear produces an angular resolution of 7.6 degrees. Thus, to achieve the resolution needed for any but the coarsest position feedback, an auxiliary gear train is required with the sensor detecting teeth on the high speed gear.

Proximity switches are, in general, rugged, compact and easy to mount. Typical packages are 2 in. long by 1/4 in. diameter threaded barrel and 1/4 in. square solid plastic dual-in-line packages (D/P). Most can be operated with data line levels to 15 volts and are thus reasonably noise tolerant. Generally, proximity switches require three leads: power, ground and data.

Incremental Optical Encoders

An optical encoder consists basically of a light emitting diode-photo detector pair sensing alternating strips of transparent and opaque material on a rotating disc. An incremental encoder, as described here, senses only relative changes in angular position. Another type of optical encoder, the absolute encoder, is described later in this paper.

Optical encoders are available commercially in packages which include the optics and electronics necessary for compatibility with most types of solid state circuitry. These sensors provide as many as 2500 cycles per revolution giving about 1/7 degree resolution, and, like proximity switches, are reasonably noise tolerant. A typical package is a 2 in. - 2-1/2 in. diameter can, .75 in. - 1.0 in. thick.

Incremental encoders are available with a variety of features:

- single data line, providing count signal only
- two data lines, providing count and direction information
- three data lines, providing count, direction and zero reference.

Power and ground lines are required in addition to data lines. None of these lines need to cross the joint the sensor is mounted on.

Optical encoders have poor tolerance for axial or bending shaft loading. This shortcoming can be overcome via compliant mounting or shaft coupling techniques.

Absolute Sensors

Absolute rotational position sensors operate on a wide variety of principles. They provide rotational position data without the need for a zero reference point. The types of sensors described here are synchro-resolver, precision potentiometer, absolute optical shaft encoder and strain gauge-eccentric cam.

Synchro-Resolver

A precision resolver is a rotatable electromagnetic device which provides an output voltage proportional to the sine or cosine of the input shaft position. A resolver is similar to a transformer; a wound stator is excited with an alternating voltage. The resultant magnetic field is coupled to a multi-phase wound rotor and the voltage induced in each phase is proportional to the sine or cosine of the relative angle. The angle is then defined by the ratio of voltages in the phases. Commercially available single chip solid state devices are available to convert the rotor signal to a digital output if needed.

The raw output signal from a resolver is an alternating voltage at the same frequency as the excitation voltage. Thus, with accurate bandpass filtering at the receiver, the signal is extremely noise tolerant. Resolvers are mechanically simple and can be built with a high degree of accuracy. Resolvers are available commercially with accuracies as high as 3 arc seconds, or about .0008 degree of arc. Resolver packaging is very flexible; commercial, sealed package resolvers are available as small as 1-3/4 in. long by 1 in. diameter, weighing a few ounces. Resolvers are also available unsealed, just the rotor and stator, for mounting directly on the rotating device; however, in this configuration, the rotor-stator concentricity tolerances are quite tight (approximately .0002 - .0003 inches). Compared to other types of position sensors, resolvers require a large number of electrical connections, from a minimum of five to as many as eight or nine. Of all the types of sensors examined in this study, resolvers are the most expensive.

Precision Potentiometers

Precision potentiometers have been used widely for angular position measurement. Potentiometers are generally simple and inexpensive. They are available with virtually infinite resolution and excellent accuracy.

Generally, when used as position sensors, potentiometers are configured as voltage dividers, rather than as variable resistors. In this configuration they require three leads: power, ground and data. No leads need to cross the joint the potentiometer is mounted on although mechanical attachment is required on both sides. When used in an analog control system, the potentiometer output signal can be compared with an input signal to generate an error signal. In a digital system a simple low speed analog/digital convertor is required for interface. The output signal has a high degree of noise tolerance.

Potentiometers were used for position feedback on the camera pan and tilt mechanism of the Work Systems Package (WSP) developed at NOSC. During at-sea testing problems were encountered in the pan and tilt control system, several of which appeared to be caused by potentiometer failure or inaccuracy. (2) However, potentiometers have been successfully used on systems such as the Remote Unmanned Work System (RUWS) developed by NOSC and the Deep Submergence Rescue Vehicle (DSRV) (3).

Absolute Optical Encoders

Absolute optical encoders contain multiple photo detectors sensing alternating strips of transparent and opaque material on a rotating disc. Each detector contributes a bit, i.e., a factor of two, to the resolution of the sensor. Commercial encoders are available with as high as 14 bit resolution or about .02 degree. Absolute encoders interface easily with digital systems; interface with analog systems requires digital/analog conversion. Several different output data codes are available. Among them are natural binary and gray code which changes only one bit from one encoded angle to the next, thus eliminating ambiguity at points where the values change.

Absolute encoders have several disadvantages from a designers point of view when size, weight or complexity are factors. Each photo detector requires a data transmission line: for example, a twelve bit encoder requires twelve data lines. Alternatively, the parallel data can be converted to serial form and transmitted over a single data line. This approach involves added complexity in timing and data management. Absolute encoders, especially those with higher resolution, tend to be bulkier and heavier than other types of sensors. A typical commercial model with 1024 counts per revolution (about 1/3 degree resolution) is a can 2-1/2 in. diameter by 3 in. long. A model with 4096 counts per revolution (about .09 degree resolution) is a can 3-1/2 in. diameter by 5 in. long weighing four pounds.

Strain Gauge - Eccentric Cam

A unique type of rotational position sensor is being investigated at NOSC. It involves an eccentric cam mounted on the rotating member and a flexible cam follower with strain gauges.

Figure 3 shows the physical layout of the device. For machining simplicity during these tests, the cam used is a simple circular disc with the axis of rotation not concentric with the center of the disc. The signal produced by this configuration is a sinusoidal function of rotational angle. Different angular functions can be generated (e.g., linear) simply by modifying the shape of the cam. The strain gauges are configured in a full bridge with A_1 and A_2 the active gauges, C_1 and C_2 the compensating gauges (Figure 4).

The strain gauge rotational position sensor is simple, compact and easy to mount. One advantage is that no electrical or mechanical connections cross the joint. The device requires improvement in accuracy and noise tolerance, but initial tests indicate it as a viable method of position sensing. These tests are described later.

HIGH PRESSURE SENSOR TESTING

Apparatus and Procedure

Several rotational position sensors were tested at 10,000 psi. The test apparatus consisted of a fixture mounting a stepping motor, a 19.75:1 speed reducing gear train and an adaptor plate to mate with the various sensors (Figure 5). The motor was operated with a step size of 1.8 degree producing an angular resolution of approximately .1 degree at the output of the gear train. The entire fixture was immersed in an oil-filled, pressure compensated container which was then placed in a high pressure test chamber (Figure 6). The compensating fluid was Bray Oil Co., MIL-H-5606 Hydraulic Fluid. Initial tests confirmed the compatibility of the stepping motor with the high pressure, oil environment.

Each sensor was bench tested in the oil-filled enclosure prior to pressurization to obtain baseline data. The system was then pressurized to 10,000 psig and sensor operation tested. Pressure was then cycled from 10,000 to 0 psig five times, and held at 10,000 psig for one hour during the last cycle. Sensor operation was tested periodically during the cycling.

Results

The results of the pressure tests follow. Where sufficient data is available, the pressurization test results are compared to the baseline data. Unfortunately, the entire test series has not been completed prior to the publication of this paper; therefore, future test plans and recommendations are presented where applicable.

Proximity Switch

A proximity switch of the type using an Radio-Frequency (R/F) oscillator to produce eddy currents

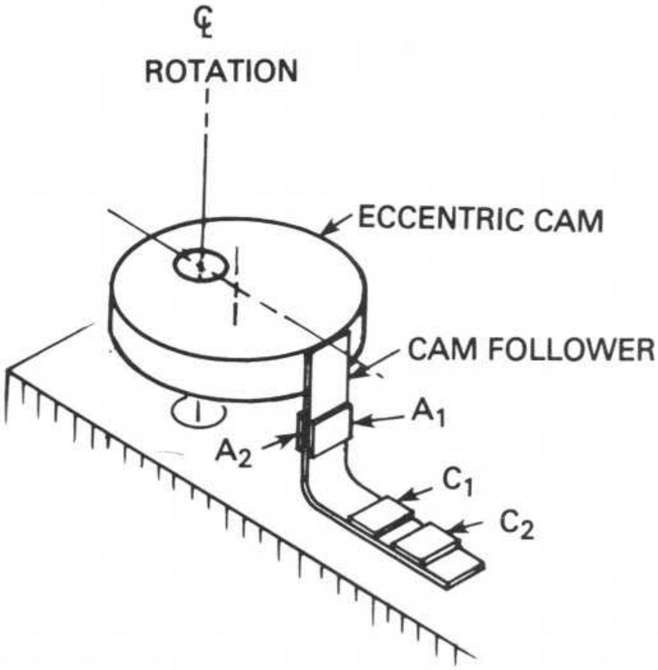

Fig. 3. Strain Gauge Rotational Position Sensor

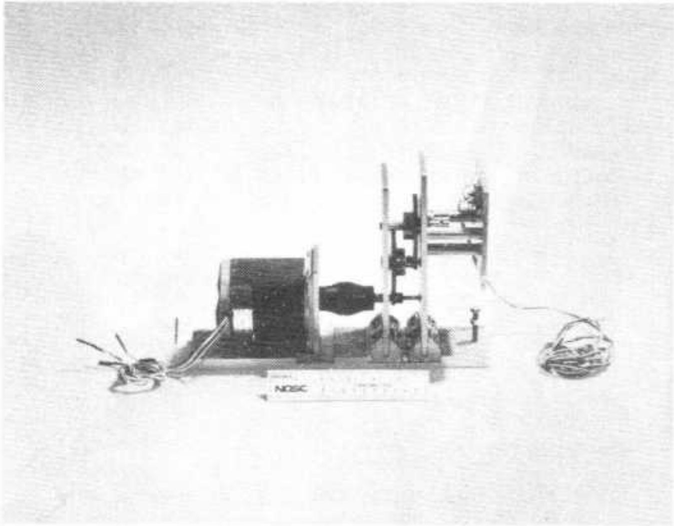

Fig. 5. Rotational Position Sensor Test Fixture

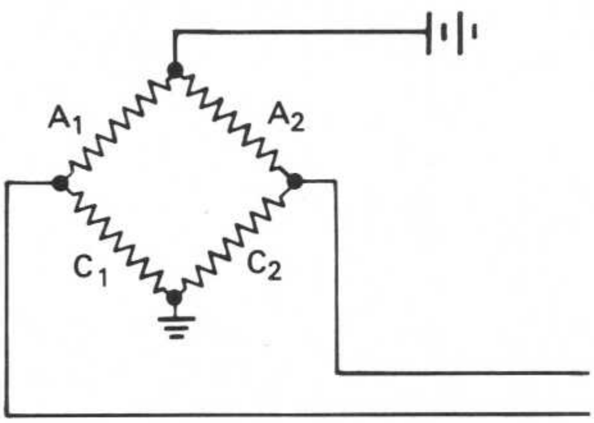

Fig. 4. Strain Gauge Bridge Diagram

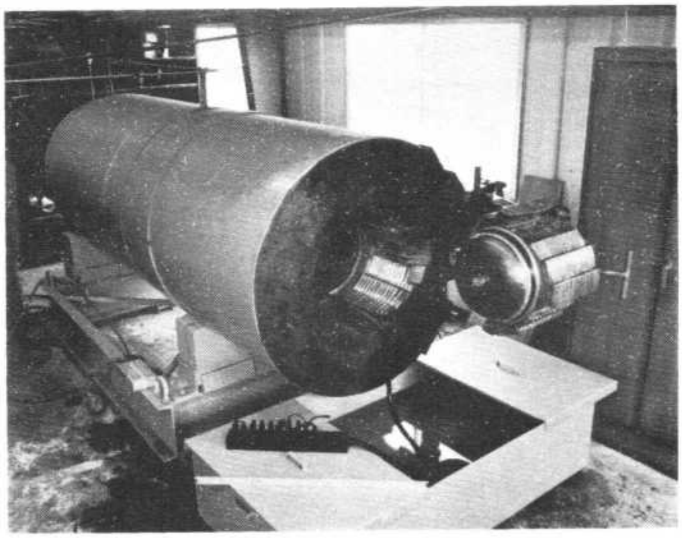

Fig. 6. NOSC High Pressure Test Chamber

in conductive material was the first sensor tested (Turck Multiprox Model BIGA 1). When pressurized to 10,000 psi it operated well for several minutes. Operation then became intermittent and the sensor failed completely after about fifteen minutes at pressure.

Subsequent disassembly by the manufacturer revealed that oil had penetrated into micro voids inside the sensor potting material. The R/F oscillator generated sufficient eddy currents in this oil to cause the sensor to remain "on" continuously. Although the manufacturer has operated similar sensors under comparable pressures in a gaseous environment, it is their opinion that the proximity sensor may not be compatible with the high pressure, oil- filled envrionment.

Although special potting procedures may correct the problem associated with the proximity sensor, it is not felt that the resolution available from this type of sensor warrants the developmental effort. Therefore, further testing of this device is not recommended.

Incremental Optical Encoder

Because of backlash in the test fixture gear train, bench tests of the optical encoder (Litton 70-LD-BI2500-1-1-1 Incremental) failed to produce data that agreed with predictions. "Bouncing" due to the gear backlash caused the encoder to produce spurious counts. Paradoxically, when immersed in oil, the bouncing was damped enough that data in good agreement with predictions were obtained. However, the encoder survived only a few minutes at 10,000 psi and then failed completely. The sensor is presently being returned to the manufacturer to determine the cause of failure. Although the sensor failed after a short period at pressure, the fact that it operated satisfactorily in the oil environment is encouraging. Its high degree of utilization in the area of industrial robots, when combined with its inherent accuracy, reinforces its potential application to deep ocean systems. Because of its larger size, as compared to some of the other sensors, it may be limited in its application; however, it is recommended that an additional series of tests be performed on it, contingent on encouraging results from the manufacturer.

Precision Potentiometer

The type of precision potentiometer used was a New England Instrument 78ESA102-1K ohm Econopot. In both bench and pressure tests the potentiometer exhibited excellent linearity and repeatability (Figure 7). In addition to surviving the high pressure test, the potentiometer used had spent some eighteen months submerged in the 5606 hydraulic fluid of an existing pan and tilt system.

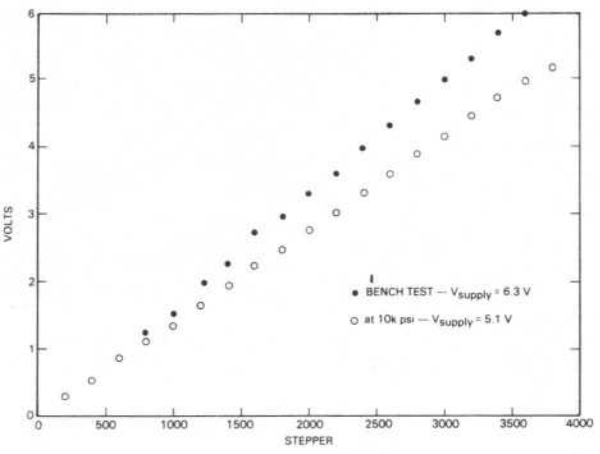

Fig. 7. Potentiometer Test Results

The intermittent problems previously experienced with potentiometer based feedback systems remains unexplained. Potential problems may involve material compatibility with oil of certain types of potentiometers or possible contamination of them during modification for pressure compensation. Therefore, it is recommended that a study be performed on oil compatibility and proper modification procedures of the various types of potentiometers available, as opposed to further high pressure tests.

Strain Gauge-Eccentric Cam

The bench tests of the strain gauge rotational position sensor, which utilized minimum length leads from the sensor to the bridge, agreed well with theoretical predictions, i.e., was sinusoidal. However, when the device was tested in the pressure chamber with its attendant long unshielded data leads and pressure vessel penetrators, the data exhibited considerable drift and poor repeatability. This occurred both at ambient and 10,000 psi pressure (Figure 8).

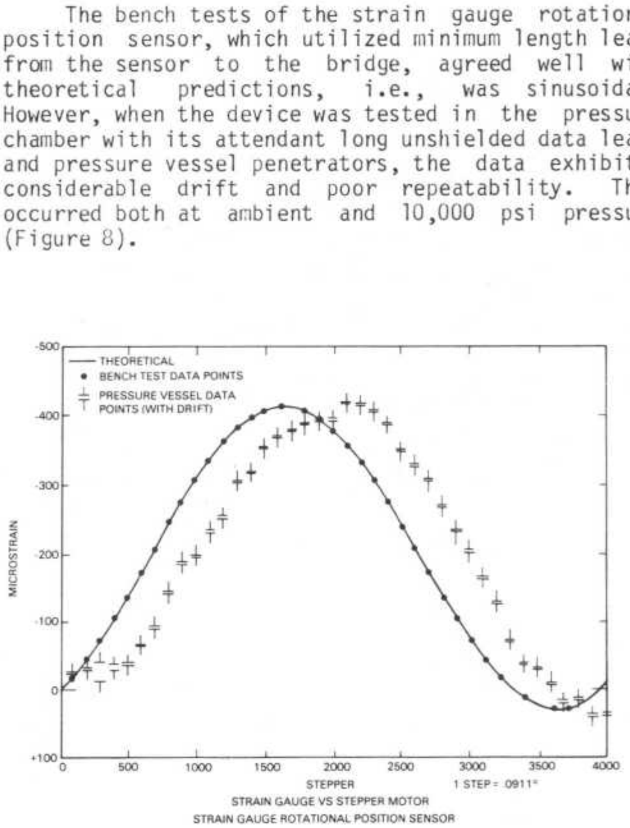

Fig. 8. Strain Gauge Rotational Position Test Results

Since raw strain gauge signals are extremely small (a few millivolts), it appears it will be necessary to amplify them before transmission more than a few inches in a noisy environment. It is recommended that an additional series of tests be performed with the inclusion of an operational amplifier at the sensor. The reconfiguration would require five leads: strain gauge power and ground, plus/minus 15 volts supply to the operational amplifier and the data line. If the strain gauge bridge were configured to accept plus/minus 15 volts, the number of leads would be reduced to three.

CONCLUSIONS AND RECOMMENDATIONS

Five rotational position sensors were investigated as candidates for use in advanced undersea systems. The five were synchro-resolver, R/F proximity sensor, precision potentiometer, optical encoder and a developmental sensor employing strain gauges.

As part of the investigation, four of the sensors, all but the synchro-resolver, which was late in delivery, were tested to 10,000 psi in an oil-filled environment. Of the four, only the precision potentiometer performed satisfactorily. The proximity sensor and optical encoder operated temporarily at pressure, then failed completely. The strain gauge sensor survived exposure to high pressure, but, due to signal transmission problems, did not give satisfactory data while in the test fixture.

Based on test results to date, precision potentiometers are the recommended rotational position sensors for high pressure, oil-filled environments. However, additional investigations addressing their adaptability to and compatibility with oil compensation should be conducted. Further development of the strain gauge sensor is recommended since transmission of strain gauge signals is a well practiced art and the problems encountered should be easily solved. Although methods of adapting the proximity sensor and optical encoder to the high pressure oil evironment may exist only the optical encoder has adequate resolution to warrant additional testing.

Final results of all tests, to include those not completed in time for this paper, will be available from the authors at a later date.

REFERENCES

1. Uhrich, R.W., "Manipulator Development at the Naval Undersea Center," NUC TP 553, January 1977

2. Wernli, R.L., "Work Systems Package/Pontoon Implacement Vehicle Operational Testing at San Clemente Island 1979," NOSC TR 553, 6 June 1980

3. Technical Manual for DSRV Operations, NAVSHIPS 0950-003-3010.

LIST OF FIGURES

TABLE OF CONVERSION

ft = feet; equals 30.48 cm

in. = inches; equals 2.54 cm

psi = pounds per square inch; equals 0.070 kg/cm^2

lb = pounds; equals .4536 kg