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TECHNICAL REPORT

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A PENDULUM INCLINOMETER FOR USE WITH SMALL DEEP-SUBMERSIBLES*

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Abstract—The authors developed a pendulum inclinometer suitable for use with small deep-submersibles or surface craft. The instrument uses a relatively short heavy pendulum and a viscous damping system for minimizing the effects of unwanted oscillatory motion. The pendulum relative motion is transmitted to the dial pointer through a flexible cord. The mechanism is designed so that the inclinometer gives a direct reading of the tangent of the angle of inclination. Adjustments are provided for levelling the instrument and for setting the dial to zero. Upper and lower clamping devices protect the pendulum suspension from damage during transit. The inclinometer has been used successfully in recent inclining experiments for the small research submarine *Alvin*.

1. INTRODUCTION

TO DETERMINE the stability of surface ships and submarines, inclining experiments are conducted in which a series of known weights are positioned a known distance, port and starboard, from the craft's longitudinal centerline plane. Inclining angles are very small, usually less than 3 deg. Inclining moments and tangents of the angles of inclination are used to calculate the metacentric height, a measure of the vessel's stability. Various means have been employed to measure inclining angles but these are not generally suitable for the typical small research submarine.

On large surface ships inclining angles are commonly measured by suspending a weight or plumb-bob on a string of known length down into the ship's hold or other below-decks space. A horizontal transverse member, fixed to the ship's structure near the lower end, is used for marking or measuring the relative pendulum motion. This method would not be a good one for small craft since the string would have to be short, making the lateral deflection very small.

Large submarines often make use of a spirit level type of inclinometer. This employs a bubble level in combination with a micrometer screw adjustment, and is a precision instrument capable of great accuracy. An inclinometer of this design has been used aboard the small research submarine *Alvin* a number of times without great success. Oscillations of the boat due to minor wave action caused the bubble to range widely from its true position and to go completely off scale part of the time, making accurate angle readings very difficult.

The inclinometer described here was developed for use aboard the submarine *Alvin* and other similar deep-submersibles. Two features common to these deep-diving vehicles are (a) limited personnel space and, (b) ready response to small waves or disturbances in the

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*Contribution No. 3690 from the Woods Hole Oceanographic Institution.

water. A logical design seemed to be one involving a short, heavy pendulum, a mechanism for multiplying its motion and transmitting this motion to a pointer on a calibrated dial, and a viscous damping device for minimizing the instrument's response to unwanted submarine motion. A prototype instrument was built following this general design, and it has been used successfully in recent *Alvin* inclining experiments (Sharp & Doherty, 1973; Sharp, 1975).

2. DESCRIPTION OF INCLINOMETER

A schematic representation of the inclinometer is shown in Fig. 1. The pendulum is a hollow metal cylinder filled with mercury and weighing about 6 lb. It is suspended from a single hardened steel pivot. At the lower end of the pendulum there is mounted a thin metal vane which is oriented broadside to the direction of motion. This vane is immersed in the viscous damping fluid which is contained in a small tank. The pendulum motion is transmitted to the dial pointer by a flexible cord. The cord is attached to a small sliding sleeve on the pendulum shaft, and makes two or three wraps around the grooved drive pulley which rotates the dial pointer. The ends of the cord terminate at small counterweights which maintain cord tension to prevent slippage. A small knob on the instrument's front panel connects to a shaft which is geared to the edge of the dial. This enables the entire face to be rotated through a limited distance for setting the scale to zero. An adjustable friction collar is built into the hub of the dial. This allows the dial to be rotated readily for zero adjustment, but holds it firmly in place after the setting has been made. Items not shown in the diagram are (a) a cross test level which permits levelling the inclinometer in athwartships and fore- and aft-directions, (b) three levelling screws with locking nuts at the base of the instrument, and (c) upper and lower pendulum clamps for use during transit (Fig. 2).

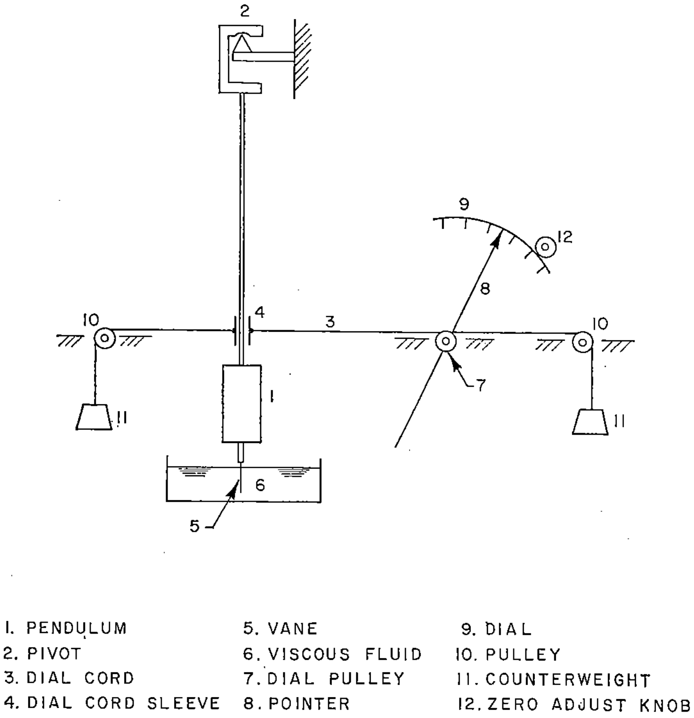

FIG. 1. Schematic arrangement of inclinometer.

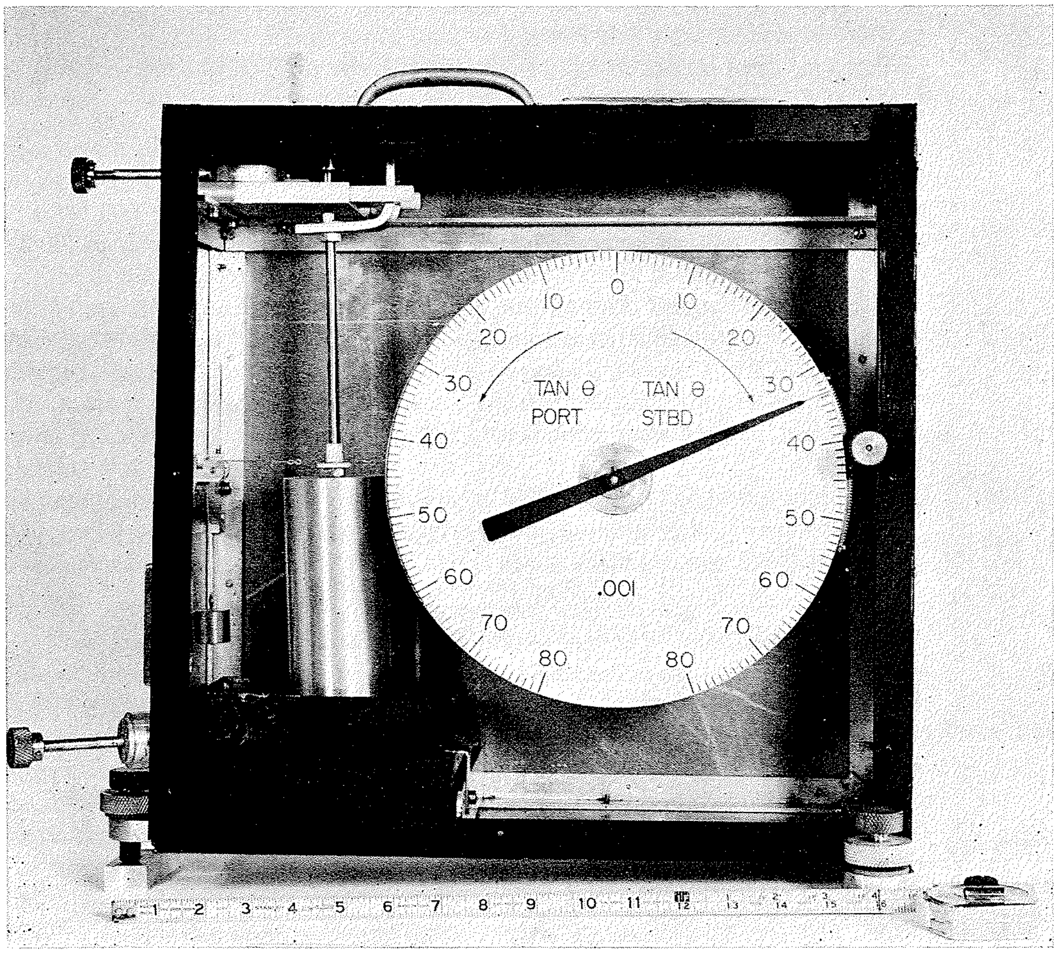

FIG. 2. Prototype inclinometer.

In use the pendulum tends to remain vertical. If the instrument housing is rotated through an angle, its motion, relative to the stationary pendulum, is seen as a movement of the dial pointer. The sliding sleeve on the pendulum shaft allows the cord to remain in a straight line configuration at all times, and the resulting cord motion is proportional to the tangent of the angle of inclination.

The flexible cord originally used was a heavy twisted cotton thread. However, radio receiver dial cord or braided cotton fishline are considered superior for this application due to their non-stretch and non-slip characteristics.

A number of viscous liquids have been found to be suitable for the damping system. Glycerin and heavy gear oil both have been used with reasonable success. The automotive engine oil additives (such as STP) or some of the silicone fluids, should work very well.

3. CALIBRATION

The base length of the instrument was carefully measured using a surface plate and a vernier height gage. Calibration was accomplished by placing one end of the inclinometer on a fixed table and the other end on a milling machine table whose height is adjustable to within 0·001 in. On a blank dial face, the zero position was marked for the level instrument. Then the milling machine table height was varied in small increments, and for each setting, the pointer position was carefully marked on the dial. Enough increments were read to cover the usable dial space, for both port and starboard inclination. For each setting the height was divided by the base length to give the sine of the angle. From this, the angle itself and the tangent of the angle were calculated. The dial markings showed the instrument to be essentially linear throughout its range, and provided the scale constant needed to lay out the finished dial.

It was found that a range of values for $\tan \theta$ up to 0·080, to port and to starboard, would nearly fill the dial. In tests with *Alvin* the maximum inclination reading has been about 0·040, while the recommended maximum for small craft is about 0·050 (Moore, 1967).

4. DISCUSSION

While the present instrument was designed and built to be used with the deep-submersible *Alvin*, it is self-contained and easily transported, and so can be used aboard other submersibles or surface vessels. The objective was to provide a device which would have sufficient accuracy and sensitivity for the tests in question, but which could be simple and rugged enough to withstand possible rough handling and resist potential damage from seawater. The selection of the single-point suspension for the pendulum and the use of simple Teflon sleeve bearings for the pulleys seemed a most logical way to meet those requirements. The single point pivot is exceptionally friction-free and is easily cleaned and mainmaintained, while the non-metallic sleeve bearings need no lubrication and are unaffected by salt water spray or splash.

The use of a flexible cord to transmit the pendulum motion has the advantage of being simple and low in mass. A linkage of rigid members would be heavier and would require additional bearings or pin connections. The possibility of slippage of the cord on the dial pulley was not overlooked, but the use of several wraps of cord around the helically-grooved pulley and the use of weights to maintain cord tension, have practically eliminated the chance of slippage.

Some of the advantages claimed for the present design are:

(a) the instrument is direct-reading,

(b) pointer motion is exactly proportional to the tangent of the inclination angle,

(c) the large dial can be read easily in a small or crowded work space,
(d) the viscous damping makes possible more accurate readings.

A simple test indicated the effectiveness of the damping system. Before the damping fluid was placed in its container the pendulum was deflected to approximately a full scale position and released. The mechanism oscillated through about 9 full cycles before coming to rest. After the fluid had been added, the same test procedure resulted in only slightly more than one cycle of motion.

For the small angles encountered in the inclining experiments, the angle (in radians), the tangent of the angle, and the sine of the angle are all very nearly equal. Therefore a simpler method of attaching the cord to the pendulum was investigated (see Fig. 4). The motion produced by this method is very nearly proportional to the sine of the angle of inclination, and in most cases the value is close enough to the tangent of the angle to be acceptable. For angles in the upper portion of the range (from about 0·050–0·080) this approximation is no longer quite such a close one, and for these angles the original cord configuration shown in Fig. 3 should be used.

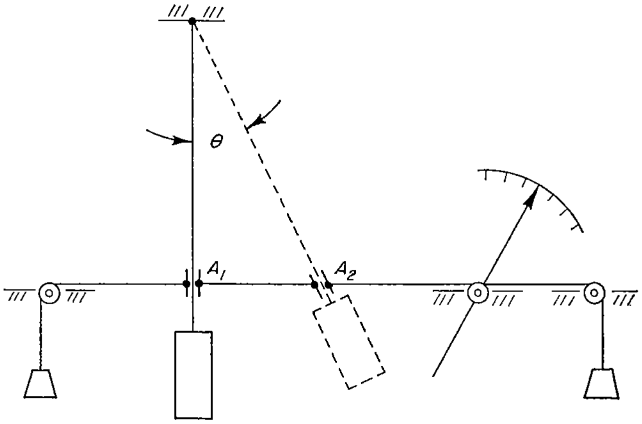

FIG. 3. Cord attached to sliding sleeve on pendulum shaft.

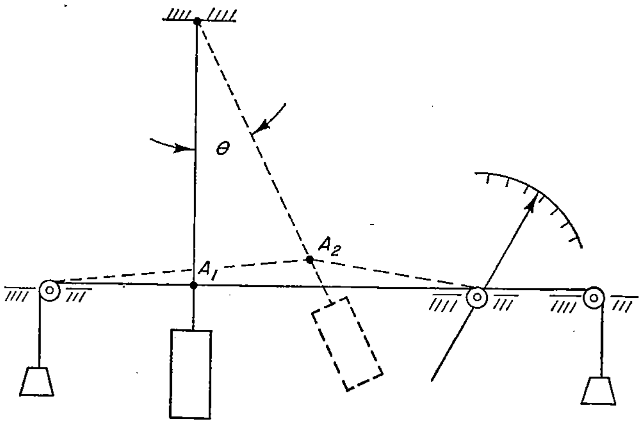

FIG. 4. Cord fixed to pendulum shaft at point A.

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Sharp, A. G. 1975. *DSRV Alvin Weight Report*, 1975, Woods Hole Oceanographic Institution Technical Memorandum No. 5-75.

APPENDIX A—INSTRUMENT GEOMETRY

Two methods were used for attaching the drive cord to the pendulum, and the results were essentially the same for both. In the first case, a light-weight Teflon sliding sleeve was mounted on the pendulum shaft and the dial cord was attached to it (Fig. 3). As the pendulum angle increases, the sleeve slides along the shaft, increasing the effective pendulum length, and allowing the cord to remain in a straight-line configuration. This method produces motion which is exactly proportional to the tangent of the pendulum angle. In the second method, a simpler one, the cord was attached directly to the pendulum shaft, at a point level with the dial pulley. Here, the cord attachment point follows the motion of the pendulum and travels through a circular arc (Fig. 4). The resulting cord motion is one which is very nearly sinusoidal, a slight error being caused by cord angularity. Calculations were done to compare the motion obtained by this means with true sinusoidal motion (as might be achieved by incorporating some form of scotch yoke mechanism). Over the range of angles covered by this instrument the maximum error is $< 0{\cdot}01\,\%$. Also very small is the error incurred in producing sinusoidal motion as an approximation to the correct tangent motion. At 0·04 rad., the usual upper limit in the *Alvin* tests, this error is about 0·08 % (less than one-tenth of a dial division for the instrument described here).

APPENDIX B—SAMPLE TEST RESULTS

Data obtained in the inclining experiments are used to construct a curve on which tangents of inclination angles are plotted horizontally and inclining moments are plotted vertically. This so-called plot of tangents is drawn for a series of very small angles (about 3 deg maximum) and is for practical purposes a straight line. The metacentric height is given by

$$\overline{GM} = \frac{wd}{W \tan \theta}$$

where w is the inclining weight, d is the inclining moment arm, and W is the vessel's total displacement. A mean value of the fraction $wd/\tan \theta$ can be found by taking the slope of the plot of tangents, and this is then divided by the displacement W to give the value of GM.

The metacentric height GB for a submerged small submarine can be found in a similar way. The vehicle is ballasted to be neutrally buoyant just below the surface of the water, and divers are employed to position the inclining weights.

Fig. 5 is a plot of the results of the *Alvin* surface inclining experiment done on March 23, 1975 (Sharp, 1975).

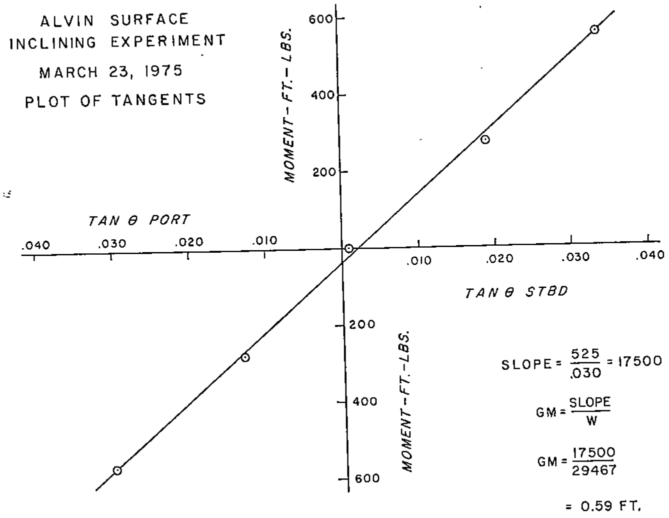

FIG. 5. Plot of tangents.

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