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Special Report 116

PENDULUM STEERING FOR THERMAL PROBES IN GLACIERS

by
Haldor W. C. Aamot

JULY 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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PREFACE

The pendulum steering principle was conceived by Haldor W.C. Aamot during an analysis of problems and methods of stabilizing thermal probes in connection with the development of the Philberth Probe. Problem areas of the lateral heat transfer conditions and the differential temperature control were resolved over the period 1964-1966.

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USA CRREL is an Army Materiel Command laboratory.

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A new concept of attitude stabilization for thermal probes or coring drills in ice eliminates instability. The center of support is placed above the center of gravity. A lower and an upper hot point produce melt penetration. The ratio of their power levels is the basis for stabilization. This is provided by the automatic control of the heater in the upper hot point.

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Introduction

Probes and drills, including coring drills, which penetrate glaciers by melting, require a means of stabilization if the required plumb attitude is to be maintained. They are top heavy because they stand on their tip – the hot point. The hot point is that nearly isothermal part which is heated and which produces melt penetration under its bearing surface. The slightest deviation from vertical results in an increasing tendency of the probe to "lean" and "topple over." This instability must be counteracted unless it can be eliminated.

Mercury steering (Philberth, 1966)* produces a correcting action which opposes any deviation of the probe attitude from vertical.

A new concept, "pendulum steering," proposed by the writer in 1964 and described here, eliminates instability by placing the support point above the center of gravity, i.e., the probe (or drill) "hangs" plumb at all times.

The principle of pendulum steering

With the support point above the center of gravity, the probe is inherently stable. Its attitude is plumb at all times. If deflected by external disturbances, it returns to the vertical attitude like a pendulum.

Even when the support point is located below the center of gravity stability can still be maintained. The requirement is that the metacenter remain above the center of gravity. The term metacenter may be used in this connection if the bearing (supporting) forces are considered synonymous with the buoyancy forces.

The support point is placed above the center of gravity by arranging the load bearing surfaces so that their combined effect, the center of support, is at the necessary height of the probe. This is achieved by either of two methods:

1. The shape of the probe is an inverted cone above the hot point. The cone surfaces are bearing surfaces with most of the weight supported near the top.

2. The probe is cylindrical. The lower section with its circular hot point has a smaller diameter than the upper section whose annular hot point is above the center of gravity and supports most of the probe weight.

Figure 1 illustrates the pendulum steering principle and the two probe configurations.

The second method, using a cylindrical shape and two hot points, is best suited from the standpoint of design and manufacturing and has been selected for this analysis.

The hot points are the bearing surfaces. They are heated for penetration by melting. The melt rate, and thereby the rate of penetration, is controlled

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* Philberth, K. (1966) Sur la stabilisation de la course d'une sonde thermique, Comptes Rendus 262, p. 456-459.

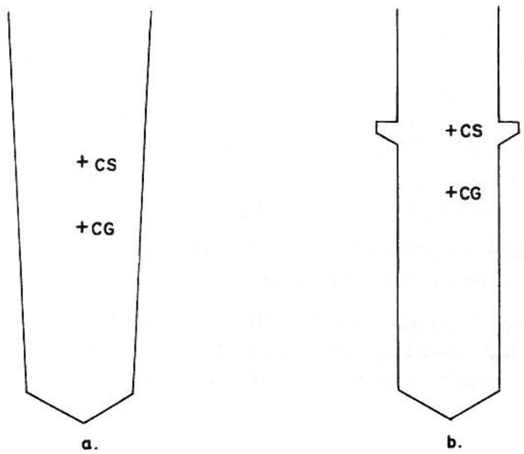

Figure 1. Two probe configurations utilizing pendulum steering are shown. In a. the hot point and the conical wall surfaces are heated for melt penetration. In b. the circular lower hot point and the annular upper hot point are heated for melt penetration. CS= center of support. CG=center of gravity.

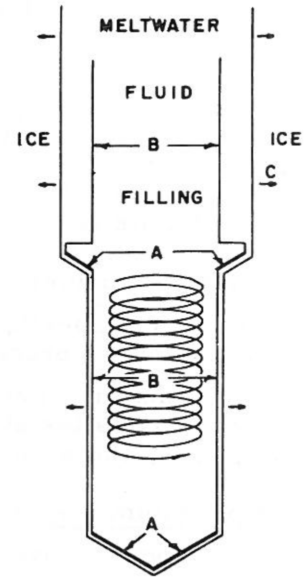

Figure 2. The heat flow pattern of the advancing probe. A: Heat for melt penetration. B: Lateral heat transfer from the probe walls. C: Heat dissipated in the ice.

by the heat input. Both the upper and lower hot points penetrate at the same rate. Therefore, their heat inputs must be correlated. If not balanced, the rate of penetration is determined by the under-heated surface: the under-heated surface supports the greatest load. Most of the load is supported by the upper hot point by intentionally under-heating it. By this means the center of support can be located above the center of gravity.

Shreve (1962)* shows that for equal bearing pressure and equal hot point surface temperature the rate of penetration of flat surfaces is equal. Therefore, if the upper and lower hot point surfaces are kept at equal temperatures, and since they have equal rates of penetration, their bearing pressures will be equal. If, finally, the upper hot point is kept at a slightly lower temperature it will have the greater bearing pressure; for equal bearing areas it will support the greater load.

Thus, as long as the upper hot point temperature is suitably controlled with respect to the lower hot point temperature, the probe is stable at any rate of penetration or ice temperature. These two parameters affect the power requirements of the upper heater relative to the lower one.

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* Shreve, R. L. (1962) Theory of performance of isothermal solid-nose hotpoints boring in temperate ice, Journal of Glaciology, vol. 4, no. 32.

Analysis of the power requirements

Both hot points require power for melt penetration; the amount depends on the rate of penetration and the ice temperature. The side walls of the probe transfer heat to the surrounding melt water and ice; the heat dissipated in the ice is a function of its temperature and the time involved.

Figure 2 illustrates the heat transfer between different parts of the probe - ice - melt water system.

Heat is generated electrically in the hot points with resistive heating elements, and in the conductors by self heating. The conductors consist of insulated cable which is stored in the probe and is payed out as the probe advances. The heat for melting "A" comes directly from the hot points. The heat dissipated laterally in the ice "C" is taken from the melt water.

Most of the heat generated in the stored conductors is transferred to the surrounding melt water. The difference between that heat "B" and the amount dissipated in the ice "C" is represented by the latent heat.

The amount of heat "B" that is transferred laterally to the melt water may be more than is absorbed by the ice. Further melting results in an enlarged hole. If "B" is less, refreezing constricts the hole, leading eventually to stalling of the probe.

The amount of conductor stored and the surrounding ice temperature both change with depth, causing the hole size either to increase or decrease. The power requirements of the upper hot point vary accordingly. The corresponding control of the heater in the upper hot point is the basis for the effective stabilization of the probe or drill.

The upper heater control

The temperature difference between upper and lower hot point is used to provide the controlling signal for the upper heater. The lower heater is held at full load continuously.

Two methods may be used to produce the signal: (1) by using the EMF of a thermocouple between the upper and lower hot point, or (2) by using the unbalanced voltage of a Wheatstone bridge (or half bridge) whose arms are resistors with high temperature coefficient of resistance (TCR), e.g., thermistors. The temperature sensors are suitably located in the hot points near the bearing surfaces.

The signal is a function of the temperature difference. It controls the power of the upper heater either by proportional control, achieved with a power transistor, or on-off control, achieved by actuating a relay or switch (mechanical or solid state).

With proportional control the operating power level stabilizes at a steady value depending on the ice temperature and the applied voltage. With on-off control the power level changes back and forth between two values in a repeating step function. The duty cycle corresponds to the thermal oscillation of the upper hot point and is a function of its thermal time constant. The ratio of "on" to "off" time corresponds to the power requirement of the upper heater relative to the lower one.

Laboratory tests

Tests conducted at USA CRREL with a model approximately 4 in. in diameter and 18 in. long have demonstrated its ability to achieve vertical attitude quickly when started with an intentional inclination. The penetration efficiency is found to be high. A circuit for the automatic control of the upper heater is being developed and tested.

The steering principle is independent of the probe or drill diameter. It is applicable to devices whose size is determined by their function or payload.

Summary

Pendulum steering, when applied to a thermal probe or thermal coring drill, provides a device that is inherently stable. Its attitude will always be plumb. If deflected by external influences, it will start its return to the plumb attitude immediately. If a continuous lateral deflection (steering) is applied its course will correspond to the resultant force vector direction.

The automatic power control of the upper hot point provides a self adjustment of the probe to different conditions of ice temperature and penetration rate. This feature makes possible a single thermal probe design that is suitable for all ice cap temperatures and a wide range of penetration rates (i.e., applied power levels). High probe speeds are generally desirable to save time but available power may be the limiting factor.

The simplicity of a thermal probe with pendulum steering suggests its possible availability at modest cost and makes it attractive as a versatile and widely applicable tool.

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13. ABSTRACT

Pendulum steering, a new concept of attitude stabilization for thermal probes or coring drills in ice, eliminates instability. The center of support is placed above the center of gravity. A lower and upper hot point produce melt penetration. The ratio of their power levels is the basis for stabilization, which is provided by the automatic control of the heater in the upper hot point. This feature makes possible a single thermal probe design that is suitable for all ice cap temperatures and a wide range of penetration rates (i.e., applied power levels). The simplicity of a thermal probe with pendulum steering suggests availability at modest cost and versatility as a widely applicable tool.

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