

A closed-loop electro-magnetic flowmeter

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Abstract In applications requiring long-term *in situ* measurements, or in the operation of remote sensors as in meteorology and oceanography, power-conserving circuits are especially advantageous. The closed-loop circuit described adjusts the coil power of an electromagnetic flowmeter when flow velocities exceed a preset threshold value. As a consequence, electrical power is saved.

1 Introduction

Several types of electromagnetic flowmeter have been reported in the literature (Tucker *et al* 1970, Olson 1972, Kanwisher and Lawson 1975). All use highly regulated coil power for the excitation of the sensor. Single- or double-coil types have been described which are excited either sinusoidally or by switched DC techniques. The flowmeter described here has a sensor consisting of a pair of sinusoidally excited Helmholtz coils. The inclusion of a closed-loop circuit in the system enables the coil power of the flowmeter to be continuously adjusted for flow velocities exceeding a preset threshold value. However, the closed-loop technique is not restricted to this type of sensor or to the method used in exciting the sensor.

A conventional flowmeter using stabilised coil power was designed and then calibrated in a tow tank for flow

velocities in the range 0.06–1.96 m s⁻¹. The design of the closed-loop flowmeter was then based on this primary calibration, and a subsequent secondary calibration of the closed-loop system was then obtained in a tank. Finally, the closed-loop system was tested in a river. Block diagrams of the conventional 'open-loop' flowmeter and the 'closed-loop' flowmeter are shown in figures 1 and 2 respectively.

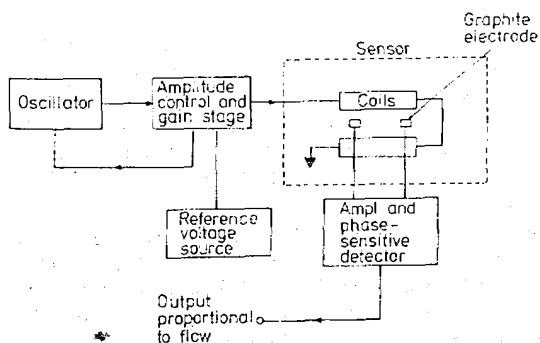


Figure 1 Block diagram of the conventional open-loop electromagnetic flowmeter system.

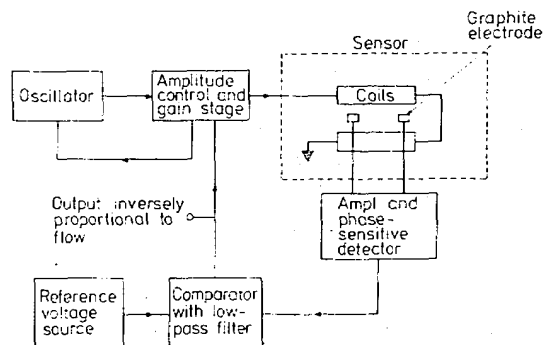


Figure 2 Block diagram of the closed-loop electromagnetic flowmeter system.

2 Operation and linearity

The schematic of the flow sensor used in the experiments is shown in figure 1. A pair of Helmholtz coils is driven by a low-frequency sinusoidal current. The induced flow signal is sensed by two graphite electrodes in the plane mid-way between the coils. The induced electrode voltage V is orthogonal to the magnetic field and flow directions, and its magnitude (in volts) is given by

$$V = uBl \quad (1)$$

where u (m s⁻¹) is the flow velocity, B (T) the magnetic flux density and l (m) the separation of the electrodes. The arrangement of figure 1 was used in the tow tank tests. The output of the Wien bridge oscillator is passed through a fixed gain stage, and thence to a driver which powers the coils. The electrode output is sensed by an FET (field effect transistor) input instrumentation amplifier. The output contains both the flow signal and the induced quadrature voltages. The quadrature voltages are cancelled by adjusting the phase-sensitive detector waveform to sample equal amounts of positive and negative excursions of the quadrature signal. The remaining flow signal is also fed to the detector which averages out noise and other unwanted signals. The detector consists of an FET switched by a suitably phased signal derived from the driver. The FET output is coupled to a buffer amplifier for transmission and display. The output of the detector is linearly related to flow velocity as shown in figure 3.

In the closed-loop system shown in figure 2, the buffer amplifier output is compared with a standard voltage reference V_{ref} . The comparator output is used to modify the drive to the coils via the amplitude control stage. The amplitude controller (common to both the closed and open systems) consists of an integrating comparator wherein a DC reference level† is compared with the full-wave-rectified

† In the open-loop system a steady DC reference source is used, while in the closed-loop system the DC level varies because it depends on the flow velocity.

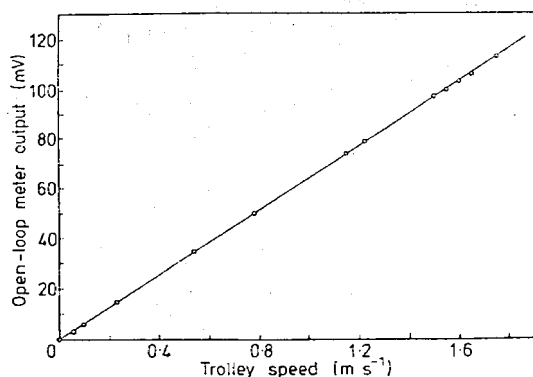


Figure 3 Calibration curve of the conventional flowmeter output with trolley velocity.

output of the oscillator. The output of the integrating comparator drives the gate of an FET so as to maintain the AC amplitude of oscillation equal to the DC reference level. The integrating comparator output thus alters the coil power so that the difference between the buffer amplifier output and V_{ref} is reduced to a very low level. The closed-loop action thus maintains the electrodes at a constant voltage by altering the coil power when there are changes in flow velocity.

Since the closed-loop system operates to maintain a constant voltage at the electrodes, equation (1) can be rewritten as

$$V_{ref} = uBl. \quad (2)$$

Since B is directly proportional to the voltage across the coils, V_c , then from (2)

$$u \propto V_{ref}/V_c. \quad (3)$$

The coil voltage will be a maximum at the minimum flow velocity. This minimum is set by the capabilities of the amplification and detection circuitry. The output of the comparator in figure 2 is limited to a +2 V swing, at which level the output to the coil just begins to clip the rail voltages. At higher flows than the minimum the comparator output decreases, thus reducing the coil voltage as outlined above. The reference source in both the open and closed systems was equal to 1.600 V with a temperature coefficient of 35 ppm °C⁻¹. Since the comparator was operated in the open-loop mode, the amplified output of the electrodes was held to better than 0.06% of the reference source.

3 Results and discussions

The conventional open-loop flowmeter was tested in a freshwater tow tank of dimensions 213 m × 3.6 m × 2.7 m. The results are plotted in figure 3. A root mean square deviation of 0.009 m s⁻¹ over a range from 0.06 to 1.96 m s⁻¹ (a factor of approximately 33) was obtained; the design and testing details are to be published in a separate article.

The tow tank results yielded the sensitivity figures for the flowmeter. Thus, the coil power and also the sensor output for a known velocity having been determined, it was possible to set the range of velocities for the closed-loop system. The sensor output after amplification was approximately 20 mV (m s⁻¹)⁻¹ for a coil power of 2 W. This sensitivity figure was subsequently increased by a factor of 3 for all further

measurements described below and the increased value plotted as in figure 3.

In order to set up the closed-loop system for tank calibration in the velocity range 0.12–1.96 m s⁻¹, the reference source used for comparison was stepped down to 8 mV, corresponding to 0.12 m s⁻¹. The output of the comparator to the amplitude control stage was then equal to about 1.65 V, and this after the gain stage produced an oscillator output of 10 V RMS just short of clipping the rail voltages. The upper end of the flow range now automatically adjusts itself to the requisite lower value.

The secondary tank calibration of the closed-loop flowmeter was accomplished in two stages since only one prototype was available for testing. In the first stage, the open-loop flowmeter was tested for its meter output. Then without disturbing these conditions, the flowmeter was wired up for closed-loop action, and the calibration repeated once more. A graph of the reciprocal of the closed-loop output is shown in figure 4. The correlation coefficient was found to be 0.998. The errors in this measurement could be largely attributed to the averaging of the closed-loop output since a filter with a large time constant had to be incorporated into it. The low excitation frequency of 20.8 Hz required a large time constant in the phase-sensitive detector stage to

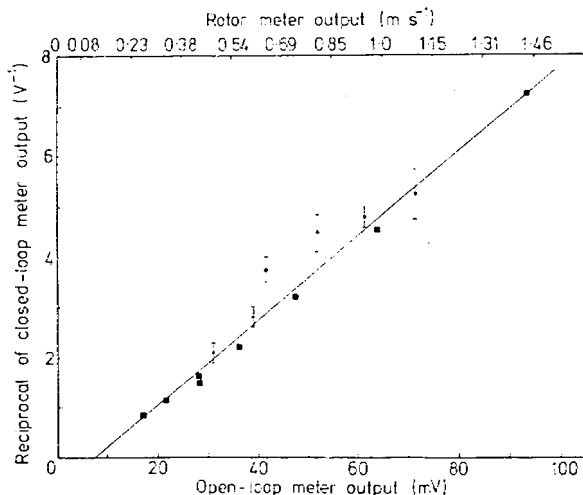


Figure 4 Reciprocal of the closed-loop meter output with the open-loop meter output in a tank (shown with the best fit through the points ■) and the corresponding field points (shown with error bars) using a rotor current meter.

obtain a low-ripple DC level for error comparison with V_{ref} . This time constant enforced a larger time constant in the comparator to maintain reasonably steady oscillator outputs. The overall time constant was kept equal to several seconds as the type of oceanographic work for which the flowmeter was designed did not demand faster response characteristics.

The location chosen for the field trials of the closed-loop system was a river where a large volume of outflow or fresh water to the open sea created layers of differing flow velocities. The reciprocal of the closed-loop output was recorded against the flow velocity as measured by a mechanical rotor flowmeter with a time averaging of 25 s. The rotor flowmeter had previously been calibrated in a tow tank and subsequently against the open-loop flowmeter in the field. The field data

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points and their associated error bars are shown in figure 4 for comparison with the tank calibration points. Data over only a limited range were obtained since these were the prevalent conditions during the field trials. The agreement is surprisingly fair despite the large uncertainty in the rotor flow measurements brought about by its own inherent limitations, and the natural variations of flow normally encountered in the field.

4 Conclusions

An electromagnetic flowmeter employing a closed-loop technique has been described in detail and tested in the field. The system feeds more power to the sensor coils when the flow velocity is low, and less power when the flow signals are large. It is therefore useful where long-term monitoring of flow or a similar type of measurement is required. In conditions where a large range of velocities is encountered, this system is especially advantageous, as is seen from the power saving of approximately 1000 for a velocity range of 33.

It is felt that the field measurements could have been improved upon if the closed-loop measurements were recorded simultaneously against the output of a calibrated open-loop flowmeter. This would avoid the uncertainties introduced by a rotor current meter.

The inverse relation between flow velocities and coil voltages is easily converted to read as directly proportional quantities by the use of divider chips or appropriate inverting circuits. One method satisfactorily tested was to convert the coil voltage to DC and feed it to a function generator integrated circuit chip. The output frequency of this is then directly proportional to the flow velocity. This is readily transmitted over reasonable cable lengths as would be required in the case of a submerged flow sensor and an on-board read-out unit.

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