Electronic Instruments and Computers for Sailing Yachts

R. N. B. Gatehouse
(Brookes & Gatehouse Ltd.)

This paper contains a brief survey of a series of instruments which have been developed for use in sailing yachts. It then outlines the principles of two computers; one navigational, the other for sailing performance indication. It does not cover radio navigational aids, echo sounding or radar. The data requirements are: 1. Navigational, comprising distance run through the water, heading, leeway angle. 2. Functional, comprising speed through the water, direction of the apparent wind and speed of the apparent wind.

1. NAVIGATIONAL DATA. For measuring distance run, the classical towed rotator type of log, fitted with a mechanical or electro-mechanical revolution counter has been largely superseded in racing yachts by logs employing through-hull sensors on account of drag considerations and the inconvenience of having to shorten the line when sailing slowly in shallow water. It still finds favour in cruising yachts on account of its generally lower price and its simplicity.

A substantial amount of development work on through-hull logs has taken place since 1938. The methods that have been used fall into two categories: (i) Those which measure distance directly and therefore require data processing devices to indicate velocity. (ii) Those which measure velocity directly and require data processing devices to supply distance data. In the first category are the impeller and the vortex shedding system. In the second are the force logs which depend upon the drag forces on a strut, the pitometer which uses the well-known pitot tube principle, the acoustic log which depends upon time-differences in the propagation of acoustic waves between transducers under the hull, the electro-magnetic induction log which uses the Faraday principle and the radio-doppler system which has been developed for hovercraft.

From this list, only three systems have emerged as marketable devices for yachts: the impeller, the force log and the pitometer. The others have been discarded, presumably on the grounds of excessive cost or of impracticability.

Work was undertaken by Brookes & Gatehouse, starting in 1961, to investigate the order of accuracy obtainable in through-hull logs when the sensor is close to the skin of the yacht. These investigations showed first that the boundary layer beneath the hull of a typical racing yacht was nowhere more than 1 in. thick and was only about ½ in. thick at a position 5 ft. aft of the forefoot, the position finally chosen for the sensor.
Operation of the sensor outside the boundary layer was therefore practicable. Secondly, they showed that the ratio of the flow rate at the sensor to the yacht's speed was constant over the available speed range, thereby eliminating the need for applying non-linear corrections when calibrating the log for a particular hull. An elegant method of investigating linearity was evolved, in which the sensor was an impeller and the total number of revolutions made by the impeller over a fixed water-distance was measured at different boat speeds. For a perfectly proportional flow rate this total will be constant. The accuracy of this method was estimated to be better than 0.1 per cent, being limited only by variations in mean current velocity over the duration of the 'runs' in the two directions and by the length of the 'run'.

The impeller system was finally chosen for production, the force log and pitometer being ruled out on account of their non-linear response which gives rise to difficult technical problems when attempting to derive a distance output. A disadvantage of the impeller is its susceptibility to becoming stopped by fine seaweed, but this is largely overcome by the accurate installation of a blade-like deflector in front of it. The main advantages of the impeller are its linear output and the suitability of the output signal to digital processing for distance measurement, thus avoiding the 'drifts' inherent in analogue systems. The impeller diameter is 0.7 in. and its pitch is about 3 in. (Fig. 1). Transmission of the rotational

FIG. 1. The impeller and pick-up unit of the Harrier log
data is effected electromagnetically, a cylindrical, diametrally polarized magnet being fitted inside the impeller and a coil of many turns of fine wire being installed in the mounting for the supporting fin of the impeller. The complete probe unit is inserted into a tubular skin fitting which penetrates the hull. Withdrawal is practicable with the vessel afloat. An a.c. signal of 0.1 mV r.m.s. is developed at 1 knot, and one cycle of a.c. is generated in each revolution of the impeller. Fig. 2 is a block diagram showing the method used in processing the probe signal to obtain distance run and speed. The probe signal is initially amplified to a level of about 1 volt. A frequency divider circuit comprising 8 binary bistable stages then increases the effective pitch of the impeller by a factor of $2^8$ or $2^6$; i.e. to a value of 60.8 ft. or 0.01 n.m. This low-frequency signal is applied to the electromagnetic 6-digit log counter which therefore indicates distance run in increments of 0.01 mile up to a maximum total of 10,000 miles. For the indication of speed, the probe signal is fed into a frequency measuring circuit. The d.c. output of this circuit, which is connected to a milliammeter, is proportional to the probe signal frequency and hence to the speed of the boat.

FIG. 2. Block diagram of Harrier combined log and speedometer

*Heading* is invariably measured by magnetic compass, and improvements in recent years such as damped gimbaling and stronger magnets has made the modern yacht compass a dependable instrument even in rough water. In steel yachts the war-time aircraft magnesyn transmitting compass is sometimes used, the master compass being mounted as high as possible above deck to minimize deviation errors.
A recent development is the Hestia steering indicator. This is a form of transmitting compass employing a 'left-right' type of indicator for the helmsman, which is similar to that used in the aircraft radio-compass homing equipment (Fig. 3). The desired heading is set on the dial of the transmitting compass and the helmsman has merely to maintain the pointer of the indicator in its central position. The transmission system utilizes the Hall-effect probe as the sensing element for the field set up by a compass magnet. When the vessel is on the correct heading the flux lines are parallel with the plate of the probe element and no signal is developed. Heading changes on either side of this null position result in flux linkages with the probe and the consequent generation of an error signal, the amplitude of which is proportional to the sine of the heading error and this sign of which depends upon whether the error is positive or negative (to starboard or port). The direct sensing of the Earth's magnetic field, as opposed to using the intermediary of a compass magnet, is not practicable in those areas of the world where the angle of dip is large as the accuracy
of the instrument would be critically dependent upon the maintenance of a horizontal plane of reference for the sensor.

Leeway is caused by the side-force of the wind on the sails and hull and results in a crab-wise motion of the vessel. The leeway angle, which is the angle between the yacht’s fore-and-aft axis and the direction of motion through the water, reaches a maximum value when the yacht is close-hauled, this value varying between about 2° and about 10° depending upon design factors, the strength of the wind and the state of the sea. It is therefore an important item of navigational data. So far as is known, no practical leeway indicator has been developed for installation in a sea-going yacht, for evidently flow-angle measurements made close to the hull cannot be correlated in a predictable manner with the leeway angle. The navigator of an ocean racing yacht must therefore have recourse to tank-test data for the model hull and to experience gained through repeated comparison between the estimated position and the true position as obtained by visual bearings.

2. SAILING DATA. The processes carried out by the crew in making the yacht sail involve sail-trimming, the adjustment of the geometry of the sail plan (including sail curvature), the alteration (by heading and sheeting changes) of the angle of attack of the wind, the adjustment of trim tabs, retractable keels, &c. To assist the crew in optimizing this multiplicity of variables, the following instruments have been developed:

- Water speed indicator
- Apparent wind direction indicator
- Apparent wind speed indicator

It is unfortunate that one of the vital elements of data, leeway, is not available, for with modern keels of high aspect ratio and aerofoil shape the maintenance of the correct angle of attack of the water-flow is of great importance in connection with windward efficiency.

The whole process of optimization is carried out by trial and error, each parameter being varied incrementally, in turn, until the calculated or observed performance has reached a maximum value. The criterion for the assessment of performance to windward or down-wind is the so-called 'speed made good' (Vmg) which is the boat’s velocity resolved in a direction parallel with that of the true wind vector. Windward or leeward destinations, even if they are not directly up-wind or down-wind, are reached in the shortest time if Vmg is maintained at its maximum value.³ The design of a computer for the continuous presentation of Vmg is briefly described in Section 3. Although prohibited by club rules in British ocean racing the use of computers will nevertheless serve a useful purpose in enabling yachts to be ‘tuned up’ and experimented with more rapidly, and to better effect, than is possible at present.

The measurement of speed has been covered in Section 1. It is of interest to note that electronic ‘magnifiers’ have been produced to assist in trim-
ming for maximum speed. These devices amplify the current output of
the electronic speedometer by a factor of between five and ten and at the
same time introduce a d.c. offset, the output being fed to a large
milliammeter. Speed variations of the order 0.05 knot are then easily
discernible, which order of change is often significant in calm water.

The apparent wind angle is defined as the angle between the fore-and-aft
axis of the yacht and the direction from which the wind appears to be
blowing to an observer on the yacht. When sailing to windward the true
test of a helmsman's skill is his ability to maintain this angle within
certain closely-defined limits which vary according to the wind strength
and sea state and which have been determined either by calculation from
instrument readings or as the result of long experience of racing a particu-
lar yacht.

The accuracy of wind-flow measurements in the vicinity of a yacht is
affected by the presence of the sails. Experiments were carried out in
1964 on board the author's 24 ft. (water-line) Lion-class masthead sloop
Reflection to determine whether the apparent wind angle could be meas-
ured and presented with sufficient accuracy and smoothness to enable
the yacht to be trimmed for maximum windward Vmg.\(^1\) The measure-
ments made were subject to considerable dispersion due to wind-shifts,
turbulence and to the motion of the boat, but a sufficient number was
taken to establish, with a high confidence level, that with the sensor placed
two feet ahead of the mast centre-line and six inches above the masthead,
the error of measurement of wind direction due to sail deviation seldom
exceeds 3° and is independent of wind velocity. The error is such as to
make the apparent wind angle greater than it really is.

No other position for the sensor is practicable for use on all points of
sailing. Wind-tunnel tests made at the University of Southampton,
which were conducted on a one-sixth scale model of a masthead-rigged
ocean racing yacht (Yeoman XIV), indicated that the error was about + 7°.
No theory has yet been advanced to account for the large difference
between the two results.\(^4\) Any explanation would be of academic interest
only, since the acid test of several years' practical experience indicates
that when Vmg is maximized by instruments, with a sensor installed at
the stated position, Vmg is indeed at its highest value!

A combined direction and speed sensing unit together with the helms-
man's indicators is shown in Fig. 4. The delta-shaped wind-vane is
critically damped and drives two precision sealed potentiometers having
very low driving torque. One of these has the 3-wire dessyn transmitter
configuration and the other is a simple potentiometer having active
sectors between 15° and 50° on either bow. The first operates the 360°
indicator; the second an 'expanded' centre-zero meter display which is
used for fine heading adjustments when sailing close-hauled. (It is in the
close-hauled mode of sailing that the highest discrimination and accuracy
are required.) Fluctuations of the indicators due to turbulence and wave
motion are attenuated by a combination of viscous and electrical damping.
Some instruments of other manufacture utilize the a.c. synchro data transmission system.

The cup-type rotary anemometer is used almost exclusively for the measurement of wind velocity at sea. It has the advantages over pitometer, hot-wire, strain-gauge and other systems of affording high accuracy without the need for individual calibration, and of having a linear response. The requirement for low weight and windage aloft in racing craft called for some departures from standard practice in anemometer design. These included the use of high-grade, miniature stainless steel ball races for the rotor shaft and the development of a virtually drag-free transmission system. The diameter of each cup is 1 in. and the length of its supporting arm is 1¼ in. The rotor is moulded in nylon (Fig. 4). Calibration checks at the low-speed end of the range were carried out on the carriage of the model ship test tank of the Davidson Laboratory, New Jersey, U.S.A., while the others were made in the wind tunnel at Southampton University. Departures from linearity did not exceed 0.5 per cent within the speed range 2–60 knots.

The data transmission system employs a miniature reed switch operated by two bar magnets attached to the rotor shaft. Two switch closures occur per revolution, each closure causing a charge to be transferred
from a small 'bucket' capacitor into a larger 'reservoir'. The reservoir drains into the indicating meter. The scale can be made either linear, or of logarithmic shape, by simple alteration to circuit design.

3. COMPUTERS FOR NAVIGATION AND SAILING. The ideal computer for dead reckoning will accept heading, boat velocity, current velocity (from prepared tables) and leeway data and feed out continuously the departure and diff. lat. which will have been set to zero at the time of the last fix. The cost of such an instrument would probably be such as to render it uncompetitive with some long-range radio aids as Loran C and Omega.

Hadrian was designed with economy as a primary consideration, which resulted in the need to plot tidal set and leeway manually and to re-set the computer whenever a substantial change in heading should take place. The read-out is in the form of a pointer display of cross-track error, calibrated in units of 0.01 n.m. from a present course. The D.R. position is plotted by reference to this quantity and to the distance run by the log.

The principle of operation is the derivation of cross-track velocity, obtained by the multiplication of the boat's speed by the sine of the heading error ($\sin \theta$) and the integration of this product with respect to time. A block diagram for the system is given in Fig. 5. Analogue, rather than digital computation, was chosen since the input quantities were in the form of analogues. The speed of the vessel, $V_s$, as measured by Harrier appears as a continuous direct current derived as the reciprocal of the time interval between successive log pulses, averaged over several pulses.
The sine of the heading error, \( \theta \), as measured by *Hestia* (Section 1) appears also as d.c. The integration of the product \( V_s \sin \theta \) with respect to time is carried out by means of a reversible miniature motor, based on the 'mess-motor' instrument developed and used by the Germans in the second World War for programming the V-1 missile. The motor drives two pointers through a gear train, one of which indicates in units of one nautical mile; the other in units of 0.01 nautical mile.

As mentioned in Section 2, the objective when sailing to windward or down-wind is to maintain the component of the yacht's speed, \( V_s \), resolved in the direction of the true wind, at its maximum value. On other points of sailing, the objective is simply to maximize \( V_s \).

Referring to the vector diagram in Fig. 6 for a yacht sailing to windward it is seen that the yacht's velocity vector \( V_s \) gives the effect of a headwind component \( -V_s \) which compounds with the true wind vector \( V_T \) to give a resultant, or apparent, wind velocity \( V_A \). It is therefore impossible to measure \( V_T \) directly when on board, and consequently the greater part of the computation of \( V_{mg} \) is concerned with the derivation of \( V_T \). The angle between the yacht's track and the vector \( V_A \) is denoted by \( \beta \) and that between the yacht's track and the vector \( V_T \) by \( \gamma \). \( V_{mg} \) is given by \( V_s \cos \gamma \). The angle between the yacht's track and her fore-and-aft axis is the lee-way angle \( \lambda \). To compute \( V_{mg} \), therefore, the following quantities have to be measured:

\[
\begin{align*}
V_s & \quad \text{(maximum of } V_s) \\
V_A & \quad \text{(apparent wind velocity)} \\
\gamma & \quad \text{(apparent wind direction)} \\
\lambda & \quad \text{(lee-way angle)}
\end{align*}
\]
By the trigonometry of Fig. 6 we have:

\[
V_{mg} = \frac{V_s^2 - V_A \cos \beta}{(V_A^2 + V_s^2 - 2V_A V_s \cos \beta)^{1/2}}
\]

The solution of this equation electrically would require equipment both too costly and bulky for general use. The further complication of correcting the measured values of \( V_A \) and \( (\beta - \lambda) \) to allow for the errors introduced by the heeling of the yacht make an exact-solution computer impracticable.

In a research contract for Brookes & Gatehouse the University of Southampton has built an analogue computer which solves a simplified equation and presents \( V_{mg} \) on an electrical meter in the cockpit. The computer contains about 100 transistors and consumes about 5 watts from the yacht's 12-volt d.c. supply. Sailing trials have indicated that the errors due to the simplification are acceptably small and that the device saves much time in trimming for highest \( V_{mg} \) over the method of using a manual slide-rule type calculator. Further development is in hand to discover and compute a quantity which attains its maximum value simultaneously with \( V_{mg} \) and which is substantially independent of changes of wind velocity. Such a quantity could be called the sailing 'figure of merit'. Trimming would then be further simplified since the indication given by the meter would not vary with wind strength, and valid observations of the effect of changes of trim, &c. on performance could be made without having to wait for periods of constant wind velocity.

4. YACHT INSTRUMENTATION IN THE FUTURE. Design trends at the present time are mainly towards reduction in size and weight and improvement in reliability of existing types of instrument. These trends are being assisted by the emergence of the 'integrated' form of circuit construction (the I.C.) as a commercially economic method, even for quite small-scale manufacture.

Many yachtsmen feel that the science of sailing and navigational instrumentation has already advanced too far, and some clubs have accordingly imposed a ban on the use of certain instruments in races held under their auspices. In the absence of a demand for new devices by the owners of racing yachts, the pace of development is certain to slacken. Were no restrictions to be imposed by the clubs one would expect development work to be concentrated mainly upon sailing computers and the miniaturization of receiving equipment for such high-precision radio aids as Decca and Loran. Inertial systems of navigation would be unlikely to receive much consideration in view of the very high cost of the associated gyroscopes and accelerometers.

REFERENCES

Twentieth Anniversary Convention of the Australian Institute

The Australian Institute celebrated its twentieth year by organizing, on 10 and 11 October 1969, a convention, held in Basser College of the University of New South Wales, Sydney, with the general theme 'Navigation in the '70's.' This Institute was represented by the Executive Secretary and the American Institute by Captain Alton B. Moody. Some 200 members and others attended.

The papers presented included The Navigation of James Cook in the Pacific, by the Institute's President, Captain Brett Hilder, an account the more interesting because Captain Hilder, of the Burn Philips Line, himself navigates in many of the more remote areas travelled by Cook. J. I. Davis, General Manager of Sea-bridge Australia Ltd., gave some interesting figures about Australian shipping. For long-term development against growing competition from the air, he saw the future for all but the bulk trades in extremely fast craft which could be operated with some flexibility, such as hovercraft. P. J. Reynolds, Superintendent of Navigation of Pan American Airways, described the F.A.A.-sponsored testing of military analogue inertial navigation systems, the development of civil airline specifications for INS, the engineering testing of digital systems and finally the application of inertial systems to long-range civil aviation. Captain John Young of B.O.A.C. gave an operational view of the navigation equipment planned, and some ideas on other possibilities, for the Concorde. Captain Moody, now with Western Geophysical, described some of the new systems which rely on inertial/doppler up-dated by satellite for very accurate position fixing (largely for geophysical work) at sea.

Dr. E. G. Bowen, Chief of the Radiophysics Division of C.S.I.R.O., and a Past President of the Australian Institute, described the astonishing variety of celestial objects emitting radio waves, the study of which has been made possible over the last thirty years through radio astronomy. Lewis Wainwright of the Department of Supply talked about radio control of spacecraft and radio lines between spacecraft and the Earth. Finally, Mr. Richey attempted to define the part which the Institutes of Navigation might play in the changing scene of navigation. It was in the sphere of navigational philosophy that he felt they were pre-eminently fitted to contribute.

The proceedings were rounded off by a banquet in the evening at which the guest of honour was the Director General of Civil Aviation in Australia, Sir Donald Anderson.

Altogether the Convention was a remarkable tribute to the vitality of the Australian Institute and to the continuing dedication of the people who serve it, some of whom have been at its centre from the start.