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H. Irving Pratt
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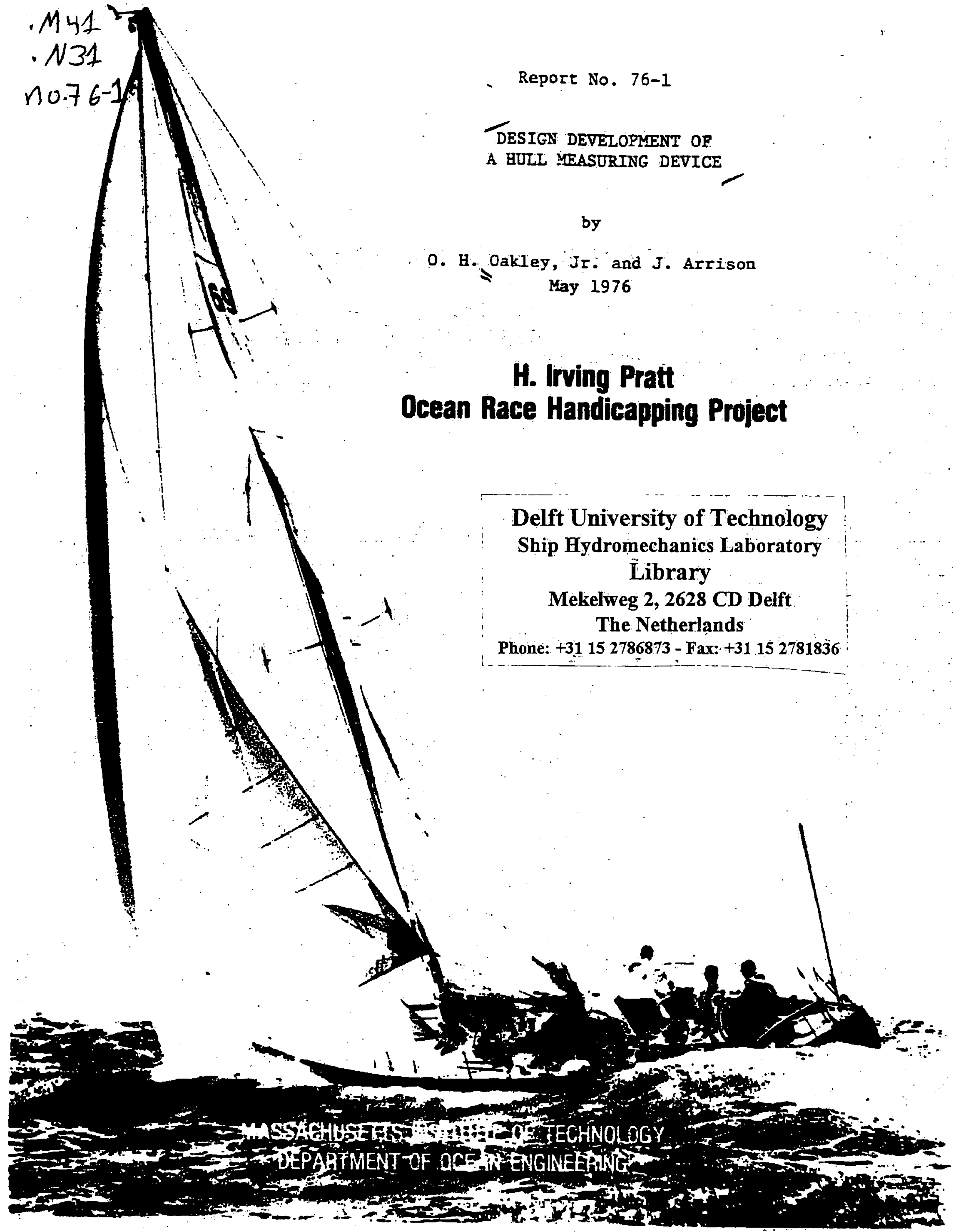

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF OCEAN ENGINEERING

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(Prepared for the 24 January 1976 Meeting of the New England Sailing Yacht Symposium)

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Design Development of a Hull Measuring Device

ABSTRACT

In order to handicap a yacht, a large number of specific (and rather complex) hull measurements are now required. The procedure is time-consuming, offers little redundancy, and yields only incomplete information on the shape of the hull. This paper describes the design and testing of a relatively inexpensive hull-measuring instrument for obtaining a rapid and complete description of the hull form. Data is taken in cylindrical polar coordinate format at arbitrary stations by measuring the length and angle made by a string extended from the instrument to a point on the hull. The offsets are stored on a miniature digital tape recorder and are easily accessible to the computer for smoothing and analysis.

INTRODUCTION

This is a report on the design and construction of an instrument used to obtain the offsets of a yacht hull. The device permits data to be taken at arbitrary stations in polar coordinate format by extending a string to the desired points on the hull. The offsets are recorded on miniature cassettes by a digital tape recorder and are transmitted, with suitable interfacing, over the phone lines to the computer for processing. Before presenting a more complete description of the device and its method of operation, something of the history of yacht hull measurements and the instrument design philosophy will be given.

The number of competitors and the relative intensity of the competition in yacht racing has greatly increased over the past twenty years. The handicapping process, in an effort to keep pace, has become increasingly complex and has demanded an ever greater amount of information describing the hull geometry. However, the methods employed to obtain the desired measurements have changed very little from those used in the last century. Admittedly, a skilled measurer equipped with plumb bobs, tape measures, and plenty of time can obtain almost any geometric quantity desired. The tools of the existing system probably represent the ultimate in simplicity. On the other hand, available time and the requisite skills, if not scarce commodities, have become extraorinarily costly. As a result, ersatz quantities are still being used in lieu of the precise information desired by the rulemakers. This has also required the measurer to become an interpreter and arbiter of the rating rule; jobs presuming a familiarity and competency not necessarily associated with those required for physical measurements. The subject of yacht measurements has therefore become one of the items for investigation under the NAYRU/MIT Yacht Handicapping Project.

Quantitative information characterizing (and differentiating between) competing yachts forms the basis of all rating rules. Precisely what quantities are superior measures of boat speed and the levels of accuracy needed to obtain them are open questions. Early formulations of the rating rules demanded simplicity in the measuring process and in the formula above all else—and that was about all they achieved. Equitable handicapping and well found yachts designed to the "spirit" of the rule have not exactly been the hallmarks of the past century of racing.

Required hull measurements have varied greatly through the years. Initial rating rule formulations were based on the Custom House Tonnage, a volumetric approximation using simply length, beam, and depth of the hold.[1] This was quickly replaced by the "displacement rule" which used the vessel's actual weight. It is not known how the displacement was measured during this period, 1847 to 1856,[2] but protested boats

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1 D.D. Strohmeier, 1974, "Yacht Racing," The Chesapeake Sailing Yacht Symposium, Jan., Collected Papers, S.N.A.M.E.

2 C.L. Poor, 1937, <u>Men Against the Rule</u>, The Derrydale Press, New York.

actually appear to have been weighed. The hull was then ignored for a few years under the pure sail-area rules. In 1859 the Waterline Area Rule was adopted which required the extreme waterline length and beam measurements. This rule favored the smaller boats and the solution was sought by changing the time allowance tables rather than the rating formula.

Hull measurements became more complex in the 1870's with the adoption of the Cubical Contents Rule. Sectional areas were determined at five stations along the waterline and Simpson's Rule used to compute the displacement. The "cubical content" of the overhangs was then added. More measurements, however, did not lead to a better rule since the many loopholes in the formula allowed radical exploitation. Hull measurements were again simplified under the Seawanhaka Rule in 1883, requiring only waterline length. This measurement holiday ended in 1902 with the Herreshoff Rule. The formula was relatively simple, requiring only the hull measurements of L and displacement, L being the average of the l.o.a. and the l.w.l. at the "quarter-beam points." However, additional measurements were required to determine if there existed "excesses" in the width of the stern deck and the waterline. The displacement was determined by sectional area measurements at specific locations. This basic format was retained through the adoption of the Universal Rule in 1931.

The Lippincott and CCA versions of the rating rule in the 1940's and 1950's again altered the basic formula, but the hull measurements remained moderately complex requiring information to be taken at specific locations and under special conditions. The intent of any given measurement had long since been obscured due to the approximate nature of the rule or the arbitrariness of the form of the correction factors. This has been carried to the extreme in the current IOR Rule. In 1972, it was said that "the number of people that completely understand it (the IOR Rule) could be seated comfortably in the main saloon of a beamy 22-footer."[3] The size of the saloon would have to be considerably larger today. There has been a definite period of adjustment while designers discovered the IOR's assumptions and shortcomings. There are now many new designs that clearly have less displacement and more stability, for example, than the required measurements and formula would imply.

Alterations and adjustments in the rule will probably always be necessary as long as the designer is an active participant in the sport. This is not necessarily bad, yet the rulemakers, in their efforts to provide equitable handicapping, are frustrated by the lack of precise information on the hull geometry and are at a disadvantage when compared with the designer. Rule changes that require new measurements are not popular with the yachting public. It is apparent that there are a number of advantages to be gained from a single but thorough measurement of the hull. For example, if the complete hull geometry was available, changes in the rule would not require remeasurement. Different rules or formulas could be computed from the same set of information thereby freeing the rulemakers to alter as needed and the race committees to run races as they see fit. The measurer could concentrate on the problems of measuring the hull to the desired level of accuracy without having to worry about rule interpretations. A complete description of the hull, in the form of offsets, would facilitate checking the data for inaccuracies. Bad or unfair points could be deleted or faired and the desired rating rule formula computed with less chance of a serious error caused by a single bad measurement. With these thoughts in mind, it was decided to investigate the possibility of developing a device that would facilitate the procurement and analysis of data characterizing the hull geometry.

DESIGN PHILOSOPHY AND REQUIREMENTS

In order to obtain a better description of the hull geometry than is provided by the current IOR measurement procedure, more data will have to be taken. It is clear that without some form of automatic sensing and recording device, the time required for measuring and data transfer to the computer would be greatly increased. Many potential methods exist and have been considered. Underwater and photographic techniques were rejected due to cost and severe technical difficulties. A number of remote sensing devices suggest themselves, for example those based on acoustical, infrared, and lasar ranging principles. The lasar and infrared techniques are relatively well established and have found both military and commercial applications. However, all of these remote sensing devices were rejected since they appeared to be either too sophisticated to rely on, too inaccurate for the present application, required more than one person to operate, or were too costly. The latter requirement was by far the most limiting factor. Too costly an instrument would certainly impede its adoption, hence the desire to use more or less conventional mechanical

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3 J. Hammond, 1972, "The 13th Rule," Yachting Magazine, April, p. 50.

and electrical technology.

Measurements from several points to a single point on the hull, or vice versa, would be difficult since, in general, access to the hull is likely to be limited by cradles, supports, and neighboring boats. While not essential, offsets taken in more or less the standard fashion, i.e. at numerous stations along the length, would facilitate the smoothing, checking, and interpretation aspects of the problem. If the measurer can perform much of the required alignment the resulting offsets are likely to be of reasonable quality and would require only minor conversions and smoothing. Schemes that collect data from a few locations require very precise determination of these special points. Any inaccuracies or errors may make the data useless for automatic analysis. Offsets taken at known stations appear to be reasonably recoverable if a number of points or an entire station are lost.

Automatic recording and data transmission are considered essential if there is to be a significant increase in the amount of information to be handled. Key punching hundreds of offsets from data sheets is likely to introduce many errors. This of course, must be traded off against the possible failure of the recording device. The danger should be minimized with periodic checks and service. At an additional cost, the data could be monitored by continuously comparing the recorded signal with the input.

Once in hand, the raw data must be scaled and the desired quantities computed for the evaluation of the rating. If the offsets prove to be sufficiently accurate, the computation could proceed without smoothing and only cursory checking. The current design goal is to keep errors below 0.01 feet. It is more likely, however, that some bad points will exist and that there will be small random errors through the data. Again, if they are small, they will not affect the computations. Otherwise, simple fairing techniques are available to smooth the data. While this involves more computations, it may significantly reduce the accuracy requirements and hence the measuring time in the field. Computing costs are considerably less than measurer and yard costs.

One of the arguments in favor of storing information on the complete hull geometry is that many different rating formulas could be computed and certificates issued. It should be noted that the present formulation of the rule, with its requirement for measurements to be taken at precise locations, does not lend itself to rapid measurements. The precision necessary to locate particular points may be a stumbling block for automatic analysis. Checking and smoothing the offsets of a lumpy hull could prove to be tricky and time consuming. This is especially unfortunate if the lumps have little to do with boat speed. Clearly displacement, wetted surface, prismatic coefficients computed at various waterlines, angles of entrance, and so on, are the most logical describers of the hull geometry relatable to boat speed. The majority of these coefficients and quantities are relatively insensitive to local aberrations. Some smoothing of the actual geometry may be acceptable if the desired quantities are still sufficiently accurate. The act of taking more data should actually reduce the need for local precision. This presumes, of course, a reformulation of the present rule in terms of the above quantities rather than specific measurements.

DESCRIPTION

Data is taken at arbitrary stations in polar coordinate-format-by-extending a string to desired points on the hull as illustrated in Figure 1. The distance along the hull is measured simply by using a metal tape starting from some arbitrary reference point. The longitudinal distance and a code designation are recorded by first setting two sets of thumb wheels on the case to the appropriate values at each station. When the string is extended to the hull and the record button pushed, all four numbers are recorded sequentially by a digital tape recorder. The four, four-character numbers are:

i) a code number indicating the boat and/or the nature of the offset being recorded;

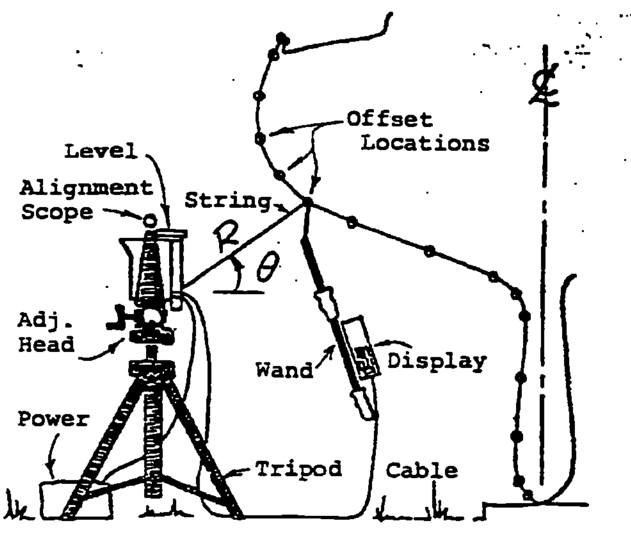

FIGURE 1 Section View of Apparatus

ii) the distance along the hull of the station being measured;

iii) an angle proportional to the string extension;

iv) the angle made by the string and the case reference angle or horizontal.

Repeated recording of the second item is presumably redundant if many points are taken at each station sequentially. However, for automatic analysis of the data by a computer program or for the recovery of data after a recording error, such redundancy may be of great value. Further details of the prototype are given in the following subsections.

Mechanical System

The string being used is made of Kevlar and has essentially zero stretch. It is stored on a drum connected to a Neg'ator Constant tension spring yielding approximately a two pound pull and virtually no catenary (cf. Fig. 3 and 4). The angle made by the string with the horizontal is sensed by a light weight arm with a small hole only slightly larger than the string diameter. In order to avoid the use of scaffolding, the string is connected to the end of a wand to facilitate reaching to the deck and the hull. The wand has a Delrin tip to reduce wear on the string and damage to the yacht. The record button is located at one of the hand grips for ready access. Digital readouts of the data and an alignment meter, to be described below, are also provided on the wand for constant monitoring by the measurer. The instrument itself sits on a tripod with an adjustable head having (ideally) four degrees of freedom. A sighting scope, mounted on top of the case, is used for alignment.

Alignment

Two types of alignment are required. The first calls for the instrument to be positioned, squared and levelled at successive stations along a fixed line in space, called the instrument baseline. Some form of rail along which the instrument could be slid rapidly from one station to another was the original scheme. It soon became apparent that the requirements for portability and ruggedness were incompatible and that the rail concept would not be acceptable. The simplest one-man system appears to be one involving the adjustment of the height and angle of the instrument so that the attached sighting scope becomes aligned with two remote targets, one of them being a set of cross hairs. Initial trials were unsuccessful due to the use of a low quality rifle scope. A regular sighting level, however, appears to be more than adequate. The second alignment requires the string to remain in a plane perpendicular to the longitudinal axis as illustrated in Figure 2. This is accomplished by strain gaging the string sensing arm for longitudinal motions. The string is first aligned in the reference notch on the case and the strain gage bridge is zeroed. Any longitudinal motion of the string is displayed by a meter situated on the wand. The measurer need only refer to the meter while holding the string to the hull and moving down the station. This procedure has proven to be accurate and exceedingly simple to follow in practice. The tripod for the prototype is rather complex, having adjustments in three degrees of freedom. A patient measurer may be able to perform the same adjustments with a simple tripod at a considerable savings in cost, however the fine adjustment features appear to be necessary for rapid and precise alignment.

Measurement Signals

The distance to the hull is obtained by sensing the number of turns made by the string storage drum using a shaft encoder. This is an electronic device that outputs a series of square wave pulses, many times per revolution, that are counted by the digital logic circuit. The angle made by the string and the case reference (or horizontal) is sensed by another encoder. These are shown schematically in Figure 3. As noted earlier, the longitudinal distance obtained from the tape measure and a code number are entered by setting a group of thumb wheels located on the front of the instrument case.

Recording System

The digital electronic circuity (see Figure 5) probably represents the greatest deviation from an otherwise straightforward (mechanical) system. The comparative complexity and the potential threat to reliability of an electrical (vs. mechanical) system appears to be a necessary evil. Since the data is to be processed by a digital computer, it would be ridiculous to introduce an extra step in the data transfer process. Key punching is time consuming, costly, and likely to introduce more errors. Clearly a digital tape recorder is the most desirable storage medium short of an on-line hookup to the computer. The sensor/recorder and recorder/computer interfacing are non-trivial but commonplace electrical circuit design problems. The present circuit appears to work well, but further testing is needed to ensure that it can withstand the rigors of transport and typical boatyard conditions.

The recorder is a Micro Vox Digital

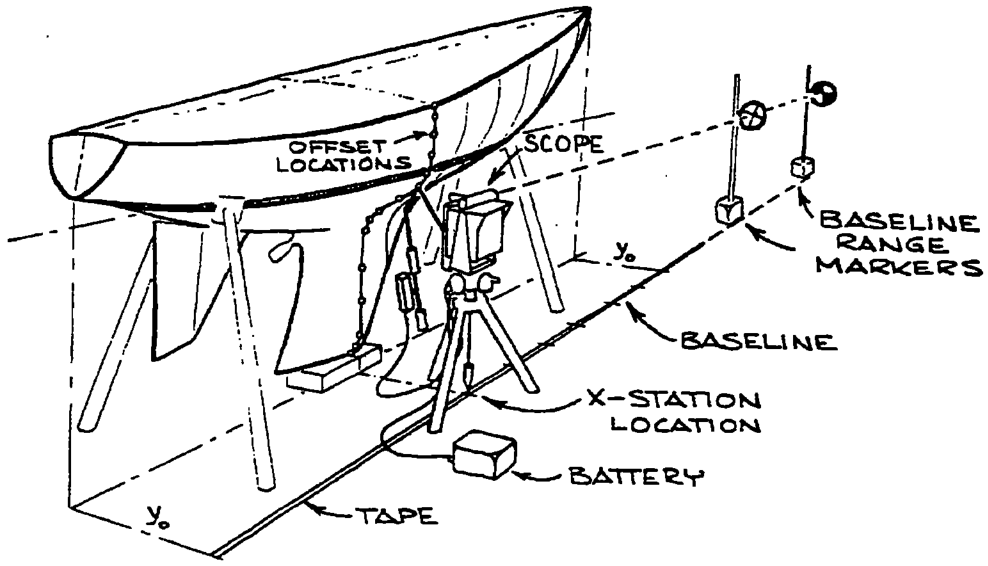

Figure 2 Instrument Alignment

Data Storage System, a single channel, miniature, digital tape recorder made by Micro Communications Corp. Data is written onto a miniature loop of magnetic tape, called a Wafer, which is roughly the same size as a book of matches and can be sent through the mail in an ordinary envelope. The recorder contains the clock that regulates the digital circuitry. The logic circuit keeps a continuous count of the pulses emitted by the shaft encoders. Counts are added as the string is extended, and subtracted as it retracts. The power must therefore be left on during the measurements. If the power is interrupted the circuit automatically rezeroes itself. It is therefore essential that the string then be allowed to retract to the reference position on the case and the system rezeroed. Otherwise, the reference point and angle will be at an unknown wand position. As long as the length of the string is not changed, the calibrations are fixed and the system may be rezeroed as many times as desired. The circuit continuously samples the thumb wheel inputs, displays the current readings at the wand, and writes them out in series on the tape when the record button is pushed. Ample power is provided by a twelve volt car battery insuring stability and ready access in remote measuring locations.

<u>Write/Read System</u>

The prototype configuration calls for the instrument to contain a write-recorder only. The principal element of the digital circuitry is the random access memory (RAM). It stores the current value of the shaft encoder positions. The RAM is four bits wide (every access references four bits), and 16 words long. Only the first eight words are used. These eight are divided into two groups of four, one for the angle count, and one for the length count. Each of the words is a binary coded decimal (BCD) digit. This allows direct readout for the display. For ease of

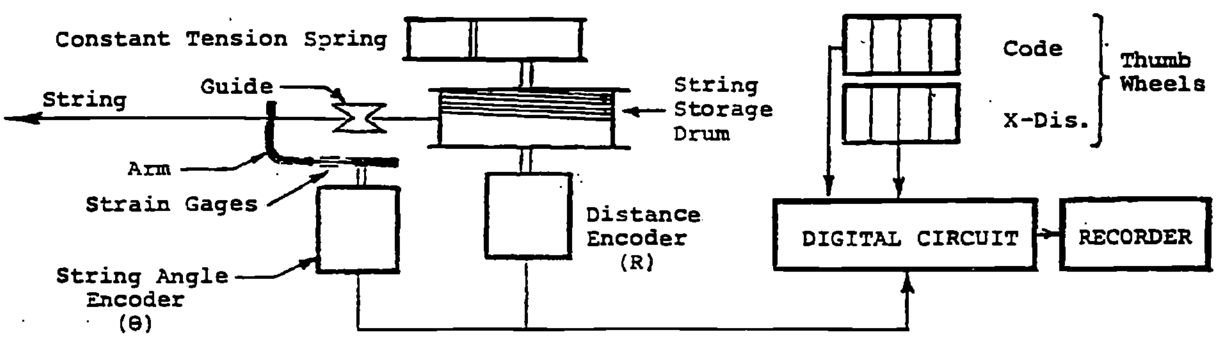

FIGURE 3 Schematic View of the Measuring Device

adding, the first digit (word aero) is the least significant digit of the first work.

At 500 KHz, every digit is read, incremented or decremented as necessary, and written back into the RAM. At 1/16 of this speed (31 KHz) the shaft encoders are examined to see if they have changed. If they have, an increment or decrement of the least significant digit is called for. The remaining digits are incremented or decremented depending on the carry from the previous digits.

The display works on a multiplexing scheme. Of the twelve light-emitting-diodes (LED) segments. only one is active at a time. At approximately 1 KHz, the digit being displayed is changed. Specifically, the digit number and value are sent serially from the main electronics box to the display. Serial transmission is used to keep the size of the cable to a minimum. The display contains all of the logic necessary to decode the BCK digit, and to drive the seven segment LED.

Writing to the tape recorder is initiated by pressing the record button on the wand. There are three phases of the write operation. First, the tape recorder is turned on, and a delay occurs while it comes up to speed. Second, each group of four words is loaded into a shift register, in reverse order of position, then sent serially to the tape recorder. The reversal of the digits converts the digits to logical order, with the least significant digit last. The third phase consists of letting the motor in the tape recorder come to a complete stop. In principle, if the record button is pressed too rapidly in succession, the tape will not be read correctly as there is too short an inter-record gap. This has not proven to be a problem in practice.

The Wafer or tape is read by a separate read-recorder with the interface circuitry for the digital computer. The real electronics are also organized around a RAM. Each data point of the tape causes the read system to cycle through four states. First, the tape recorder is turned on and the ready system waits for it to come to speed. The 64 bits of data are then read, formed into four bit word (digits), and stored in the ram. The third phase loads a ten bit shift register with the equivalent of the digit. After the computer indicates that it is ready to receive data, there 10 bits are shifted out at the bit rate (currently 300 Hz). This is repeated for each of the 16 characters. After the characters are sent, a special character follows to indicate that the line is complete. Future designs may include a read/write system in the field instrument so that the recorded data can be monitored continuously and sent to the computer over the phone lines using any available data link. The separate write/read system is attractive since it reduces the cost of individual field units and offers a measure of security. Tapes generated by the field unit can only be read by a Micro Vox read system, presumably located with the organization charged with the analysis duties.

METHOD OF OPERATION AND ANALYSIS

The measuring procedure is as follows. After assembling the equipment, the two targets are set up so that the instrument base line is approximately parallel to the centerline and the water line, but need not be precise. The device (Figure 6) is located at the first desired station and aligned with the targets with the aid of the fine adjustment screws on the tripod head. The station location is measured with the tape and entered onto the thumb wheels along with the boat/station code. The string is centered in the reference notch and the strain gage bridge and counting circuit are zeroed. Using the wand, the string is then extended to the hull keeping the alignment meter centered. If the measurer is content with the displayed coordinates at a selected point on the station, the record button is pushed and the data is automatically written onto tape. Between five and fifteen offset points are usually sufficient to define any staion. At the completion of each station, the tripod is moved down the hull a short distance, realigned, the new longitudinal distance and code are entered, and the process repeated. The canoe portions of most hulls rarely require more than ten stations for adequate definition. However, as many as twenty may be necessary to define the profile, lumps, and chines. It usually requires less than a minute to take the data at each station. Positioning and aligning the tripod at successive stations takes more time, but the entire process requires less than five minutes per station. The total man-hours needed to measure the hull should represent a significant reduction from the current requirements.

In addition to the standard offsets at each station, some additional information will be required. It will be necessary to identify a few points defining the waterline and possibly the centerline. These can be indicated by using a unique code designation for easy computer recognition. This information will be used to transform the offsets from the arbitrary instrument base line coordinate system to a standard reference system.

The method of data analysis will depend greatly on what is to be done with the information. The first step is to plug the Wafer into the computer for storage. After scaling, the offsets should be inspected for inconsistencies and bad points. A typical mistake is to forget to reset the longitudinal distance after moving to the next station. This fact is usually noticed after the station readings are taken and an error code, along with the proper x-distance can be recorded. The data must then be corrected during the computer processing. To date, all such mistakes have been recoverable and there have never been any "bad" data points.

Since the instrument coordinate system is centered some distance away from the centerline plane, it is convenient to translate and rotate the offsets to a more useful origin. A convenient scheme is to assume, unless otherwise indicated by the code number, that the first point on every station is on the centerline. A least-squares fit can then be used to shift the offset to the revised centerline. Obviously only three points, as a minimum, are required to define the centerline plane, but multipole readings and the least-squares fit reduce the importance of any one centerline measurement. Figure 7 is a straight line plot of the data points, shown by triangles, taken off a thirty-four foot yacht in under two hours. The missing points were caused by cover and support interferences and the data was taken at unequal station spacings. While it does not appear that any smoothing of the raw data would be required, spline fit routines are available. The visual inspection of a body plan is probably the fastest and most reliable type of checking procedure. This also means that no hard copy of the body plan is generated. With experience, most of the analysis process can probably be automated. This would give the administrative organization a great deal of flexibility to provide whatever services are desired by the rulemakers and the yacht racing public.

CONCLUSIONS

The quality of the handicapping process depends not only on the formula employed, but on the accuracy of the measurements taken for its evaluation. The current measurement procedure and the formulation of the IOR rating rule have had a decided influence on design, not all of it yielding better boats. It is not obvious that pinched ends, lumps, and chines, for example, contribute to faster and more seaworthy yachts. Nevertheless, such characteristics have been encouraged largely by the measurement procedure and its relation with the rating rule formula. The rulemaker and owner would benefit greatly if the desired fundamental quantities were obtained by a simple, yet thorough, measurement of the yacht hull.

A device has been described that provides the necessary hull information on digital magnetic tape accessable to the computer for processing. The time required to take this additional data is actually less than is being used now. The introduction of such a measuring device should help to provide the quantitative information, rather than ersatz measurements, necessary for accurate rating and logical handicapping.

ACKNOWLEDGEMENTS

A major portion of the design and construction effort was expertly handled by Stan Knutson sho did all of the electronics.

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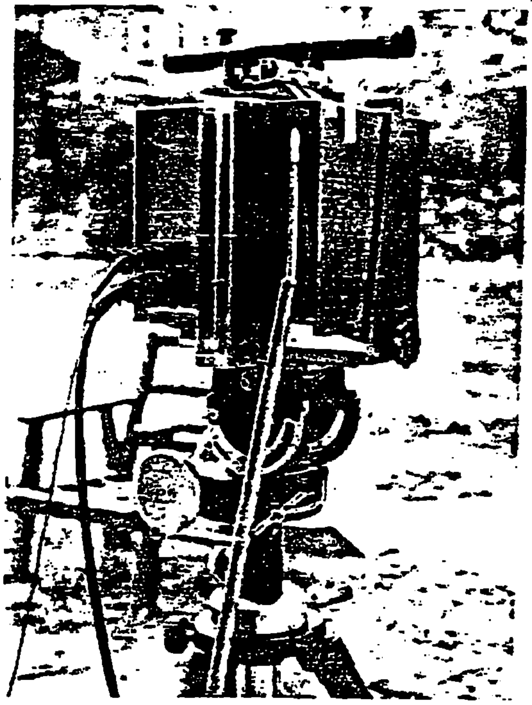

Figure 4 Case, Tripod, and the Tip of the Wand.

Figure 5 Digital Electronics.

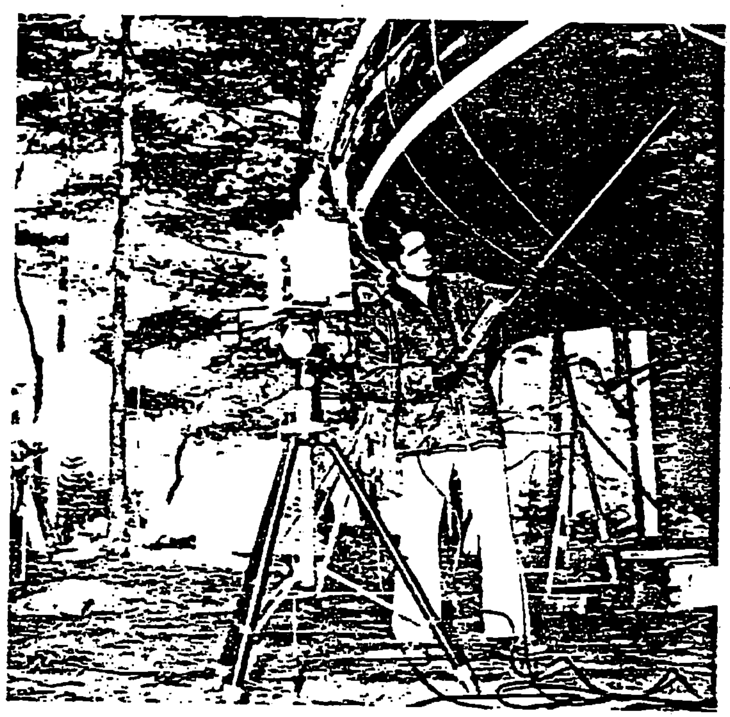

Figure 6 The Measuring System in Operation.

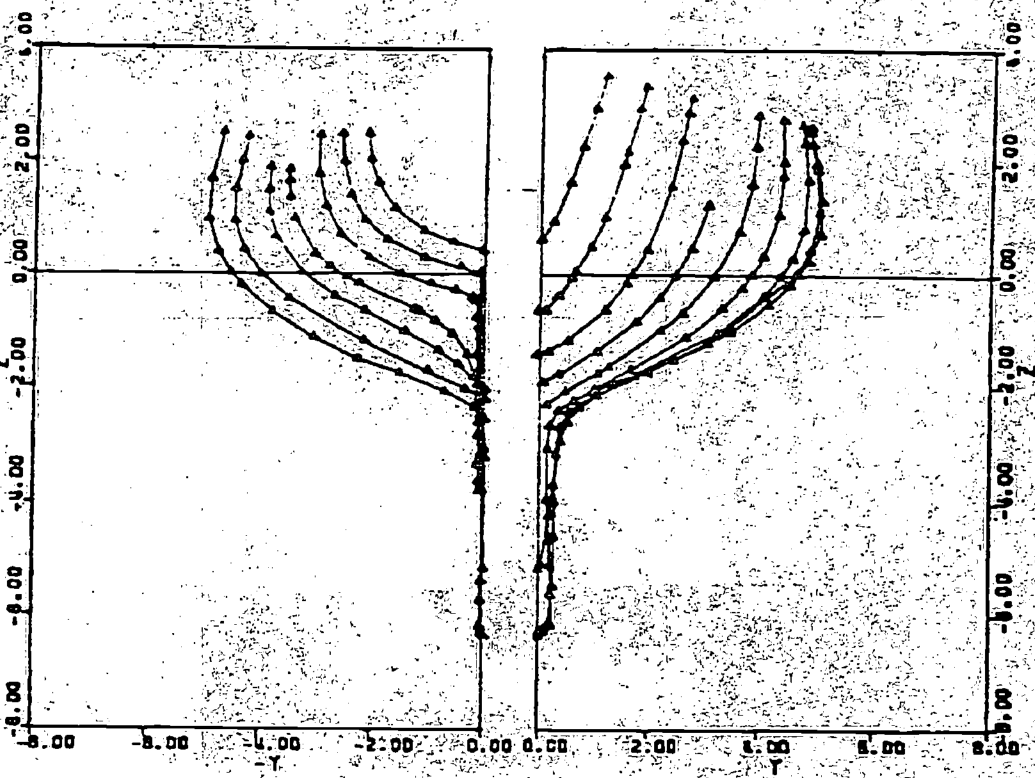

Figure 7. Straight Line Plot of Rotated, Raw Data