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Wave Surface Configuration

Readily obtained apparatus enabled the mapping of the wake of a ship model in a test basin.

ABSTRACT: *A photogrammetric system employing a pair of Rolleiflex wide-angle cameras, a universal reduction printer, and a Balplex 760 plotter is used to measure the surface configuration of a ship wake produced by a ship model towed through a large shallow model basin. Problems of camera lens distortion, photogenics of the water surface, synchronization of camera shutters, object control, corrections for systematic errors, and data portrayal are studied. Measurement in the Balplex models consisted of wave profiling and water surface contouring at 0.2-inch intervals. The model scale was 1:8. Evaluation of accuracy of data when compared with still-water measurements and with gage recordings, indicate an estimated overall accuracy of 0.5 mm. in the Balplex model.*

INTRODUCTION

WHEN MEASURING A strict three-dimensional wave surface using conventional gages, the fidelity of reproduction is drastically limited by the number of gages that one is able to install from a practical standpoint. Furthermore, the influence of the gages themselves may disturb the natural state of the surface, depending of course on such factors as wave velocity, amplitude, type of wave generation, and so forth.

The ideal measuring system for establishing a three-dimensional portrayal of the surface defined by a wave pattern, such as a ship's wake, is one which: (a) is fairly simple; (b) affords a practical infinity of measured points of the surface at one instant of time; (c) does not introduce energy into or take energy from the wave system to be measured; and (d) is not influenced by time lag, surface tension, or other disturbing elements of the measuring system. The photogrammetric system approaches this ideal. For this reason, it seems desirable to investigate the adaptation of some form of photogrammetry for application to the problem of defining a wave surface.

Photogrammetry is a system in which an object or an event in time and space is optically recorded onto a sensitized film or plate by means of an appropriate camera, and in which the subsequent image is measured in order to define, portray, digitize, or in some way classify the object or event. Stereo photogrammetry implies the use of two photographs of the object or event in order to be able to reconstruct the object or event in complete three dimensions.

If the object to be measured is in a static state, then one camera is used at two different positions in order to obtain the stereoscopic pair. However, if the object or event is in a transitory or ephemeral state, two cameras are essential. Furthermore, the two photographs must be exposed simultaneously or nearly so, depending upon the time rate of change of the object or event. A water wave surface can be considered as an object of a transitory nature, and thus it must be measured photogrammetrically. By this method, the surface is literally *frozen*, and the results are measured at the convenience of the investigator.

PRESENT STUDY

The purpose of the study reported in this paper was to determine the feasibility of applying the stereo photogrammetric method to

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the measurement of the wake of a ship model produced in a model basin. The hydraulics study included the investigation of the pattern, form, amplitude, and decay of a ship's wake as the ship moved through shallow water at various speeds. Secondary information was the correlation between ship length and wave period at various velocities, ship attitude, and the energy distribution function astern of the ship in shallow water conditions.

The model basin measures 64 feet by 150 feet by $2\frac{1}{2}$ ft., completely enclosed in a large steel-frame building. It was filled with 8 inches of water for this study. The sailing line for the ship model was located on the centerline of the basin, with provisions for towing the model at varying speeds by weights and pulleys. The ship model was 5 feet 4 inches long and 8 inches across the beam.

Cameras

Two wide-angle Rolleiflex cameras with 55 mm. Carl Zeiss Distagon objectives were used for the photography. The two cameras had been calibrated previous to the study by the method of Sewell (1948) in order to determine the focal length of the lenses, the principal point of the focal plane, and the radial lens distortion. These elements are required for the subsequent reduction of the photographic data. A generalized Distagon distortion curve is shown in Figure 1.

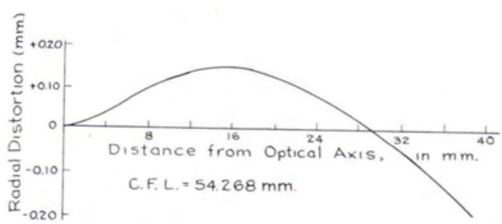

FIG. 1. Distagon distortion curve.

The Rolleiflex cameras are equipped with adaptor backs which receive plate holders containing glass plates. The camera, adaptor back and the plate holders are shown in Figure 2. Glass plates are desirable in order to insure planarity of the image at the instant of exposure and to preclude distortions due to possible film buckling in the focal plane.

In order to provide synchronization between the firing of the two cameras, a pair of Rowi pneumatic air releases were coupled by a copper tube tee to a common air bulb such that the length of hose from the tee to each of the actuating cylinders at the cameras was the same.

Controls

The Rolleiflex cameras were used because they afforded flexibility of location, a fairly large size format, and good physical stability. The fact that these cameras and the Distagon objectives were designed not for metrical but for pictorial photography was recognized at the outset. The fairly large radial distortion has little or no effect on the quality of pictorial photography but *does* introduce appreciable distortions in a photogrammetric measurement system, resulting in secondary systematic errors. Also, the fact that the Rolleiflex cameras do not contain fiducial marks forced the investigator to establish the principal points of the photographs in a manner which could introduce sizeable random errors.

Because of the probability of a combination of troublesome systematic and random errors occurring, an overabundance of control points was necessary in the object space. These points were physically realized by means of 1-inch square white targets containing $\frac{1}{8}$-inch circular black dots, and mounted in a horizontal position atop $\frac{1}{4}$-inch rods which extended about four inches above the water surface. The rods were threaded into base plates to afford the necessary stability. After they had been positioned in the basin, as shown in Figure 3, the elevations of the targets were determined by means of a K & E PL5022 tilting level and a light steel band graduated to $\frac{1}{64}$ inch. The distance between two sets of targets was measured directly with an ordinary steel tape measure. These latter measurements were used to establish scale in the subsequent photogrammetric measurements.

FIG. 2. Rolleiflex camera and adapter back accessories.

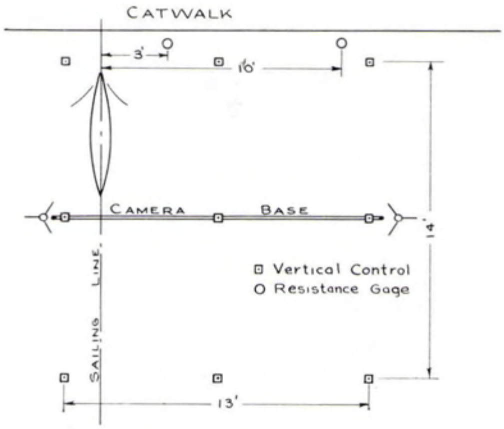

FIG. 3. Arrangement for control, photography, and towing of ship model in model basin.

ARRANGEMENT OF CAMERAS AND CONTROL

The area of interest to the investigator is shown in Figure 3. The nine vertical control points (used also for scaling) were located as indicated. The small diameter of the rods was considered by the hydraulic engineer not to have disturbed the ship wake pattern any significant amount.

The camera base consisted of a 2-inch by 4-inch aluminum channel beam into which were tapped holes to receive machine bolts to hold specially-designed *C*-brackets. These brackets were mounted in such direction so as to give each of the camera axes an angle of 20° off the vertical and convergent toward one another. This constitutes the classical 20° convergent photography arrangement used in aerial cameras for special-purpose mapping of terrain of relatively low relief. The convergency of the camera axes enchances the accuracy of vertical measurements compared to parallel-axis photography covering the same area.

Two tripods, consisting of legs made from 3-foot lengths of $\frac{3}{4}$-inch galvanized steel pipe, and uprights made of 18-foot lengths of 2-inch galvanized steel pipes, held the channel beam in position to support the cameras. The tripods were guyed to structural members of the building. The cameras were mounted 14 feet apart, and at a height of 19 feet 4 inches above the water surface.

Special fixtures, called Rolleifixes, which automatically position the Rolleiflex cameras were secured to the *C*-brackets, and the cameras were then mounted on the Rolleifixes. Finally, the shutter-actuating cylinders of the pneumatic release were attached to the cameras, and the hoses brought over to a catwalk spanning the basin in order to be convenient of access to the photographer.

It is to be noted in Figure 3 that the base was oriented normal to the direction in which the ship model was towed. This orientation was necessary to eliminate possible false stereoscopic parallax being introduced by movement of the water surface between exposures due to slight non-synchronization of the shutters.

PHOTOGENIC DEFINITION OF THE WATER SURFACE

One problem which plagues the hydraulics researcher is the difficulty of photographing the surface of a body of water. Because of the transparency of water, the surface character must be enhanced in order to provide a satisfactory photograph. This problem was overcome in a most satisfactory manner by broadcasting the confetti obtained from an IBM card-punch machine over the water surface before each run of the ship model. These punches have excellent photogenic characteristics because, being light in color, they contrast well with the almost total lack of light from the towing tank itself, and they are small enough to conform to the water surface with high fidelity.

DEFINING DATUM

In a perfect stereo photogrammetric system, the only requirement for control would be the elevations of three non-collinear control points located near the water surface together with the elevation of the water surface itself in a state of rest, and a measured distance between two points lying near the water surface. The Rolleiflex system however, not being designed for photogrammetric measurements, is subject to systematic and random errors, as previously cited. These errors combine to produce model warpage. If it can be assumed that random errors can be kept relatively small, then the effect of the systematic errors can be eliminated by some form of calibration technique. The technique used in this study was self-contained. It consisted of photographing the water surface in the quiescent state prior to the test runs of the ship model. It is sufficient to mention at this point that all measurements of the surface of the ship wake were ultimately referred to the measurements of the undisturbed water surface in order to reduce all measurements to datum and thus eliminate model warpage caused by the systematic errors and those random disturbances which could be evaluated.

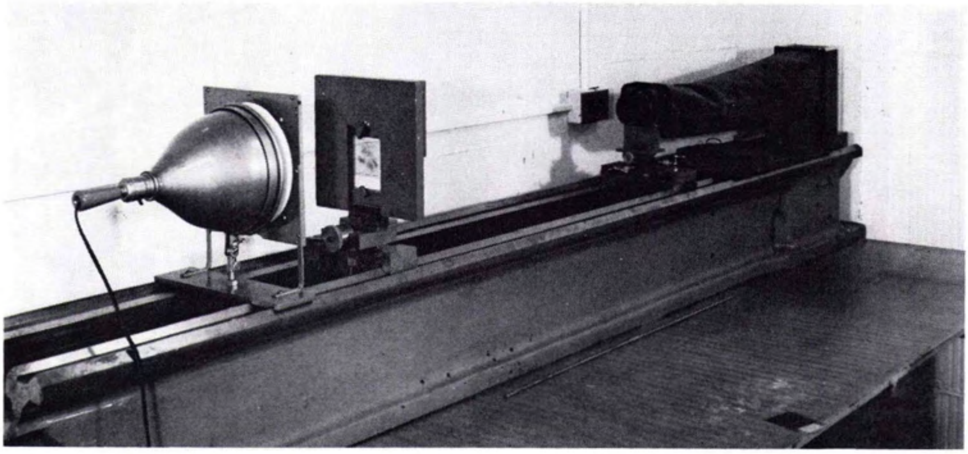

FIG. 4. Universal reduction printer.

AUXILIARY INSTRUMENTATION

In order to obtain independent measurements for use in verifying or establishing the reliability of the photogrammetric system, two resistance gages were installed as shown in Figure 3. Each gage contains a pair of probes connected to one branch of a Wheatstone bridge, and which extend into the water. The water itself closes the circuit of that branch. As the water rises, the resistance in the branch decreases, causing an unbalance in the bridge, which in turn produces an increase in current in the cross bridge. The output from the bridge is conducted to an oscillograph which records the height of the water on a drum recorder.

The vertical scale of the gage is calibrated quite simply by raising or lowering the probes with reference to a vernier, and either noting the vertical displacement on the drum recording, or adjusting the circuitry to bring the vertical displacement to some predetermined spacing on the recording paper. The horizontal scale is presumably established by the speed of the recording paper past the recording pen. The horizontal scale is thus a time scale.

PHOTOGRAPHY

Kodak Tri-X film was used in order to obtain the necessary speed under the conditions of ambient lighting. The card-punch confetti was broadcast over the target area by means of a long-handled spatula from a position on the catwalk shown in Figure 3. This in itself was an awkward operation both because of the large area to be seeded and because of currents in the basin which tended to move the confetti out of the target area.

The first synchronous exposure was made of still water to establish the datum control. The exposures were made at 1/60 second at *f*/4 0. The cameras were set to focus at 20 feet.

The ship model was then towed at speeds of 2.22, 2.78, 3.20, 3.94, 4.20, 4.45, 4.55, 5.07, 5.65 and 7.32 feet per second. The first three runs were exposed at 1/60 second at *f*/4.0; the remaining seven runs were exposed at 1/125 second at *f*/4.0. The first three speeds produced deepwater conditions in that the ship wake which was generated did not *feel* the bottom of the basin. The next four speeds produce shallow water conditions below what is referred to as critical speed. The last three speeds also produced shallow water conditions, but above the critical speed.

REDUCTION OF NEGATIVES TO DIAPOSITIVES

In order to obtain the same horizontal and vertical scales in the steresocopic model, the negatives were reduced in a specially designed universal reduction printer, shown in Figure 4. The printer accepts diapositive plates for Multiplex and Balplex plotters as well as negative plates produced in the Wild P30 phototheodolite and the Rolleiflex cameras. It is equipped with a Goerz Red Dot Artar process lens with a 16½-inch focal length mounted on the compound head of a jewelers lathe. The distance from the edge of the lens barrel to the diapositive plane is established by means of a gage rod of appropriate length, (32.000 inches in this study), and the remaining distance set off by means of the longitudinal motion of the compound head, giving the necessary image distance from the rear node to the diapositive plane. The negative plate holder is set at the appropriate distance from the front edge of the lens barrel to the negative plane in the same manner, except that the final value is obtained by the micro-motion of the negative plate holder. This establishes the appropriate object distance from the front node to the negative plane.

The Balplex 760 plotter in which the measurements were made has a principal distance of 55.00 mm. The object and image distances were established in the reduction printer to be compatable with the principal distances of the two cameras when focussed for an object distance of 20 feet.

Diapositives were exposed on Kodak medium contrast Aerographic Positive plates 11 cm. by 11 cm. by 0.090 inch. The plates were processed in Kodak developer D76 for a period of $3\frac{1}{2}$ minutes at 70°F.

Balplex Instrumentation

The Balplex 760 plotter is an ellipsoidal-reflector, double-projection stereoscopic plotting instrument containing lenses set at 55-mm. principal distance to give an optimum projection distance of 760 mm., or 30 inches. The lenses are capable of being canted about an axis normal to the optical axis so that when the projectors are oriented with 20° convergence, the plane of best definition can be made to lie parallel with the surface of the mapping table in the plotting space. This satisfies the condition, formulated by Scheimpflug, that the negative plane, the lens plane, and the image plane must all intersect in a common line.

The vertical distance from the camera base to the water surface was 232 inches. This fixes the Balplex model scale at 30/232 or, more conveniently, $\frac{1}{8}$. That is to say, 1 mm. in the Balplex model is the equivalent of 8 mm. or 0.314 inch in the model basin, both horizontally and vertically.

Relative orientation of the two projectors was performed using the targets, these points having been designed for the dual function or relative and absolute orientation. The considerable amount of lens distortion of the Distagon objectives, when enlarged by 13 diameters in the Balplex projectors, would certainly preclude the possibility of obtaining relative orientation in a satisfactory manner if the photography conformed to the normal parallel-axes orientation of the cameras. As the 20° convergence and the B/H ratio selected for the photography give an overlap of about 100 percent, and because both camera lenses produce essentially the same distortion curves, the y-displacement at any point in the model area caused by one photograph is essentially equal to the y-displacement caused by the other photograph. However, difficulty was encountered in obtaining a satisfactory overall orientation, no doubt due to a combination of random and systematic errors in this relatively crude system.

The model scale was set by reference to the distance between targets. Leveling was performed on the corner points. After an average overall fit to the four corner points was obtained, all the vertical control points were read and recorded.

MEASUREMENT IN CONTROL MODEL

A 5-cm. grid was ruled on the Wild coordinatograph covering an area approximately 30×36 inches. The grid was placed on the map table under the control model which represented the water surface at rest, and centered approximately beneath the projector base. The control points were plotted onto this grid for future orientation.

The elevation of each grid intersection was measured in the model and recorded to 0.1 mm. The total usable area measured approximately 24×29 inches. Rows and columns were numbered for correlation with subsequent measurements. These readings defined the first approximation to the datum, and varied over the area by a maximum of 1.6 mm. in a fairly systematic fashion. In effect, the datum appeared as a broad dome in which the middle was 1.6 mm. higher than the corners. It was not perfectly symmetrical, no doubt reflecting random errors of interior orientation and also relative orientation.

SELECTION OF LINES FOR MEASUREMENTS

In a study such as the one under discussion, the photogrammetrist and the hydraulic engineer must consult together at the point when the surface phenomenon is ready to be measured. The hydraulic engineer must delineate, quite precisely, which area is to be measured or which line is to be profiled. One of the distinct advantages of the Balplex plotter over all others for this type of analysis is its capability of showing the entire model at one time. The engineer can then scan the model, make a judgment as to which areas or which lines will give the most information for the investigation at hand, and then indicate these areas to the photogrammetrist.

In order to present the entire model for critical study, the grid sheet was placed on a drafting board which, in turn, was blocked up so that the grid sheet intersected the mean datum. The orienting device shown in Figure 5 was used to orient the map sheet beneath the projectors by reference to the control points previously plotted on the grid.

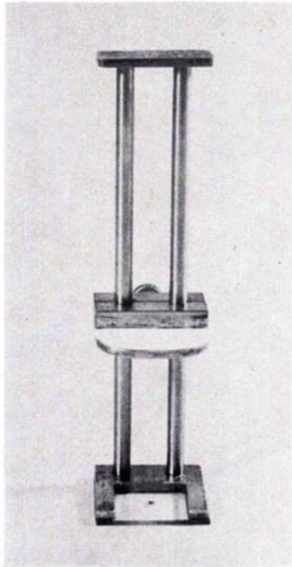

FIG. 5. Orienting device.

DEEP-WATER RUNS

The deep-water models were all measured by identical procedures. The 5-cm. grid was plotted on vellum, and a correction diagram, derived from vertical control readings, was superimposed. The corrected datum elevations were recorded at each grid intersection. The vellum was then blocked up on a drafting board to coincide with the average datum in the model and was oriented by means of the device shown in Figure 5.

The hydraulic engineer and the photogrammetrist then delineated the crest lines of the bow wakes and the stern wakes as shown on the measurement diagram of Figure 6. Selected cross-profile lines were also drawn. The sailing line, the side of the ship model, and the gage line for the nearest resistance gage were also drawn. These lines were then marked at $\frac{1}{8}$-inch intervals (corresponding to 1-inch intervals in the model basin), and the sheet was then reoriented to the Balplex model.

In order to determine the attitude of the ship model at various speeds, the height of the bow and the stern were measured. This is the point at which the camera synchronization can be checked. At the low speeds, the shutter speed was set at 1/60 second. This interval represents a distance in the Balplex model of approximately 0.05 inch at model speed of 2.22 ft/sec, increasing to 0.08 inch at model speed of 3.20 ft/sec. The ship model thus appears blurred in the stereomodel. Now if the shutters are out of synchronization by say 1/100 second, a y-parallex will be produced of the order of 0.7 to 1.2 mm. over the ship. No significant parallax could be detected, probably due to the blurring of the images. The shutters were thus considered to be in satisfactory synchronization for these low-speed runs.

Profiles measured along the crest lines of the bow wake produced at a speed of 3.20 ft/sec are shown in Figure 7. These profiles were used by the hydraulic engineer to establish the peaks of the crest, among other things, in order to measure the angle of these peaks with the sailing line, as shown in Figure 6.

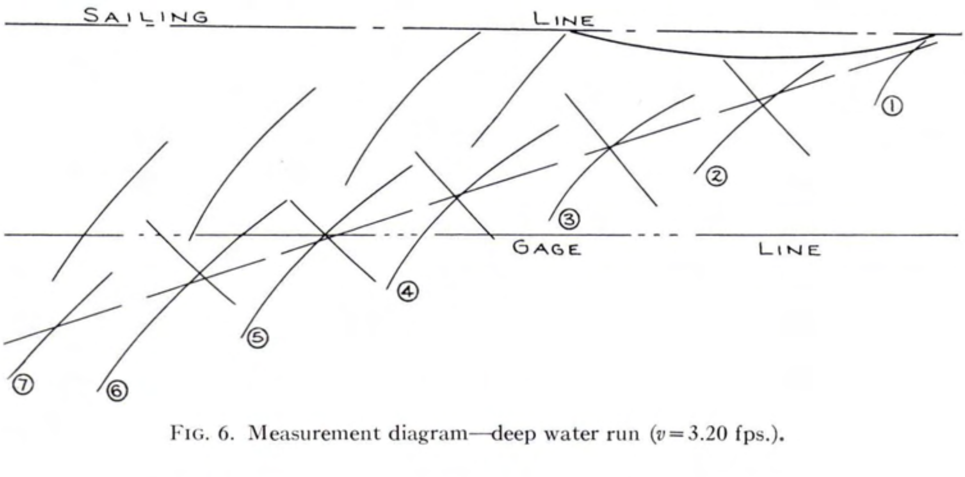

FIG. 6. Measurement diagram—deep water run ($v=3.20$ fps.).

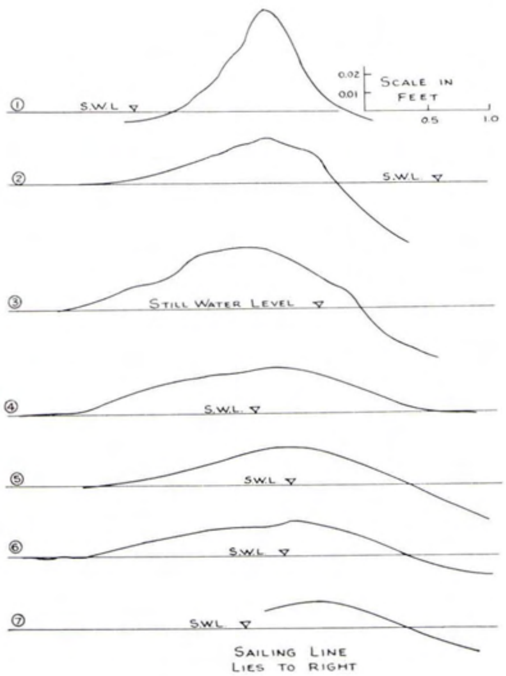

FIG. 7. Crest profiles—ship model speed = 3.20 fps.

The profiles taken along the gage line were used for comparison with the resistance gage recordings. The profiles taken along the sailing line and the side of the ship were used to determine the periods of the transverse wake (not shown in Figure 6) at various speeds, and to determine the decay in amplitude of these waves astern of the ship.

Shallow-Water Runs

The measurements of all the shallow-water runs took the form of surface contouring, with a contour interval of 0.635 mm. in the Balplex model, corresponding to 0.2 inch in the model basin. A correction diagram was prepared for each stereo model, based on the readings of the vertical control points following the leveling operation. The correction diagram was then used to prepare the corrected datum grid for each model respectively. The grid, containing the numerical values of the corrected datum, was then oriented beneath the Balplex model. As the contouring proceeded, the tracing table reading was more-or-less continuously corrected (actually in steps of 0.1 mm.) to reflect the true height above or below datum. Spot heights along broad crests and troughs were read to provide greater fidelity.

The heights of the bow and stern above datum were measured in each run. Only at the highest speed (7.32 ft/sec) did the photography show the shutters to be out of synchronization. The y-parallax over the ship model in this case amounted to about 1.5 mm., indicating a delay of the order of 1/175 sec. Also, at this speed, y-parallax in varying amounts was detected in the model surface due to the physical horizontal displacement of the water as the wake passed over the area. The y-parallax was eliminated over this model from area to area by a BY-motion of one of the projectors in order to perform the contouring. Any false x-parallax of course contributed to errors in the contouring.

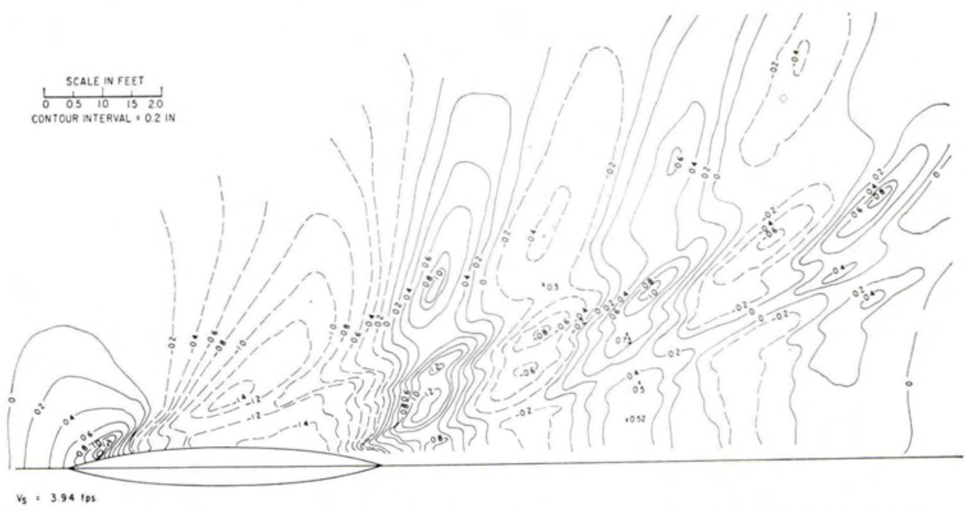

FIG. 8. Ship wake contours, $v = 3.94$ fps. Dashed contour lines lie below still-water datum.

FIG. 9. Ship wake contours, $v=4.55$ fps. Dashed contour lines lie below still-water datum.

Contour maps of three of the runs made under shallow-water conditions are shown in Figures 8, 9, and 10. The speed of the run which produced the configuration shown in Figure 8 is the lowest of the shallow-water tests. This map shows the three sets of wakes very clearly, the bow wake, the stern wake, and the transverse wake. The high points of the crests can be inferred quite easily. Wave lengths are also easily measured.

The configuration in Figure 9 was produced at a speed of 4.55 ft/sec., as the ship approached critical speed. The first bow wake is seen to approach an angle of 90° with the sailing line. Water is observed to pile up in front of the ship model. Wave length is increased. The broad transverse wakes, evident in Figure 8, are not readily apparent at this higher speed.

The highest speed, 7.32 ft/sec., produced the wake shown in Figure 10. The angle of the first bow wake has fallen off very drastically, a characteristic of supercritical speeds. The ship is moving too fast for the water to pile up in front. Transverse wake is not readily discerned.

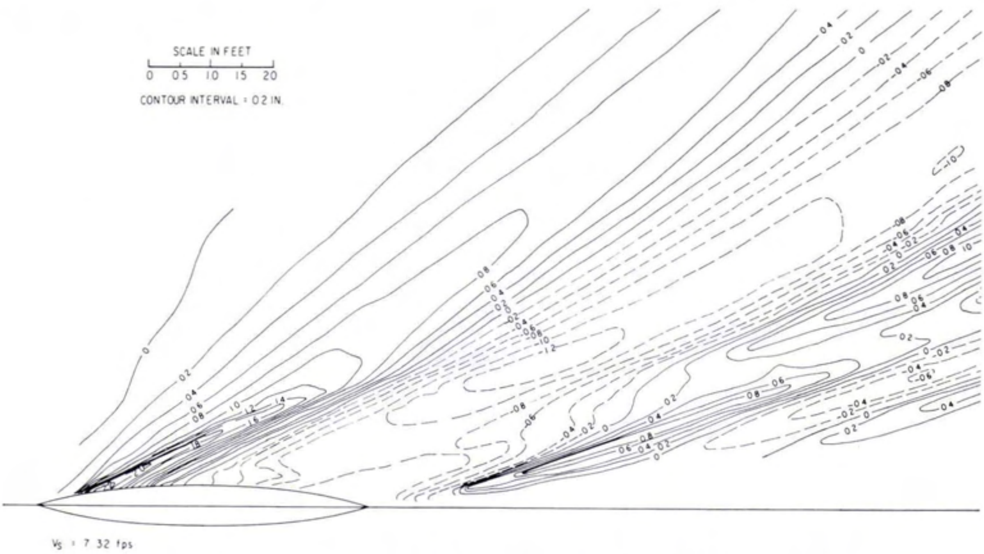

FIG. 10. Ship wake contours, $v=7.32$ fps. Dashed contour lines lie below still water datum.

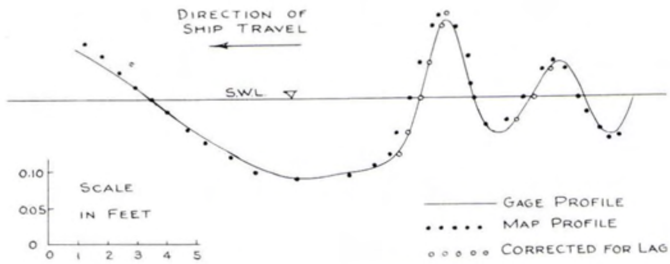

FIG. 11. Gage-line profile comparison ($v=4.45$ fps.).

These are but a few obvious phenomena which can be determined from the contoured wakes. Any desired profile may be taken from the map. The surface can be digitized to analyze the energy distribution in the water. The maps afforded the hydraulic engineer a complete quantitative three-dimensional picture of the surface of the water which can be subjected to a variety of hydrodynamic studies.

VERIFICATION OF ACCURACY

Probably the most positive test of the accuracy and fidelity of geometric reconstruction obtained by the Rolleiflex-Balplex combination is that of taking the readings over the entire model of the water in its quiescent state. This was discussed earlier, in which case the model was leveled to the four corner vertical control points. The resulting discrepancies are due mainly to systematic errors of objective distortions and random errors of principal point marking (Konecny, 1965), relative orientation, and stereo-operator error. Given the premise that the major portion of systematic warpage can be identified by means of enough vertical control judiciously positioned in the model area, the remaining maximum random errors in this system are found to be of the order of ± 0.4 mm. measured vertically in the Balplex model. The investigator believes that the system can produce overall accuracy of the order of 0.5 mm. at Balplex model scale.

As an indication of the accuracy of the contour maps, a profile was taken along the gage line 3 feet out from the sailing line on the map of the run at 4.45 ft/sec. This profile is shown in Figure 11. The map profile is compared with that obtained with the gage recording device.

The chief sources of discrepancies between the photogrammetric profile and the gage profile are: (1) residual random errors of the photogrammetric system; (2) false x-parallax introduced by non-synchronization; (3) lag in response of recorder; (4) recorder inertia; (5) error in accepted speed of recording paper; (6) error in the accepted speed of the ship model; and (7) acceleration of the ship model through the target area. The maximum vertical discrepancy in the profiles as plotted is about 15 mm., or about 2 mm. in the stereo model. However an examination of the profiles shows a backward horizontal shift in the front slope of each wave. This tends to indicate recorder lag or recorder inertia, which when corrected for, reduces the maximum vertical discrepancy to about 4 mm., or 0.5 mm. in the Balplex model.

CONCLUSIONS AND RECOMMENDATIONS

This present investigation establishes the feasibility of a photogrammetric system in defining wave surfaces. The system itself, being only an approximation on account of large systematic errors, is shown to be adequate provided that sufficient and well-placed control is established, and that the necessary corrections are made. The data reduction, however, is quite tedious and time-consuming, to say nothing of the actual photography.

The greatest improvement in the wave-measuring system is to be found in the cameras. The Rolleiflex wide-angle Distagon covers an angular field of approximately 50° from side to side. The format size is excellent. However, the Balplex plotter can accommodate an angle of slightly over 75° from side to side. Thus, the ideal camera should have this angular coverage. A maximum lens distortion of 20 microns on a $2\frac{1}{4}$-inch square format would provide the accuracy required in this type of measurement.

The camera lens must have provision for focussing at finite distances as close as perhaps 30 inches for certain studies. This would afford the opportunity of establishing 1:1 scale in the Balplex projector.

The focal plane must contain some form of fiducial marks. Ideally, provision should be made for independent exposure of the marks because the background field in wave photography is characteristically dark. It would certainly be possible, although perhaps inconvenient, to design a vignetting frame to be placed in front of the objective, with light portions of the frame protruding into the picture area sufficiently to give background light in the vicinity of each fiducial mark.

The cameras should be capable of recycling by remote control, eliminating one very awkward step in the photography. In order to keep the camera fairly lightweight and compact, the system might preclude the use of plates. On the other hand, for high accuracy, and in many applications in the field of hydraulics, the positions of the cameras could very well allow manual changing of plates between exposures with little inconvenience.

The problem of synchronization between the two exposures is very serious because a movement of the upper surface of the water invariably takes place no matter what type of wave is generated. The obvious solution to the synchronization problem is one instantaneous pulse of high-intensity, short-duration light, synchronized with the opening and closing of the shutters.

The instrumentation and procedures adopted for this present study are to be considered as experimental only. The results are most encouraging, and they warrant further development. The idea of being able to *freeze* a transitory phenomenon such as the surface of a body of water subject to wave action, and precisely measuring this surface, is quite exciting. It offers possibilities of using generated waves to simulate other physical phenomena which can then be precisely measured.

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