“THE MONOFORM SHIP CONCEPT: DESIGN PRINCIPLES AND PRELIMINARY PERFORMANCE CHARACTERISTICS”

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ABSTRACT

Progress on the MONOFORM ship concept is discussed. Three areas are addressed; early history of the MONOFORM, hydrodynamic performance based on model tests, and future development of the MONOFORM concept.

Drag data discussed in this report show the MONOFORM to have a C_d that is higher than the C_d of the 5 ft. S^3 design tested by Dr. Lang. The MONOFORM concept is still relatively new and has more design variables to be investigated than any other ship concept, therefore no conclusion can be made yet as to whether the MONOFORM is a better alternative to the S^3 concept.

BACKGROUND

The MONOFORM design as illustrated in Figure 1 can be considered a spin-off of the S^3 design (semi-submerged ship, Figure 2) presently being investigated by the U.S. Navy. Like the S^3 concept it uses a sub-surface hull and surface piercing struts to minimize wave drag and to improve seakeeping qualities. The surface piercing struts are widely spaced apart to maximize the transverse waterplane moment of inertia thereby providing static stability. The small waterplane area concept has several advantages over a conventional surface ship. The U.S. Navy is presently engaged in studies to determine whether these advantages merit a further commitment to the small waterplane area concept. Some advantages suggested are: reduced wave making resistance, improved seakeeping characteristics and a large deck area. The reduced wave making drag of a S^3 hull is negated by its large wetted surface producing large frictional drag at low speeds, however, at high speeds where wave drag starts to dominate, the total drag will be lower than the total drag for a destroyer type hull. The small waterplane area of the S^3 design provides little change in buoyancy when a wave acts on the struts, thus the ship's response to waves is less than that for a conventional hull. This feature also suggests the capability of maintaining speeds in stormy seas. The wide transverse spacing of the struts results in a much larger deck area than that of surface ships of the same displacement. A large deck area and good seakeeping make the

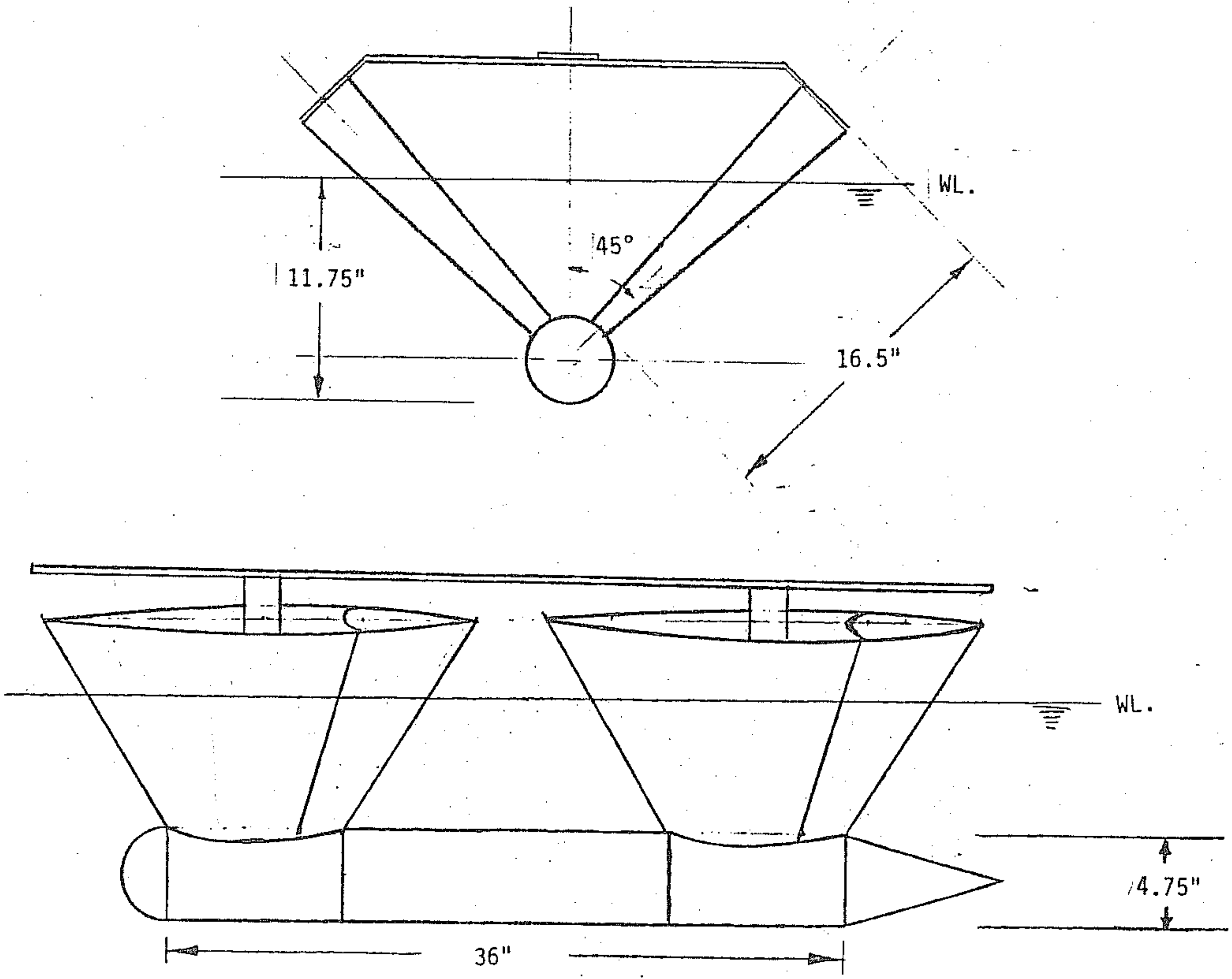


Fig. 1. MONOFORM Model as used in Tests.

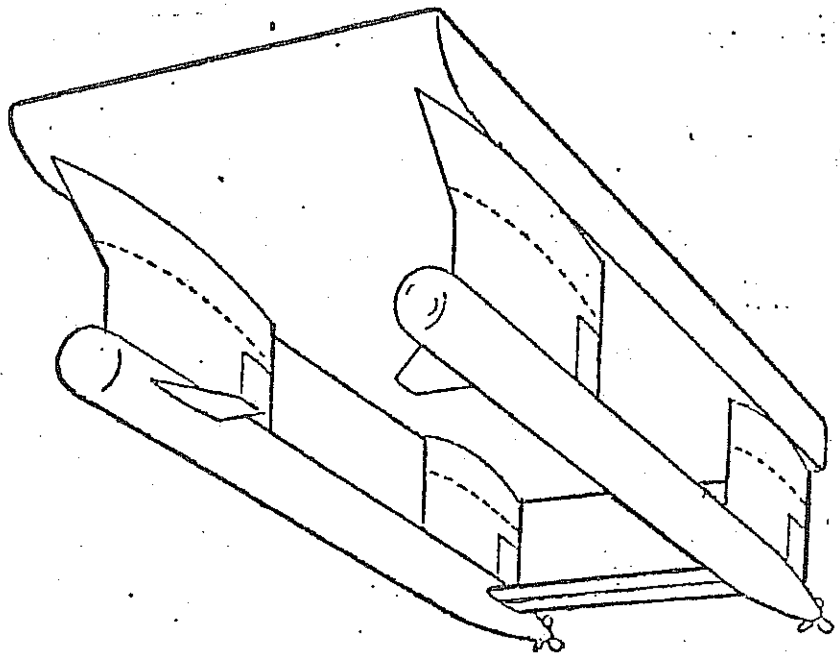


Fig. 2. NUC's semi submerged ship (S^3)

S^3 concept attractive for military applications, where helicopter and V/STOL operations are becoming more prevalent every day.

While the MONOFORM retains the advantages of the S^3 concept, it distinguishes itself from the S^3 by some additional attractive features. The elimination of one of the underwater cylindrical hulls reduces the wetted surface. If all other factors remain constant, the surface friction of the ship is reduced in direct proportion to the wetted surface reduction, which could be as high as 15-20%. The closed structure achieved by the triangle of the struts and deck is inherently stronger than the open U-shape of the twin hull concept. For the same overall strength, the V-structure will be lighter than the U-structure, reducing the structural weight and thereby increasing the payload or the fuel capacity. Unlike the twin hull concept, the MONOFORM does not require horizontal control surfaces for pitch control. The V-shaped struts of the MONOFORM, equipped with flaps, can exert forces and moments in the vertical plane similarly to control surfaces of V-tailed aircraft. The elimination of horizontal control surfaces will further reduce the drag. The presence of control surfaces that can generate forces and moments in all directions enable the MONOFORM to perform coordinated turns and to counteract heeling moments. In the event of damage to the underwater portion of one of the struts or the hull, the MONOFORM hull would experience a smaller heeling moment than a twin hull would. Thus, the damage stability of the MONOFORM appears to be superior to that of the S^3 designs. A final advantage to the MONOFORM concept is that one single cylindrical hull has more usable space than two smaller hulls and also avoids duplication of certain systems like firefighting equipment, alarms, air conditioning and communication equipment. Furthermore, in the event of an emergency, the MONOFORM provides four routes of escape while the twin hull would only allow two routes of escape per hull.

The development of the MONOFORM at Virginia Polytechnic Institute and State University has been proceeding at a slow, but steady pace. From 1975, when a feasibility study on the MONOFORM was performed for the Office of Naval Research,[1] through the present, Dr. Szeless and several students have investigated the performance characteristics of the MONOFORM concept. A number of undergraduate research projects were dedicated to mathematical analysis, model design, model building and model testing of the MONOFORM concept. This paper discusses the results of the towing test of the second MONOFORM hull model, as performed by Mark A. Tesh and the author in the VPI&SU towing tank. The primary results discussed are the relationship between the hull velocity and drag and the corresponding variation in the drag coefficient. The behavior of the model in waves at low speeds was briefly investigated, although limitations of the experimental equipment prohibited full speed seakeeping tests.

EXPERIMENTAL EQUIPMENT

A. Model

The model used in the experiment was built in the Mechanical Engineering shop at Virginia Polytechnic Institute and State University and was completed in April 1981. Dimensions are shown in Figure 1. The cylinder and endsections are made of turned aluminum and the struts are sheet metal over a frame. Several connections were provided to permit the model to be tested in the towing tank. Two mounts were installed at either end of the longitudinal support bar to mate with the model yokes on the carriage and a wooden block was fastened to the support bar to be held by the clamp on the carriage. The rudders on the trailing edge of each strut are adjustable, and were held in place with a locking screw.

The model displacement was designed to be 61.5 lbs., which is also the displacement of the 5 ft. model that Dr. Lang used for his test. Upon completion of construction however, the displacement proved to be 69.5 lbs., 8 lbs. heavier than Dr. Lang's model. Although the higher weight increased the wetted surface area, it was expected that usable results could still be obtained with this model.

B. Towing Tank

The towing tank at Virginia Polytechnic Institute and State University is a 100 ft. by 6 ft. basin filled with water to a depth of 4 ft. The carriage runs on rails along the length of the tank. The electric controls of the carriage motors permit regulation of the speed of the model as it is towed through the water. A calibrated wheel, which rolls with the carriage, permits recording the exact velocity of the model.

Several attachments are included to facilitate precise measurement of the model's behavior. Two gimbal-mounted yokes hold the fore and aft of the model, and include scales to measure surge and pitch while allowing free motion. A clamp secures the model between tests and during acceleration.

A fine steel band and low friction pulley permit the resistance force on the model to be transmitted to the balance for measurement. During the test, the balance indicates whether the resistance force is equal to a known force.

C. Instrumentation

Several pieces of equipment were installed on the carriage to help measure and record the behavior of the model. A diagram is shown in Figure 3.

A variable resistance strain gauge and bridge amplifier were used to measure the drag force on the model. After it became evident that the weight balance was impractical, the output of the amplifier, recorded on channel one of a two channel strip recorder, was calibrated to provide direct measurement of the force applied to the strain gauge. The rotational speed of the calibrated carriage wheel was recorded on the other channel of the strip chart recorder, indicating the model's speed. A 35 mm camera was attached to the underside of the carriage and

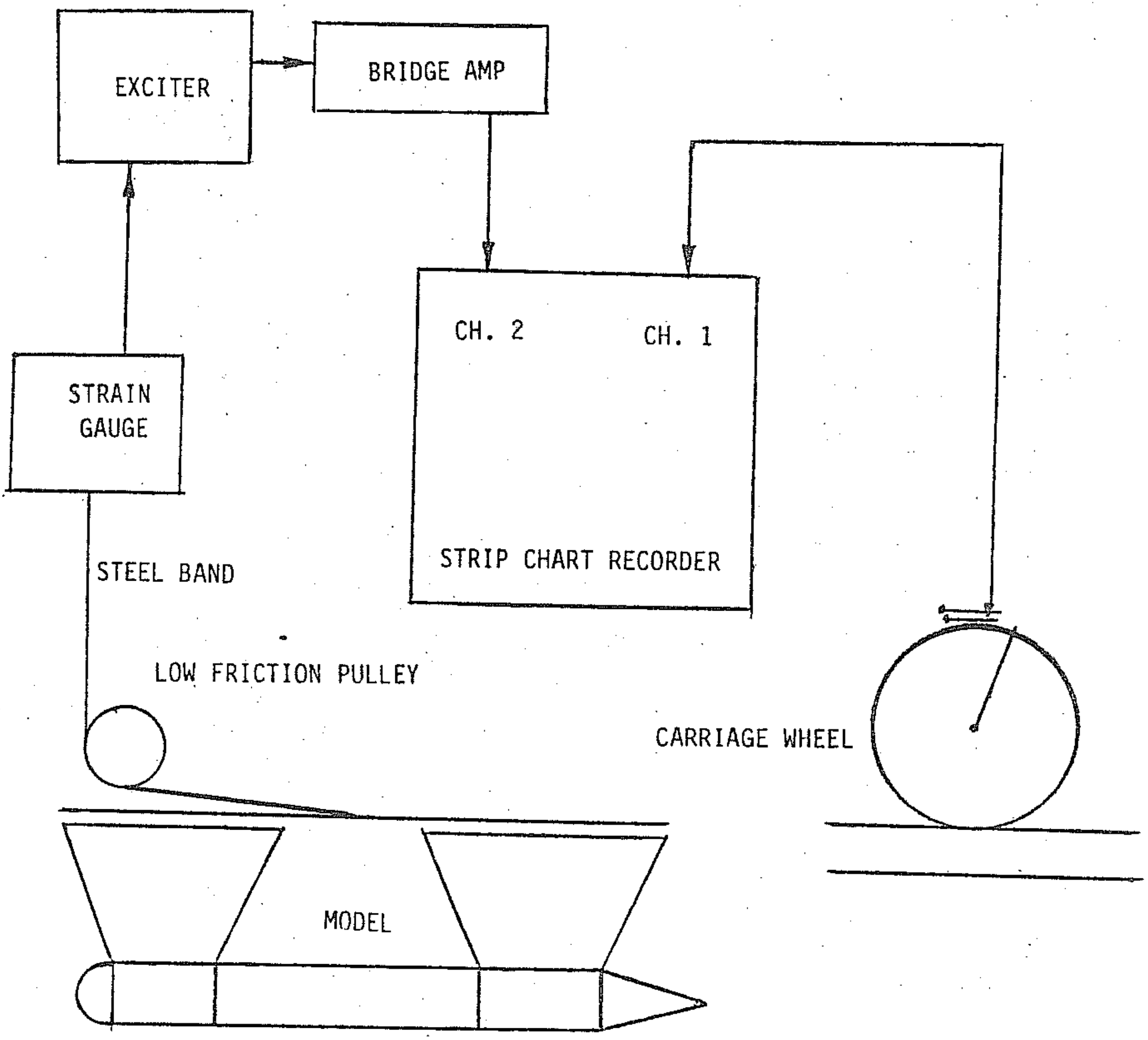


Fig. 3. Instrumentation Diagram

lights were installed to provide a photographic record of the model's behavior.

D. Wave Machine

A blower mounted at one end of the tow basin generated waves by varying the pressure over a strip of the water surface. The wavelength and amplitude of the waves could be adjusted by changing the intensity and duration of the pressure pulse over the water. Wave tests could be conducted either with the model stationary or being towed into the waves. Oblique wave angles were not possible with the given equipment.

DISCUSSION AND RESULTS

Day 1 was spent in assembling the test setup and doing some exploratory runs. To obtain an even static trim for the model a small amount of weight had to be added on the port side of the model and about two pounds of lead were added forward. The first few runs were made with a conventional setup, where the model had complete horizontal and vertical freedom of movement. It was soon noted that the model experienced excessive nose down behavior around 0.8 m/sec. The measurement procedure involving the balance and weights were also cumbersome and ineffective.

On Day 2 the same procedure was followed as on Day 1 except the forward hinge point was fixed so that the model could not attain the severe nose down attitude it had displayed on Day 1. A drag comparison at low speeds was made between a fixed forward hinge point and a free forward hinge point and it was found that this change did not alter the drag value significantly as long as the model was not allowed to move backwards relative to the carriage during a run. A backward excursion of the model would move the hinge point away from the vertical and add a horizontal drag component to the model, making the balance drag reading useless. At higher speeds it became clear that it was impossible to prevent the model from moving relative to the carriage and the need for a strain gauge to be used for drag measurements became evident. It was noted that the tail of the model would drop drastically with increasing speed. It could not be determined whether this effect was due to the fixed forward hinge point, where the model was connected to the carriage yoke, or whether this was normal model behavior. Unrestrained low speed runs indicated that the tail tended to rise, but it is conceivable that this trend varies at higher speeds. Removing the two pound nose weight to give the model an initial positive angle of attack had little effect.

Day 3 was the first day that drag data were obtained by means of the variable resistance strain gauge. The first part of the day was spent getting a complete set of drag readings at regular intervals up to a speed of 1.80 m/sec. At higher speeds the model was left unclamped during acceleration since it was discovered that oscillations in the drag reading would die out faster this way than when the model was clamped until steady speed was attained. Leaving the model unclamped was a significant improvement since the steady speed time interval became rather small at higher speed due to the limited length of the tow basin. The rest of the day was used to gain some understanding of the nose down pitching problem. This problem is partly caused by the pitching moment created by towing the model at a point nearly 14 inches above the design propeller axis.

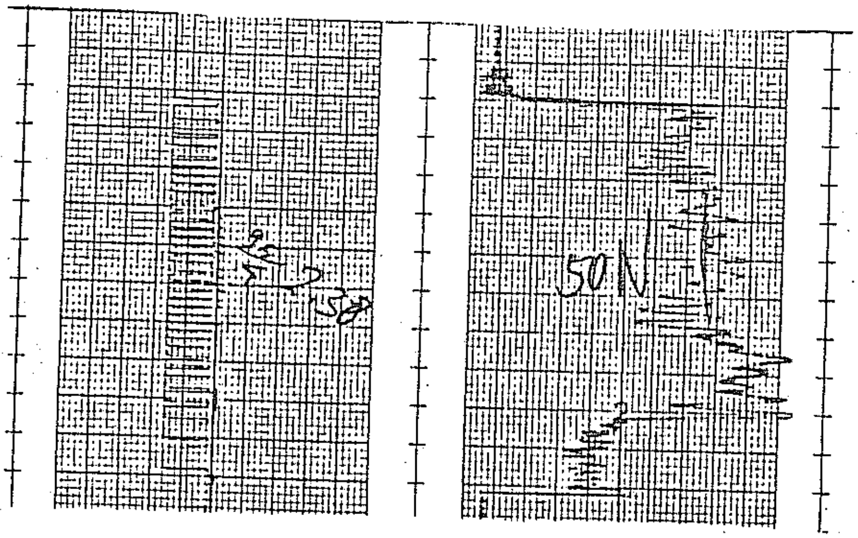
A number of runs were conducted with limited forward pitch freedom. It was suspected that once the model reached hump speed it would display a nose up attitude and would not require any forward pitch restraint. This theory proved false even at speeds higher than the hump speed. Reduction of the towing induced pitching moment, either by towing the model from below the waterline or using a self-propelled model should serve to clarify this point.

The next tests were made with the forward rudders deflected 10 to 15 degrees downward. Except for a slight increase in drag the model behaved in a similar fashion to previous tests, and no significant improvement was noted in the model's tendency to nosedive.

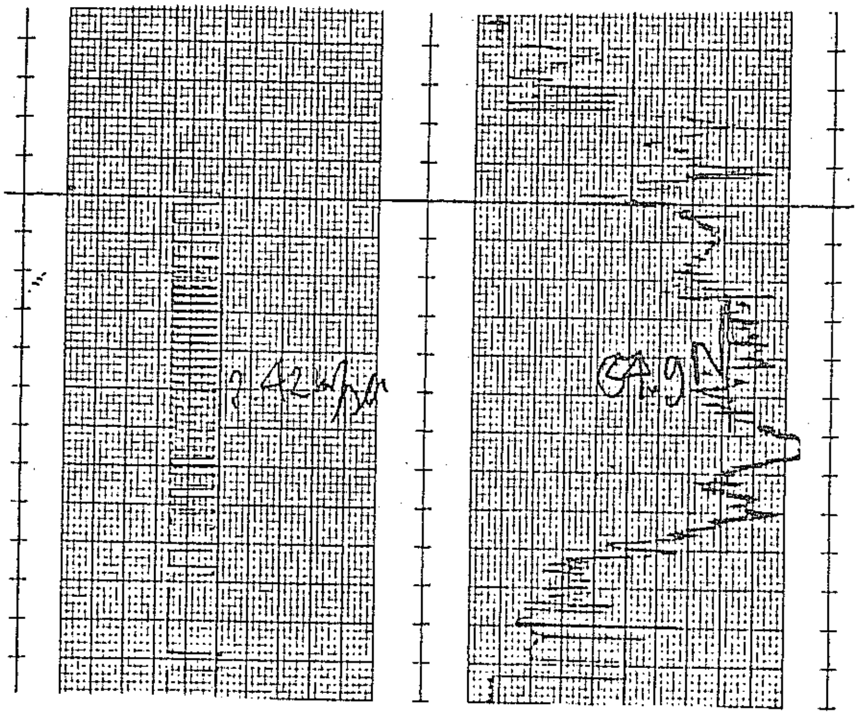
Day 4 was used for obtaining drag readings for model velocities above the hump speed and for evaluating the model's static response in wave motion. Test velocities covered the entire range possible on the towing tank carriage. Strip chart data from these tests showed the vibration introduced during the intense carriage acceleration and the short amount of time high speed was maintained. (Figure 4 and 5). Two runs were made at each speed to insure a more reliable value for drag regardless of erratic data.

A plot of drag vs speed force is shown in Figure 6. The resistance increases up to a velocity of 4.53 ft/sec (Fr = 0.78). Then the characteristic hump, typical of the MONOFORM design, is observed, and the drag drops nearly 1.5 lb. for the next 1 ft/sec increase in speed. A plot of the drag coefficient C_d vs F_r is shown in Figure 7.

When the model was disconnected and floated free in the basin, no excessive resonance was noted as the model was subjected to waves varying in frequency from 0.79 to 2.0 Hz from various angles of attack. Since no quantitative measurements could be made, no further resonance investigations were made.

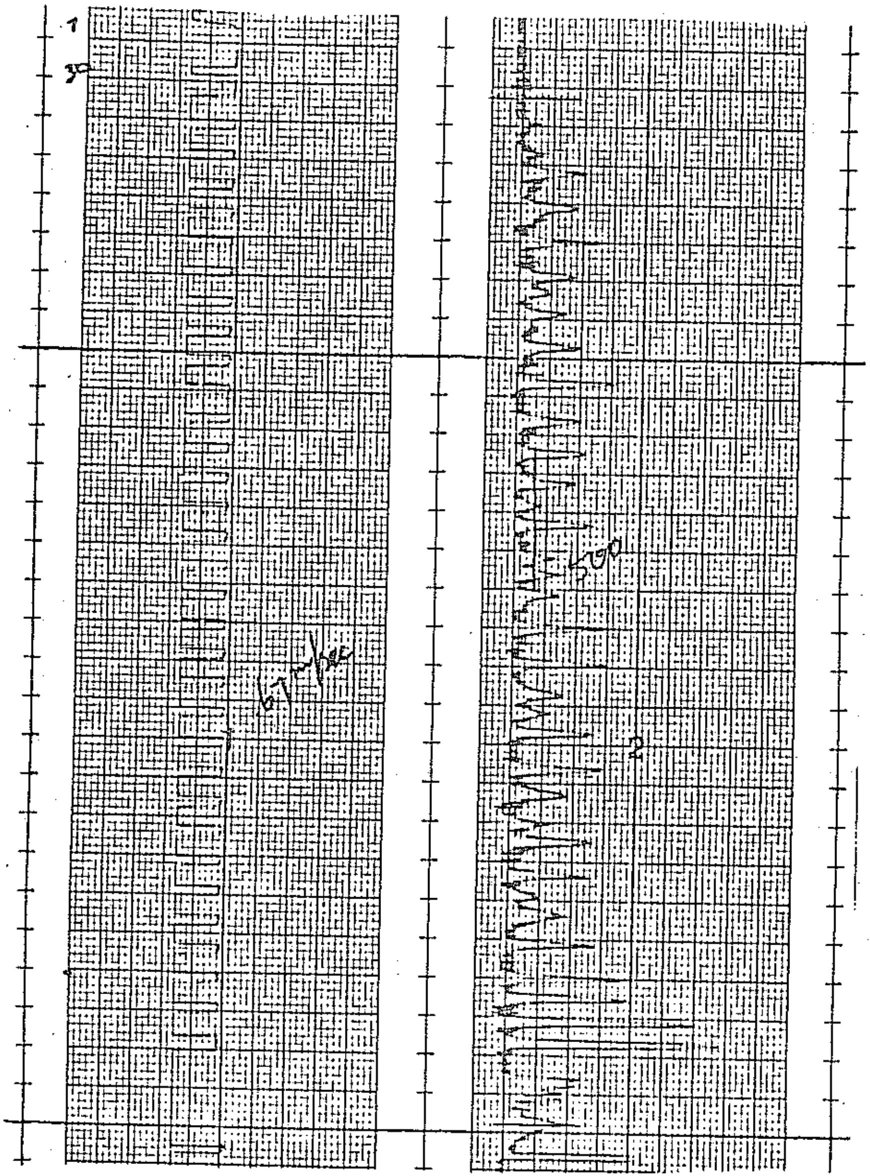


Run No. 5 V = 2.38 m/sec



Run No. 6 V = 2.42 m/sec

Fig. 4. Typical Stripchart Recording of Model Drag and Speed (No Waves).



Run No. 7 V = 0.67 m/sec

Waves at 0.79 Hz

Fig. 5. Typical Stripchart Recording of Model Drag and Speed (Waves)

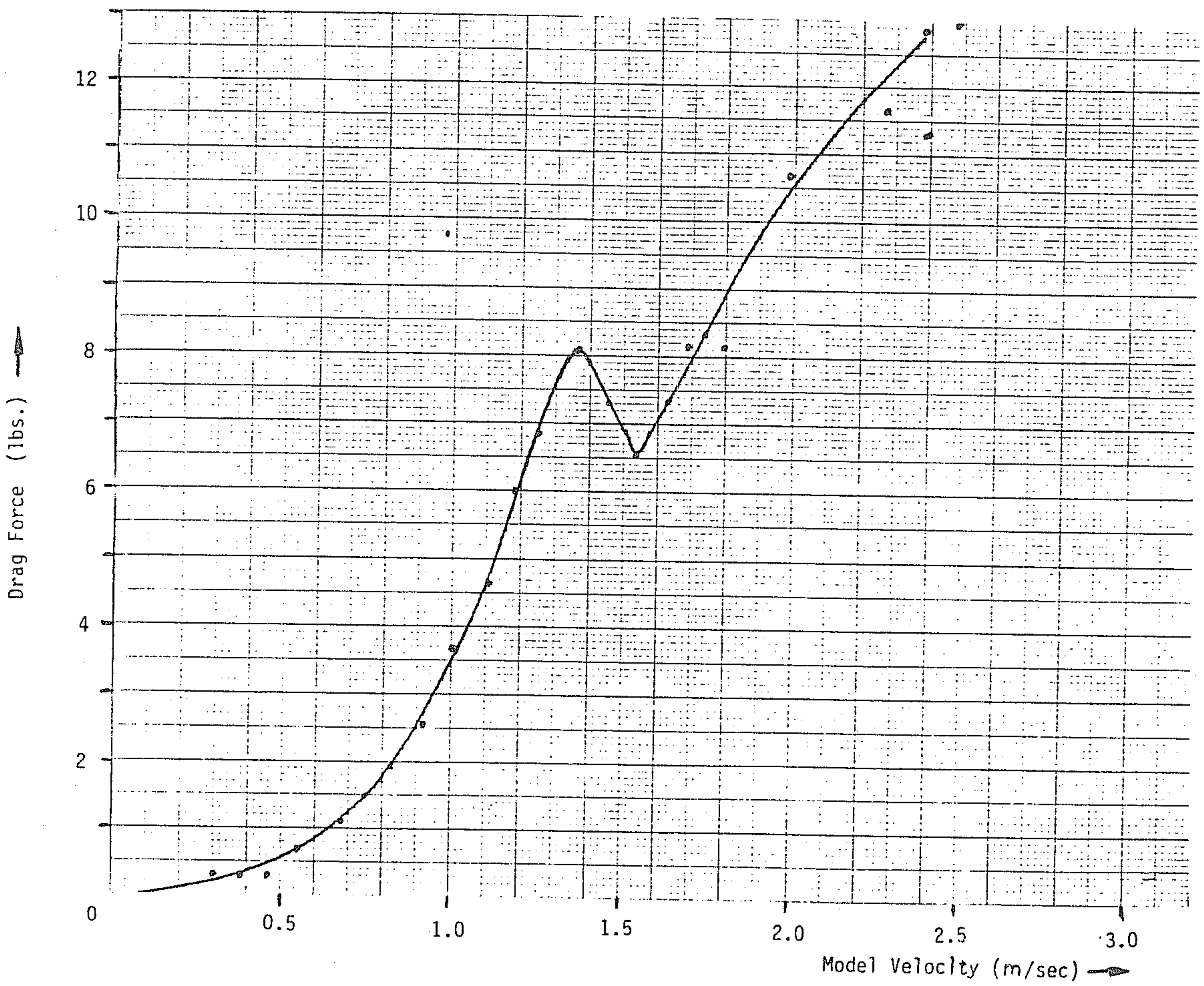


Fig. 6. Model Drag vs. Speed.

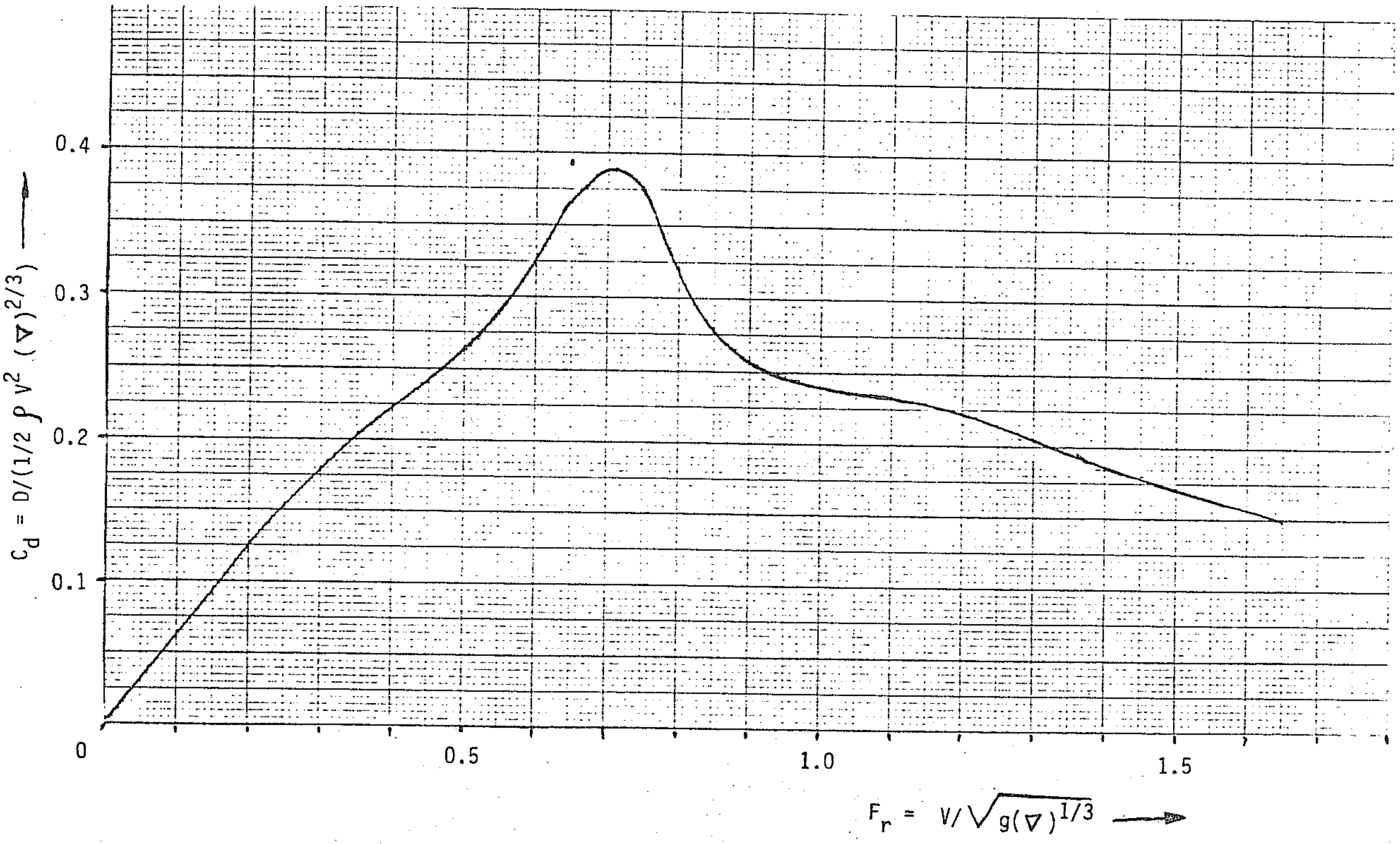


Fig. 7. Drag Coefficient vs. Froude Number.

On Day 5 the model was towed at low speeds with waves varying in frequency of 0.79 to 2.0 Hz. Only low speed data were obtained since the model could not be restrained from assuming the usual nose down attitude and care had to be taken to prevent flooding the model. Severe oscillations recorded by the stripchart recorder made drag and C_d calculations impossible. It should be noted that the most violent response of the model occurred at low speeds and at the lower wave frequencies tested.

CONCLUSIONS AND RECOMMENDATIONS

Figure 8 shows the MONOFORM drag data plotted together with the drag data of a 5 ft. model of a small craft S^3 design as investigated by Dr. Thomas G. Lang.[2] The plot shows several points of interest. First, the MONOFORM drag is significantly higher than the S^3 drag. While it was suspected that at low speeds the reduced surface area of the MONOFORM would exhibit lower drag figures than a conventional design, the results show that the low speed drag is almost twice as high for the MONOFORM. Photographic records show that wave drag was not a significant factor at these Froude numbers, therefore skin friction is the most important factor contributing to the total drag. Since the model was 8 lbs. heavier than anticipated it is conceivable that the significantly increased wetted surface area accounts for the increase in low speed drag. At the high Froude number end of the curves an interesting trend occurs. While the C_d of Dr. Lang's model is virtually constant, the C_d of the MONOFORM decreases. It is not inconceivable that with Froude numbers of around 2.5 the MONOFORM hull will approximate the C_d values of the S^3. It seems that the drag of the MONOFORM is similar to the drag of the S^3 in the high Fronde number region where skin friction becomes less important. Subsequent model tests where the wetted surface area of the MONOFORM is minimized will have to show whether the MONOFORM concept can actually compete with the S^3.

The resistance data shown in this report were obtained while the model was towed from a wire at decklevel. The high tow point induced

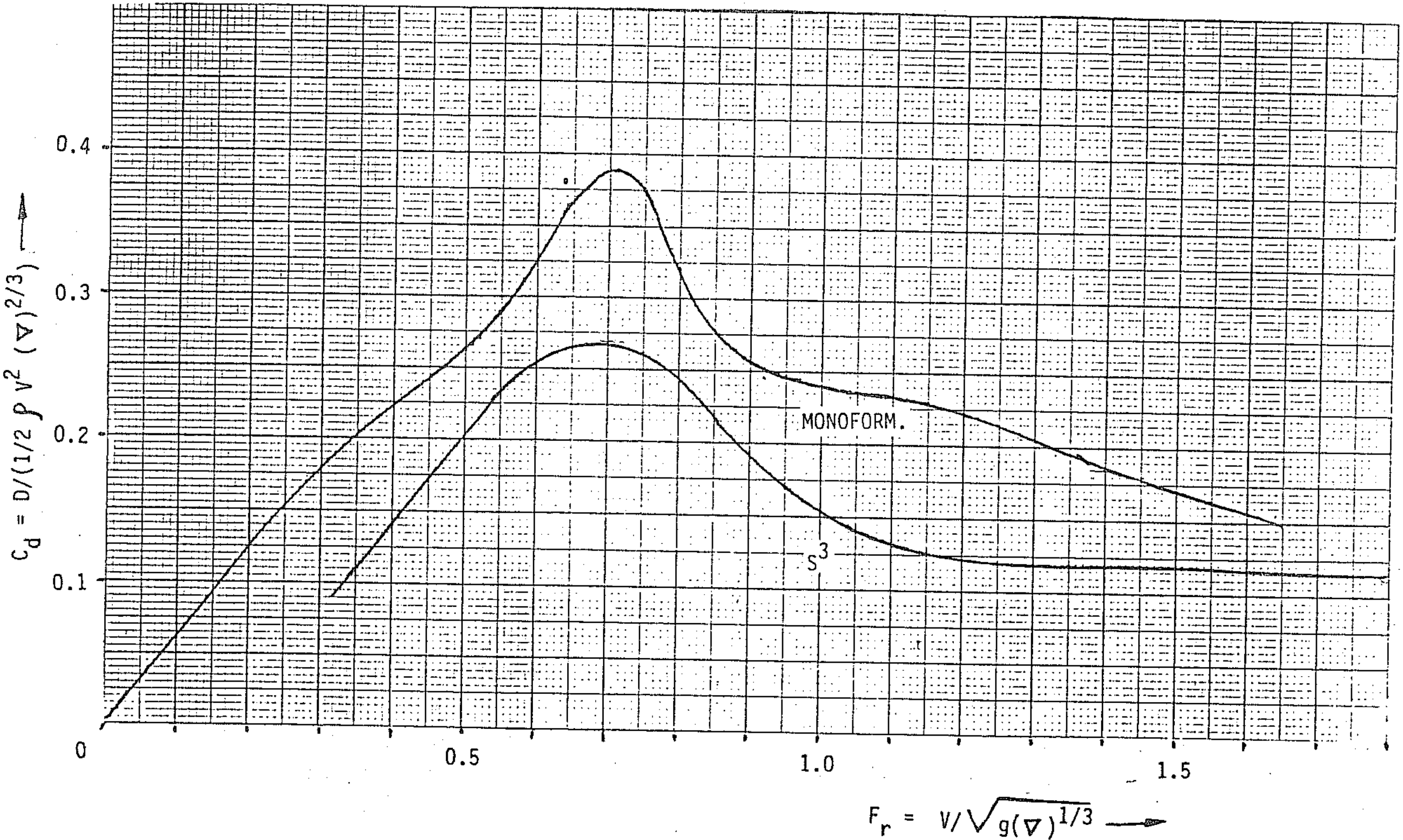


Fig. 8. MONOFORM Drag Compared with S^3 Drag

a severe nose-down pitching moment at higher speeds. This nose down tendency was restrained by fixing the vertical motion of the forward hinge point. Fixing the forward hinge point made it impossible to perform any high speed seakeeping tests. Three methods for solving the pitching moment problem have been suggested. The first approach is to tow the model from a submerged wire, although this system would be relatively easy to implement it is not known how the submerged wire effects the dynamics of the model. Another solution would be to build a self-propelled model. Aside from the financial and technical constraint of this approach it would also be impossible to test a self-propelled model in the VPI&SU towing tank since it is not long enough to allow the model to attain test speeds. A final approach would be to build a radio-controlled model. A model like this could be tested in any open body of water and could also provide insight into turning performance. A radio-controlled model, however, would be very hard to design and would be very expensive to construct. A short range alternative to a radio-controlled model would be to modify a U.S. Navy practice torpedo and to equip it with a deck and struts. The struts could be constructed such that they could be easily changed and moved along the body of the torpedo. Figure 9 shows a suggested approach. The powerful propulsion system of a torpedo will enable testing at high Froude numbers.

The MONOFORM concept distinguishes itself from the S^3 in that it has infinitely more design variables. In addition to length, strut shape, strut length, strut placement, strut chord, hull diameter and hull submergence, the MONOFORM design also has to consider variables

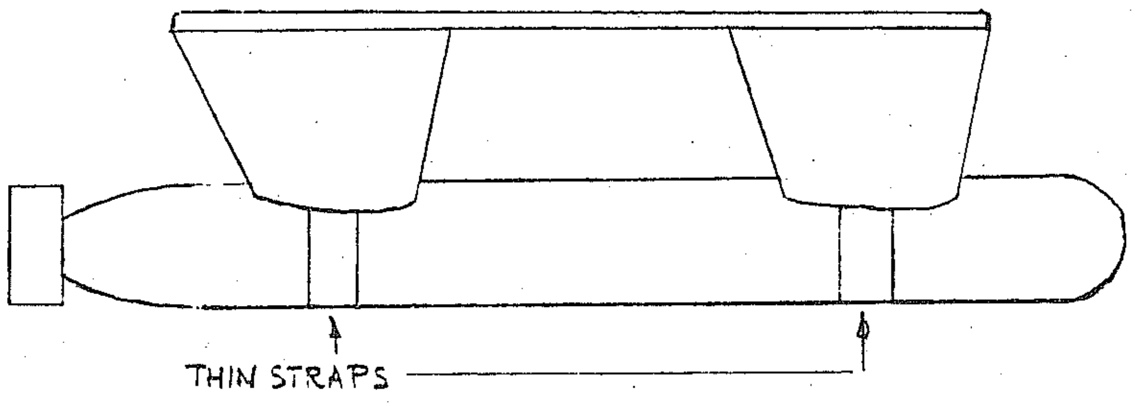


Fig. 9. Proposed Model using an Adapted Practice Torpedo.

like strut angle of attack, strut angle, strut camber, strut taper and strut flap area. It takes more time and more testing to optimize a MONOFORM hull than an S^3 hull. An analytical method for predicting drag on a MONOFORM hull also seems to be more complicated, than analytical drag prediction of an S^3 hull, since the V-shaped struts cause a rather unusual free surface behavior. The modified torpedo with moveable struts might provide some insight into these trade-offs.

No research has been performed yet to provide any insight into the optimum hull and strut arrangements of the MONOFORM concept. The presence of potentially lifting surfaces seems to indicate that a MONOFORM hull might benefit in longtitudinal stability from surfaces producing lift in a manner similar to a canard aircraft. It might be possible to analyze the dynamic stability of a MONOFORM ship using the stability equations of a canard aircraft, whereby the waves would be the upsetting forces, the struts would be the canard surface and the wing and the hull would be the fuselage. Another variation in regard to hull and strut arrangements would be to eliminate one aft strut thereby obtaining a MONOFORM as shown in Figure 10. Eliminating one strut might reduce drag increase turning performance, and reduce strut interference although close attention will have to be paid to static stability requirements.

During some recent exploratory towing tank tests of the MONOFORM model a serious problem became evident when the model displayed a large increase in draft when approaching humpspeed. This adverse behavior demands immediate attention, since it could prevent a full scale

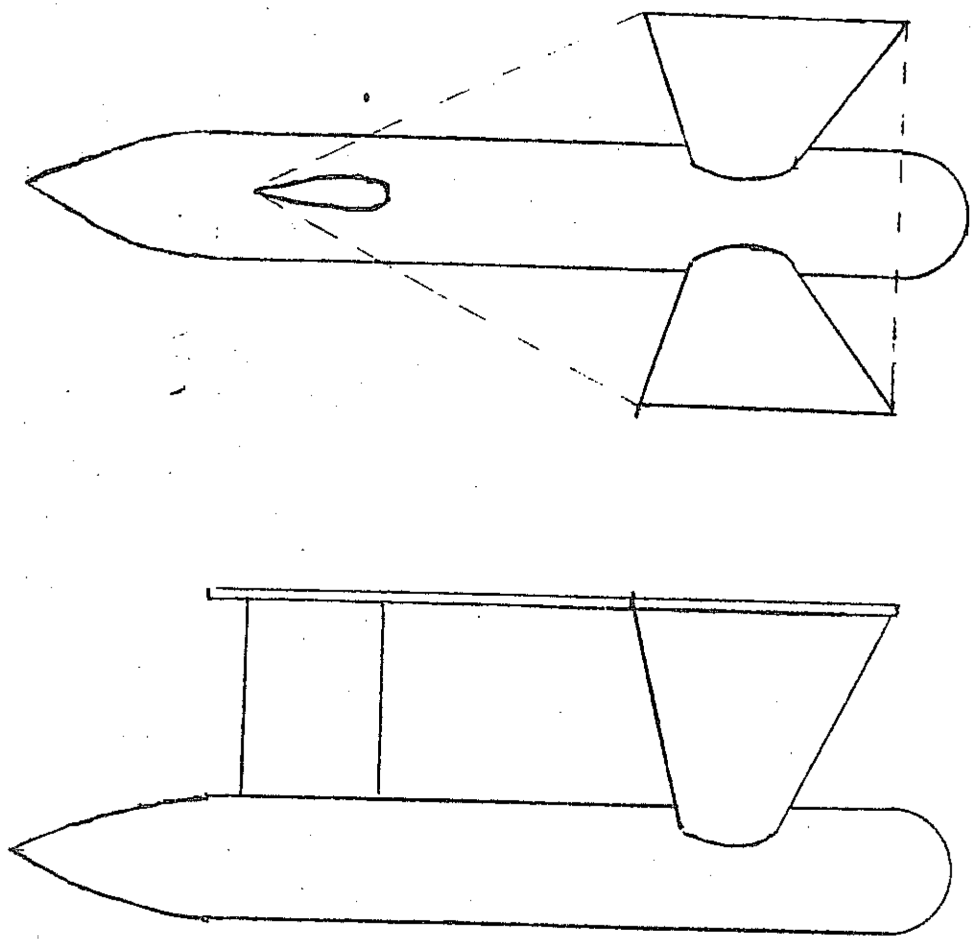


Fig. 10. MONOFORM using three struts.

MONOFORM ship from accelerating past humpspeed where it will operate most efficiently. Once moving at speeds faster than humpspeed, the model does not seem to display any increase in draft. The most obvious cause for this behavior seems to be the large bowwave which builds up between the struts. Several approaches to solving this problem can be investigated. The first approach will be to increase the length of the body in front of the first struts. It is anticipated that this increase in volume in front of the struts will cause a bulbous bow effect which might decrease the bow wave between the struts. This approach is presently being investigated and results from this modification are expected soon. Another approach to lessen the increase in draft would be to give the first set of struts a positive angle of attack, thereby lifting the model on top of the bow wave, rather than allowing the bow wave to build up above the struts. This approach refers back to the canard airplane analogy mentioned earlier. The final and most complex approach would involve optimization of the camber, shape, aspect ratio, leading edge sweep and hull intersection of the struts. This approach could prove to be extraordinarily time consuming. Since no analytical method is available, the optimum configuration will have to developed in a towing tank or circulating water channel, with a multitude of models.

It should be noted that all the observations mentioned above were made in a towing tank with a length of 100 ft. Testing in this tank requires rapid accelerations and decelerations and provides very short instances of constant speed. It is entirely conceivable that the adverse effects described earlier will not be present when more length for acceleration is available.

At the present Dr. Szeless is investigating the effects of lengthening the body of the model at various cross-sections. The results of these changes might indicate a definite direction of investigation. If these tests show no direct approach, the next step will probably be to build a new model which will facilitate quick strut changes. Although at this early stage, the MONOFORM concept has not yet outgrown the VPI&SU towing tank, it will soon be necessary to move to more sophisticated towing facilities were runs at longer sustained speeds will be possible. Since sophisticated facilities are expensive, and have limited availability, it will be necessary to build a reliable model on which quick configuration changes can be made to keep testing time to a minimum.

As is shown in this paper, the MONOFORM concept is still in its early stages. To develop a MONOFORM design that will prove to be efficient and seaworthy is going to take extended research, nevertheless the MONOFORM concept has sufficient inherent advantages to warrant further investigation.

ACKNOWLEDGMENTS

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