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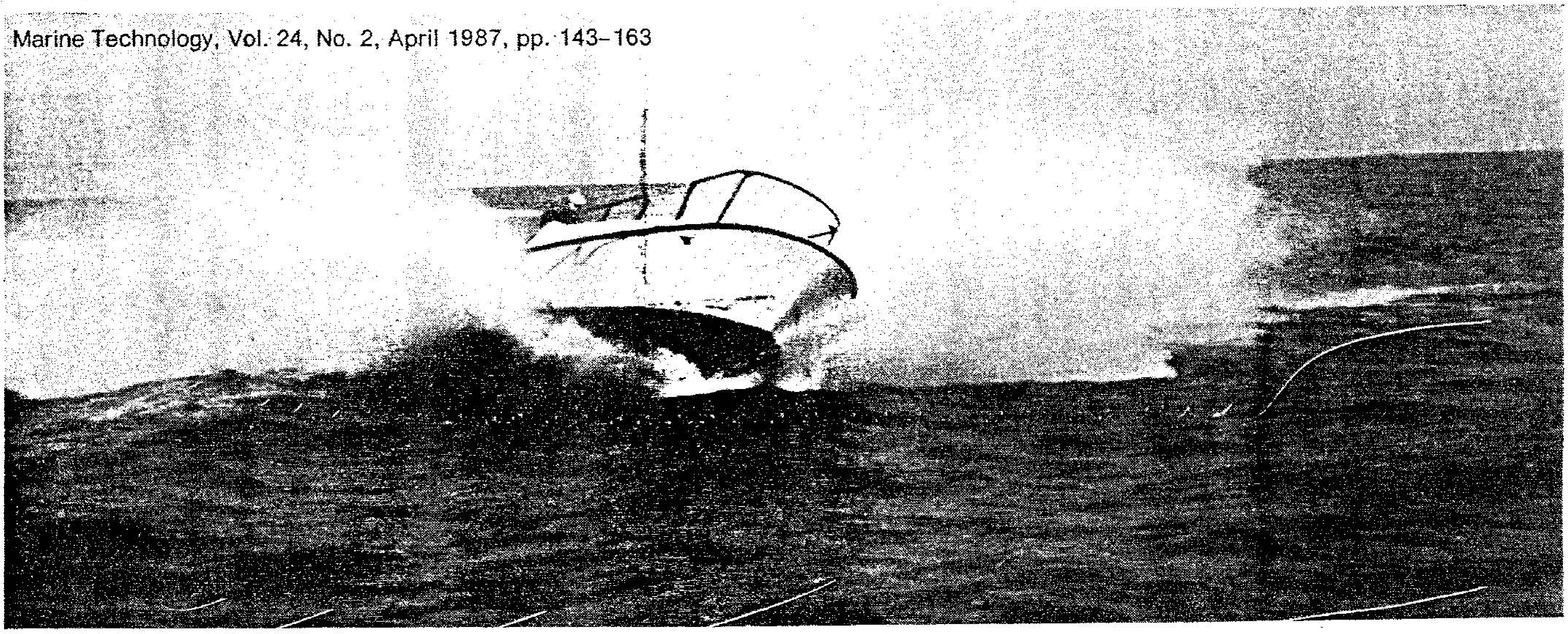

A Case Study of Dynamic Instability in a Planing Hull

Louis Codega[1] and **James Lewis**[1]

Soon after introduction into service, a class of high-speed planing boats began to exhibit a dynamic instability that manifested itself in the craft trimming by the bow, rolling to a large angle of heel to port, and broaching violently to starboard, all within five seconds. This behavior, which occurred within the craft's normal operating envelope, could not be attributed to operator causes and resulted in unacceptable operating restrictions being placed on the craft. After a number of unsuccessful attempts to remedy the problem, an investigation to research possible causes was undertaken. Concurrently, a test boat was instrumented to quantify its behavior and, most importantly, to record the hydrodynamic bottom pressures acting while this phenomenon occurs. The craft is described and initial attempts at solving the problem are outlined. The results of research on this type of phenomena in both planing craft and flying boats are presented. The instrumentation system, complex for this size craft, is detailed and the test procedure described. The results of the full-scale tests are given, along with qualitative comparisons with other craft that display a similar problem and model tests that would indicate the possibility of such instabilities. The cause of the instability is described and recommendations are made to avoid similar problems in future craft.

Introduction

In 1983, the United States Coast Guard introduced the first of 20 high-speed surf rescue boats (SRB) at lifesaving stations on the West Coast. These 30-ft craft were designed to be used as search and rescue platforms in breaking surf of up to 10 ft and are capable of operating at speeds of up to 30 knots. The hull form was similar to that of a conventional high-speed planing hull, but had some unique characteristics to allow performance as a highly maneuverable, self-righting, extremely seaworthy displacement hull. These conflicting design criteria produced a somewhat unusual boat, but not one that was particularly extreme in any way.

The craft proved to be highly successful and in many ways exceeded the operator's requirements, except in one very important regard. When operating at high speed in waves, the lead boat exhibited an unstable behavior that occurred in two ways. One was described as a decrease in running trim accompanied by large amounts of spray being thrown forward. The most common manifestation, though, was a violent roll, generally to port and reportedly of up to 90 deg, followed by an equally severe broach away from the roll, usually to starboard. During one of these occurrences, the crew was thrown completely clear of the boat. The Coast Guard immediately began an investigation of the problem and were successful in lessening the rate of occurrences, but were not able to either develop a completely satisfactory explanation or eliminate its occurrence.

It became clear that a more comprehensive approach was required, and the Naval Sea Systems Command (NAVSEA) Combat Systems Engineering Station, Combatant Craft Engineering Department, was requested to research the problem thoroughly. Additionally, they were to instrument and test the lead boat, develop an explanation for the instability and develop criteria to give designers some assurance that the problem might be avoided.

This paper begins with a description of the craft and then elaborates on its operational history. The results of the extensive literature search are discussed, with particular emphasis on flying boat research, which relates directly to the phenomenon. The extensive instrumentation systems installed on the boat are then described, along with the test program developed to quantify the behavior of the boat during the unstable mode. Test results are presented which show significant changes in the bottom pressure distribution when the boat enters its "un-

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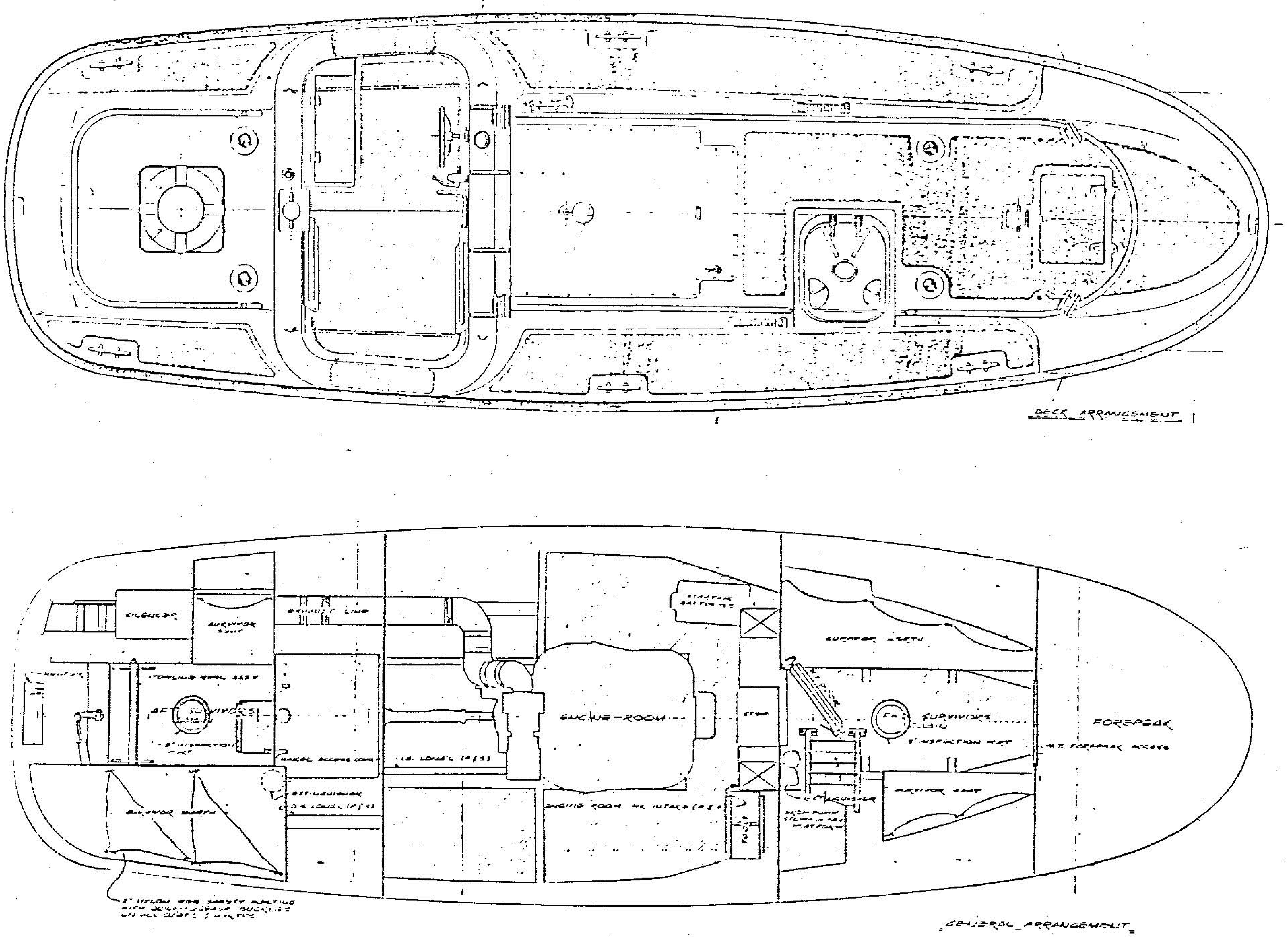

Fig. 1 General arrangement

stable" mode. Finally, tentative guidelines are presented which will indicate to the naval architect the likelihood that a new design will exhibit this form of instability.

Description of boat

The Coast Guard's 30-ft SRB was designed for high-speed search and rescue operations that involve transit through or operation in breaking surf [1].[2] The arrangement is unique, as the unusual mission might suggest. The main features of the design are shown in Figs. 1 and 2. A single diesel engine mounted amidships turns the propeller through a down-angle reduction gear, allowing the engine to be mounted nearly horizontal. Forward of the engine compartment is a survivor's cabin and ahead of this is a collision bulkhead and a watertight forepeak. The crew of two stands just aft of the engine in a rather small, open cockpit. The aft cabin encloses another survivor's compartment, the single 70-gal fuel tank, and a towing hawser stowed on a reel and accessible from deck.

The planing surface, as seen in Fig. 3, was kept narrow to improve high-speed seakeeping. The center of gravity was located relatively far forward, the aft buttocks were sloped up from the baseline, and the longitudinal gyradius was kept small to improve seakeeping while in the displacement mode in surf. The intention was to develop a boat that would quickly conform to the wave profile and ride above a breaking wave and thus avoid a heavier boat's tendency to go through the crest. In the event of a capsize, the boat is self-righting, has self-sealing air inlets for the engine and is reinforced structurally to take the load of seas breaking on deck. The boat is capable of safe operation in up to 10-ft breaking surf and can make almost 30 knots under calm conditions.

History

The surf rescue boat evolved from a desire to have a high-speed, surf-capable rescue craft for use under breaking bar conditions. The only other surf-capable asset, the 44-ft motor lifeboat, has proven itself with many years in service, but has a top speed of only 15 knots. The 41-ft utility boat demonstrates the advantages of a high-speed craft but is not capable of operating under surf conditions. The concept of a craft that combined the advantages of both the existing boats seemed feasible. A series of design studies was performed and prototypes constructed, the result of which was a 26-ft waterjet-powered surfboat [2]. This boat was tested extensively but was not suitable for operation in surf conditions because of the tendency of the pump to temporarily lose suction under heavy conditions and control problems when operating astern.

The design of the prototype SRB evolved from this boat. This 25-knot craft was very similar to the production version, but utilized a General Motors-Detroit Diesel 8V71 series engine. The propeller ran in a partial tunnel and a substantial skeg was mounted forward of the propeller.

The boat, put into trial service at a number of Coast Guard lifesaving stations, was found quite satisfactory, but a formal test program was never undertaken. The craft proved the feasibility of the concept but could not outrun breaking surf. It was felt that if the top speed could be increased to 30 knots, the craft would be able to stay ahead of breaking waves and would be less likely to be overwhelmed.

The design was modified to correct minor defects in the

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[2] Numbers in brackets designate references at end of paper.

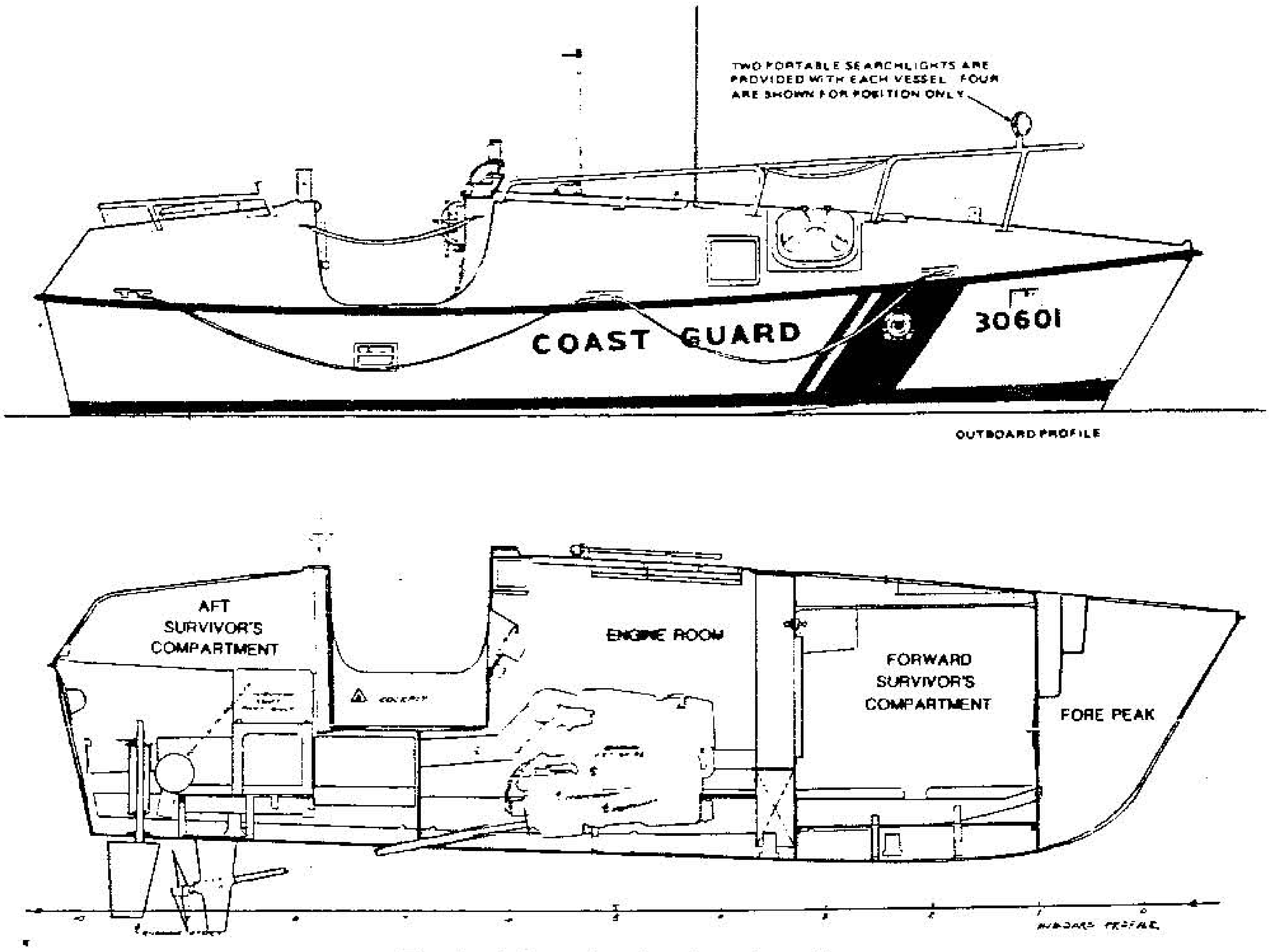


Fig. 2 Inboard and outboard profiles

prototype and to incorporate a GM 6V92 series engine. Additionally, to improve the propulsive efficiency, the tunnel was removed, the shaft was dropped to accommodate the propeller clearance, and the large skeg was removed and replaced with a small skeg below the shaft strut. Because of operational pressures, a decision was made not to build a preproduction prototype, but to go directly into a 20-boat production run.

The lead boat was sent to the National Motor Lifeboat School at Cape Disappointment, Washington State, for evaluation in 1983. It was in fact capable of 29 knots and in most ways was an exceptional boat, but soon exhibited an uncontrollable handling problem. This usually occurred, seemingly spontaneously, while operating in large swells and was described as running at a reduced trim angle, most often with a roll to a large angle of heel followed by violent broaches, all with large quantities of spray being thrown from the bow. Rare occurrences in calm water were also reported. It should be mentioned at this point that the boat was being run by Coast Guard surfmen, probably the best small boat handlers in the country. They routinely run in breaking surf, often with a boat in tow, and are certainly not reckless or inexperienced. It was obvious that the boat had some form of control problem, and Coast Guard Headquarters, Boat Design Branch began an investigation to learn about the behavior and to find a solution to the problem.

During the first formal study of the boat's behavior, it was found [3] that the coxswain could force the boat into the "unstable" condition, although not predictably. It would take a large amount of running in waves before the craft would become unstable but, as the coxswains became more experienced in the boat, it became easier for them to force the occurrence. This was generally done at high speed while taking a 4- to 6-ft swell on the starboard bow. As the boat would rise up the face of the wave, the rudder would be put hard to port and the throttle increased to maximum rpm. As the boat came down the back of the wave, it would occasionally enter the unstable mode as depicted in Fig. 4. It appeared from videotapes that this would not occur if the boat was launched into the air by the swell, but only if the combination of boat speed, rudder angle and swell shape were exactly right to allow the boat to slide down the back of the wave at high speeds, but at a low trim angle and heeled to port.

It was found that the boat was somewhat stable while in the "unstable" condition, running at a reduced trim angle, heeled over, usually to port as much as 60 deg and throwing large quantities of spray forward, blinding the crew and obscuring the boat from view. The rudder had no predictable effect on the craft, but the helmsman had some degree of control in that increased throttle forced the boat to a larger angle of heel and reduced throttle resulted in less heel or coming out of the mode completely. If the angle of roll became too great, the craft would broach violently. With practice the coxswains became proficient at keeping the boat in this bow-down, heeled-over condition for periods of up to a minute.

The Coast Guard began an investigative and corrective program that redesigned the transom wedge, which counteracts engine torque, experimented with different propellers and redesigned the rudder. The result of all of these changes was that the boat could not be made unstable in calm water and would almost always heel to port while in the unstable mode. The Coast Guard additionally suspected that the unusual behavior was due to low pressures being developed in the bow region because of the full forefoot, and they were successful in an experiment to make the boat become more unstable by installing an "inverted wedge" forward which had a blunt leading edge tapering aft toward the stern. Based on the assumption that the spray strakes were ventilating the planing surface, the strakes were glassed in to form a smooth bottom, with no effect on the instability. Additionally, 1700 lb of ballast was located as far aft and as low as possible to test the hypothesis that the longitudinal center of gravity (LCG) was too far forward, again with no noticeable effect.

The problem was exacerbated by the fact that 20 boats were either delivered or under contract. Each boat was exhibiting the same unstable behavior, although, interestingly enough, each had its own peculiarities. Some were very easy to force into the unstable mode but were very controllable once there. In others,

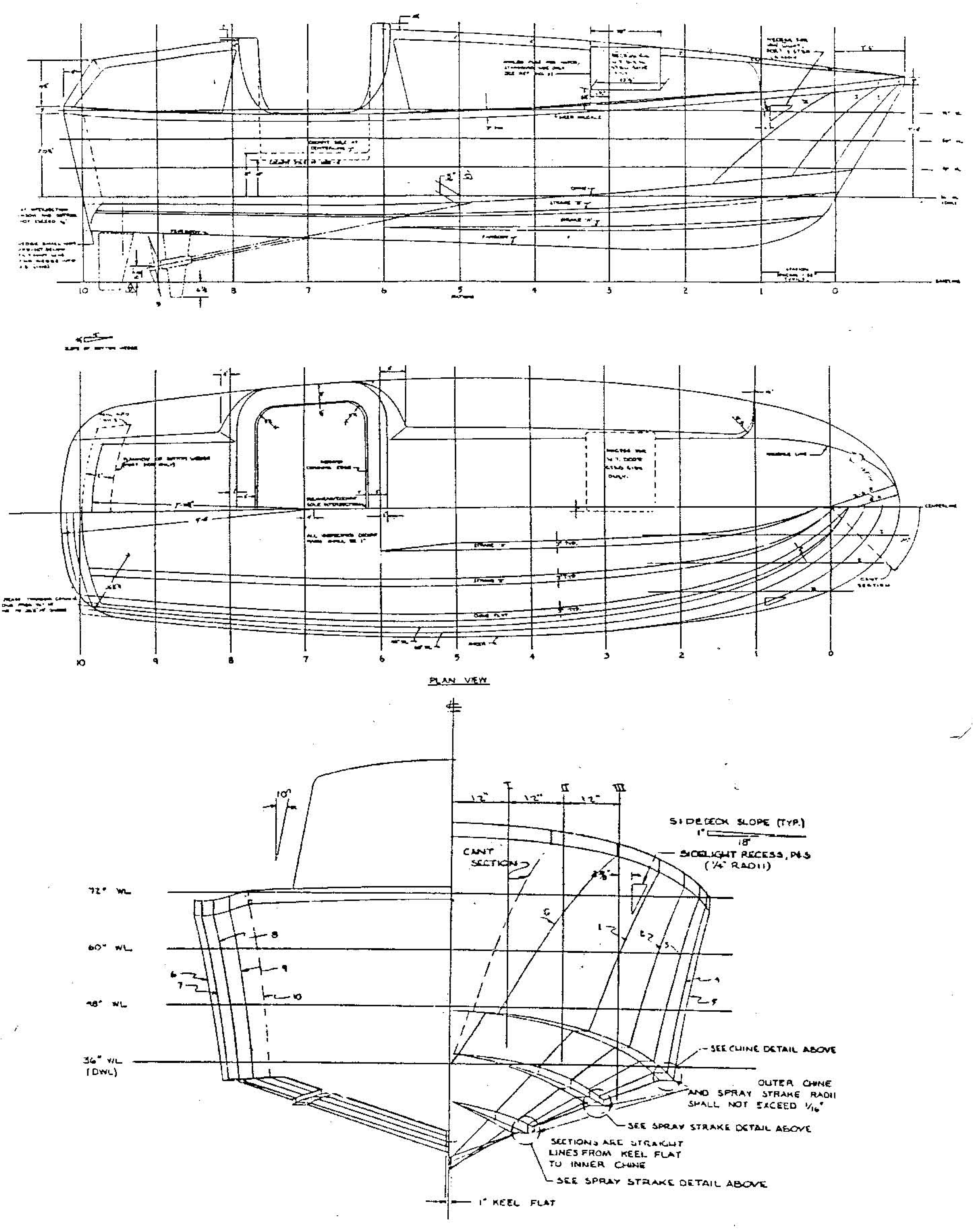


Fig. 3 Lines plan

the instability was difficult to induce, but the result was very severe. This was very difficult to explain, because the boats were identical within normal manufacturing tolerances.

It became clear that there was no simple solution to the problem. The known facts were that the prototype did not have this instability and that efforts by coxswains who had driven the production boats to force the prototype boat into this mode were unsuccessful. The changes between the prototype craft and the production boats were that the production boats were 5 knots faster, had neither a skeg nor a tunnel, and were slightly heavier. These seemingly small changes had a near disastrous effect on the boat's performance. As the Coast Guard's resources for in-house testing were exhausted, it was decided to engage the Naval Sea Combat Systems Engineering Station, Combatant Craft Engineering Department to do an extensive literature search and to instrument the lead boat, with an emphasis on bottom pressure measurements, to quantify the boat's behavior in both the normal and "unstable" modes.

Literature search

The literature search quickly focused on three items that appeared to be directly related to the phenomenon. The first of these was the effect of speed on the transverse stability (or *GM*) of a planing hull. Second was the effect of the curvature of the boat's forward shape that was the necessary consequence of bringing the relatively flat planing surfaces aft into a shape suitable for operating in waves. In many ways, these first two phenomena are related. Finally, a coupling between yaw and roll motions was investigated.

The stability of high-speed boats is routinely evaluated in the same manner as the stability of ships [4]—that is, entirely from hydrostatic forces—and the results are the classic curves of righting arm versus angle of heel for varying displacements and centers of gravity. Even a so-called dynamic analysis is really just a quasi-static approximation of the effects of wind, waves, rudder forces and off-center weights.

In reality, transverse stability is related solely to the location of the craft's center of gravity, the bottom pressures supporting the craft, and how these forces and their moments change in magnitude and direction as the orientation of the boat changes. Very simply, if a small change results in forces and moments that return the craft to its original orientation, the craft is stable. If the resulting forces and moments tend to increase the change, the craft is unstable. The textbook calculation of stability, then, is both a simplification and a confusion. It is a simplification in that it presents the calculations in an easily evaluated form that gives an exact solution for the limited case when the disturbance to the system is small and when the pressures acting on the bottom can in fact be determined from a hydrostatic calculation. This implies no forward speed. It is a confusion because it hides the real factors that govern stability.

Classical stability calculations and criteria do a very good job of guaranteeing the satisfactory performance of a relatively slow-speed hull. This is certainly due to the fact that dynamic bottom pressures as a result of forward speed do not differ much from the static case, but is also a result of the empirical way in which the stability criteria were originally developed. Thus, the application of this calculation technique to high-speed hulls falls short in two important regards. First, at high speeds the bottom pressures bear little if any resemblance to the static case, and second, the large database of satisfactory and unsatisfactory boats does not exist.

It is well documented that the bottom pressures experienced by a planing hull at speed are quite different from that of the same hull at rest, as seen in Fig. 5. Savitsky [5] provides a classic text on the subject and follows a long series of model tests performed on flying boat hulls; for example, [6-9]. However, there are some important points that should be mentioned in regard to the test results from these reports. These tests were performed on constant-deadrise prismatic planing surfaces at speeds that are considered to be purely planing; that is, the buoyant forces are negligibly small. A planing hull boat generally is designed with an afterbody shape that approximates to a greater or lesser degree a purely prismatic surface. Forward, however, are curved surfaces that are the necessary consequence of bringing the relatively flat sections aft into an appropriate bow shape.

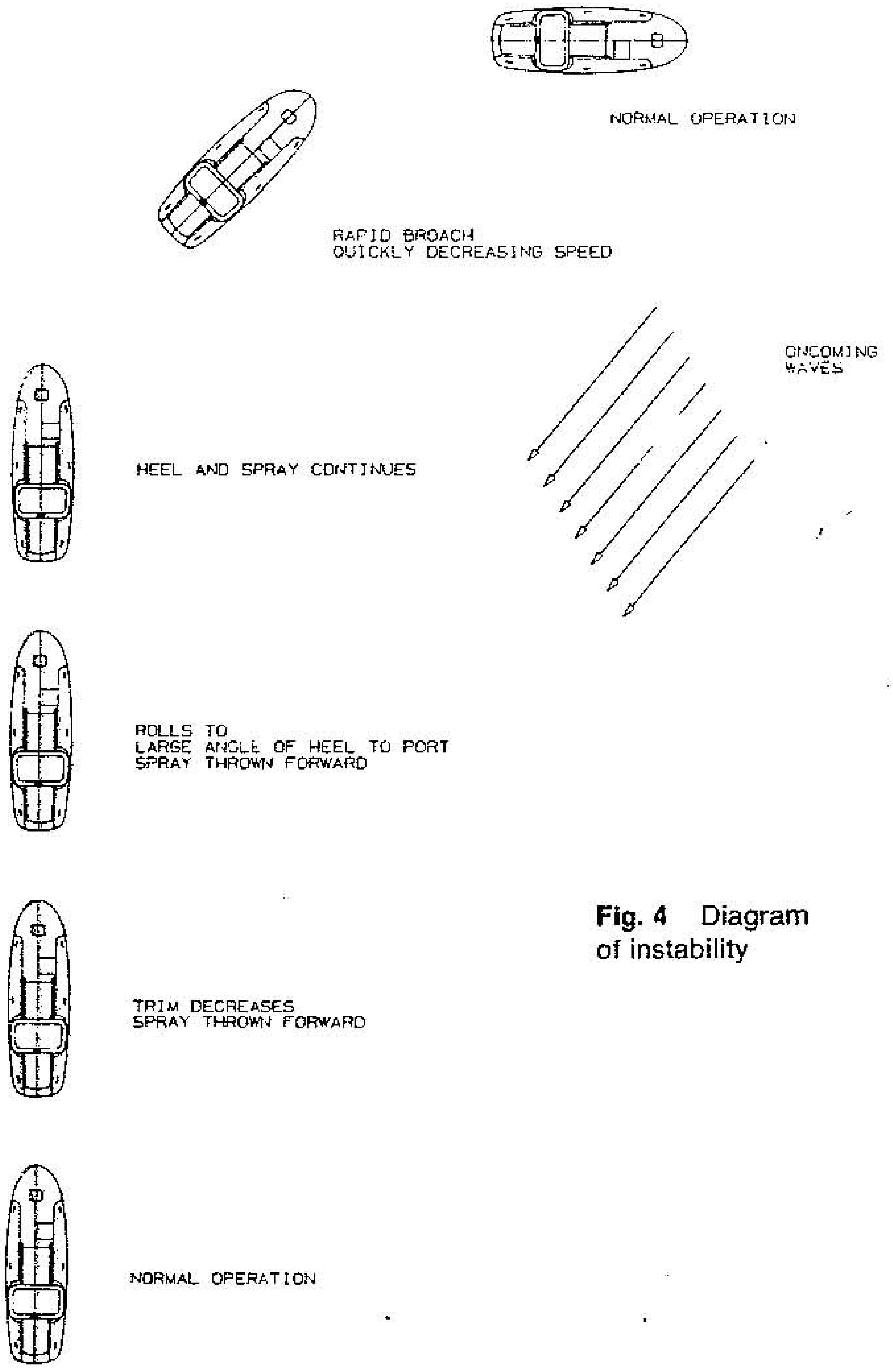


Fig. 4 Diagram of instability

Few references exist that describe the bottom pressures found on other than prismatic surfaces traveling at "planing" speeds. The pressure distribution found under a body of revolution with chine strips attached is particularly informative and is shown in Fig. 6, taken from [10]. One could question if this pressure distribution represents true planing given its usual definition, but it certainly seems plausible that a boat operating at high speed in a seaway could experience a similar instantaneous pressure distribution. Clearly, this was evidence to support the suspicion that instead of the positive pressures that would increase the transverse stability of the hull, the pressures might be less positive, or perhaps even negative over certain regions, resulting in a decrease in transverse stability.

Millward [11] and Millward et al [12] report on stability tests performed in a flow channel on a series of high-speed, round-bilge hull forms. Inclining experiments were first done on the models fixed in the design condition of trim and heave with and without water flowing past the hull. Next, the inclinings were made with the boat at its high-speed heave and trim angle, both

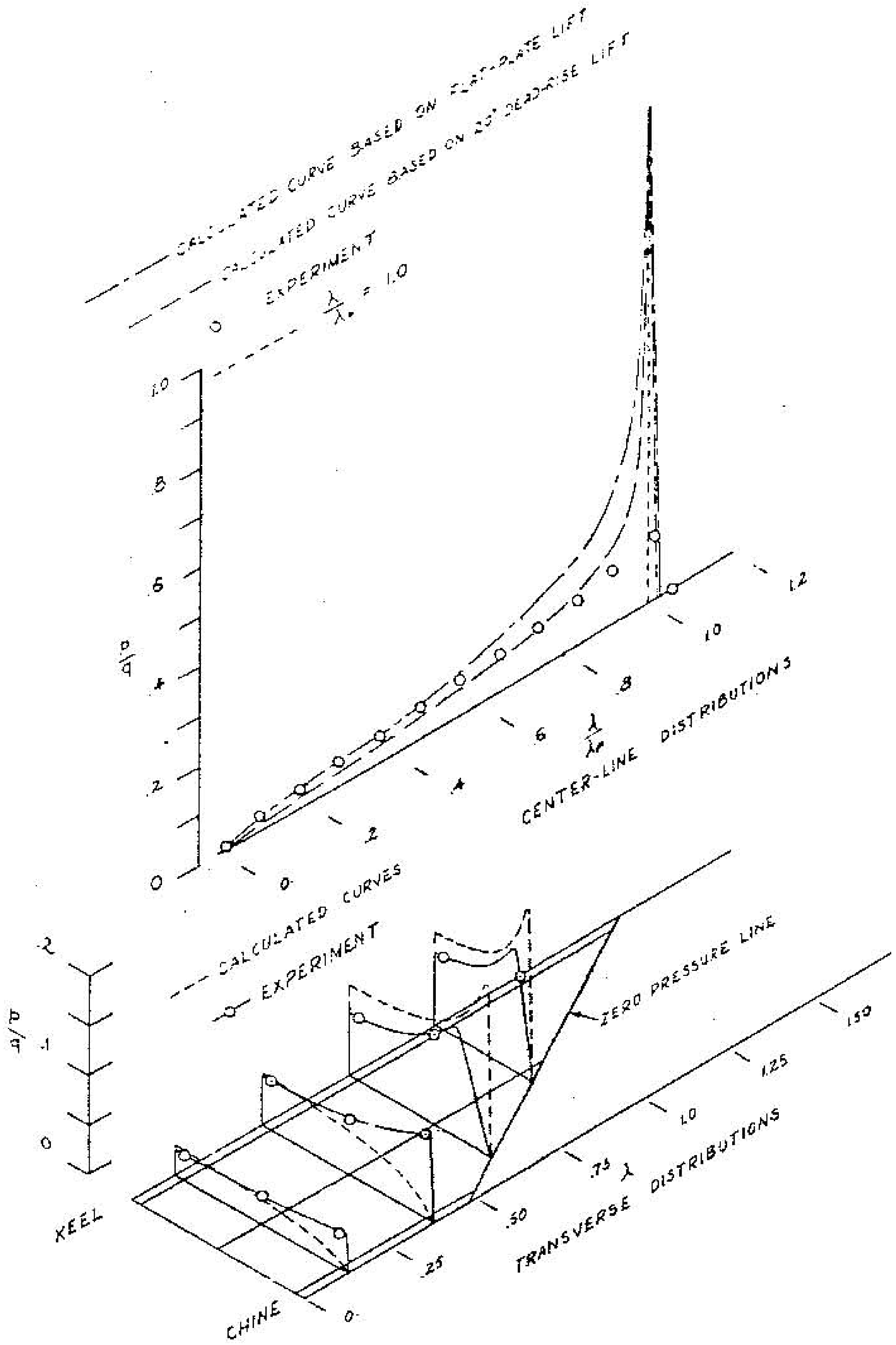


Fig. 5 Prismatic hull pressure distribution

with and without water flowing under the hull. The static inclinings at both orientations showed the expected results. The angle of heel was a linear function of heeling moment for small angles of heel, and the slope of this linear portion of the curve became less as the center of gravity was raised. The effect of heave and trim was small.

The results obtained with water running under the hull were significantly different. Low-speed tests showed that the slope of the heeling arm versus angle of heel was less than that for the static case, but still positive. At some higher speed, however, the craft became unstable and would assume an angle of loll as shown in Fig. 7. Pressure measurements showed that the instability at higher speed was apparently caused by low pressures being developed near the stern, particularly near the turn of the bilge, as seen in Fig. 8.

A series of model tests conducted on a series of hard chine planing hulls to evaluate, among other things, the effect of a wide range of factors on stability at high speeds is described in [13]. It was concluded that for some models, at least, stability decreased with increasing speed. Factors that increased the stability of the craft at speed were a low-length-to-beam ratio and large spray strakes.

The only attempt to develop a mathematical approach to the stability at speed problem was found in [14]. This reference states that the stability of a hull decreases from the static case with increasing boat speed until the craft reaches a purely planing mode, at which point the stability increases. Stability is critical in the pre-planing region where the hydrodynamic forces are such that the static stability has decreased as a result of the flow over the bottom but the planing bottom pressures have not yet developed. The mathematical development derives a "provisional metacentric height," which is the metacentric height required in the static case to ensure that the craft will remain stable throughout its speed range. It was found, however, that the agreement with experiment was not good. The calculation, it is stated in [14], can be used as a guide in preliminary design before tank test results are available, which are recommended as the only reliable way to evaluate the dynamic stability.

Two references [15,16] were found in the naval architecture literature about the effects of extreme curvature in the bow region. Both of these were similar in their claim that the effect of too much curvature forward was to reduce the stability, not only tranversely but also longitudinally and directionally, of a boat at high speeds due to the low pressures developed as a result of the curvature. It was also said that low pressures would also result in other effects, such as low trim angles and the inability to get up to planing speeds. The references were vague as to what constituted extreme curvature. Clement [17] describes experiences with a very high-speed (80 mph) craft that would occasionally adopt a large angle of heel when operating in waves. The forebody was examined and found to have areas with small radii of curvature where aluminum plating was distorted from welding to the frames below. It was suspected that these areas were causing low pressures to be developed when the craft heeled slightly and resulted in a transversely unstable condition. Three transverse rows of small wedges were installed over the curved plating so that when the area became immersed, a high-pressure rather than a low-pressure region was created, increasing the righting moment and thus the transverse stability. The result was the complete elimination of the problem.

Two references were found in flying boat literature that bear directly on the planing hull problem. Leshnover [18] describes the phenomenon of flying boat touchdowns where the hull would be sucked partially underwater, often pitch-poling with disastrous consequences. It was hypothesized that this was caused by low pressures acting under the hull due to the plane landing at a low angle of attack. A test program was set up to investigate the phenomenon. Two bodies representing typical flying boat forebody hulls were tested at varying fixed trims at speeds that would simulate landing, with the resulting vertical forces measured. The results showed that one hull, with a constant deadrise angle, would always experience positive heave forces. This was not the case for a similar hull with a warped deadrise. Figure 9 illustrates that at high speeds and negative trim angles, the forces were negative, that is, the hull was being pulled under the water by low bottom pressures. These results indicated to the investigators that curvature of the buttocks might be the cause of the low pressures. The longitudinal pressure distribution, reproduced in Fig. 10, was also measured and somewhat resembles the distribution under the body of revolution shown in Fig. 6.

Leshnover [19] developed the theory further and reported on the results of tests on a series of six related flying boat models. The series consisted of three variations of quarter-beam buttock shape and two deadrise distributions, one constant and one warped. Each hull was run at three speeds, two depths of immersion, and nine trim angles ranging from 3 to −5 deg, with both vertical force and pitching moment being measured. The results from the worst case, Figs. 11 and 12, show that both the heave force and trimming moment are negative at trims of less than zero degrees, indicating that the tendency of a flying boat in the same attitude would be to pitch further down and heave down more. The likelihood of a flying boat diving increases as

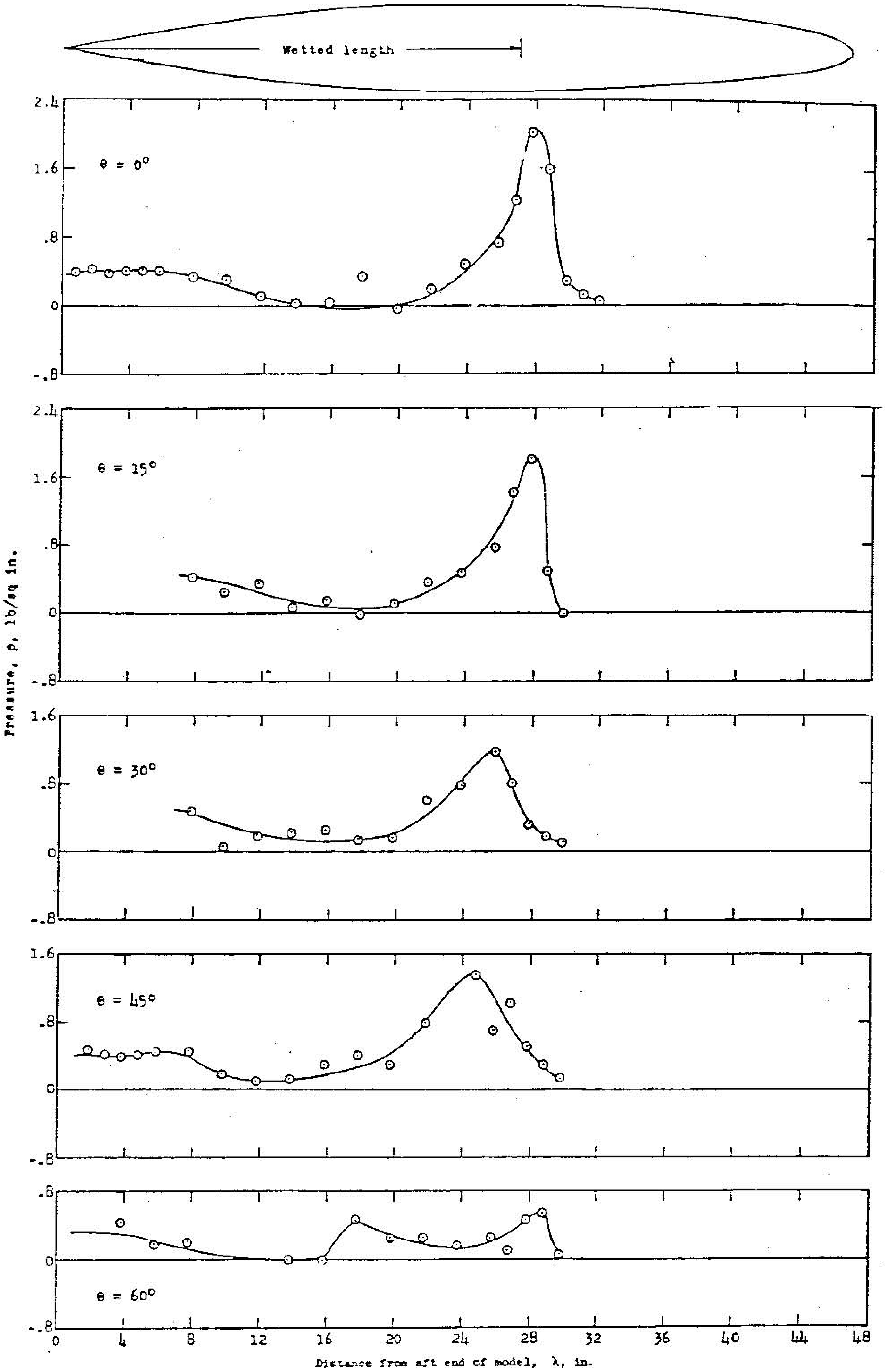


Fig. 6 Body-of-revolution pressure distribution

the heave force and pitching moment become greater in magnitude, but negative. It was again found that some models would always develop positive forces and moments regardless of trim angle, speed or depth of immersion. Others, however, would develop negative heave forces, pitching moments, or both, under certain test conditions. The results were plotted with heave forces on the X-axis and pitching moments on the Y-axis and were found to lie within a narrow band, as seen in Fig. 13. A relative diving index, on a scale from 1 to 5, was assigned to each of the test results and a statistical analysis performed to determine which model characteristics were significant to the diving phenomenon. It was found that for a given quarter-beam buttock, a warped deadrise produces a greater probability of diving than does a constant deadrise. For a given deadrise distribution, the diving tendency increases as the buttock shape changes from a gradual curve throughout the models length to a relatively flat curve aft with a small radius of curvature forward. At shallow immersions, the deadrise distribution affects

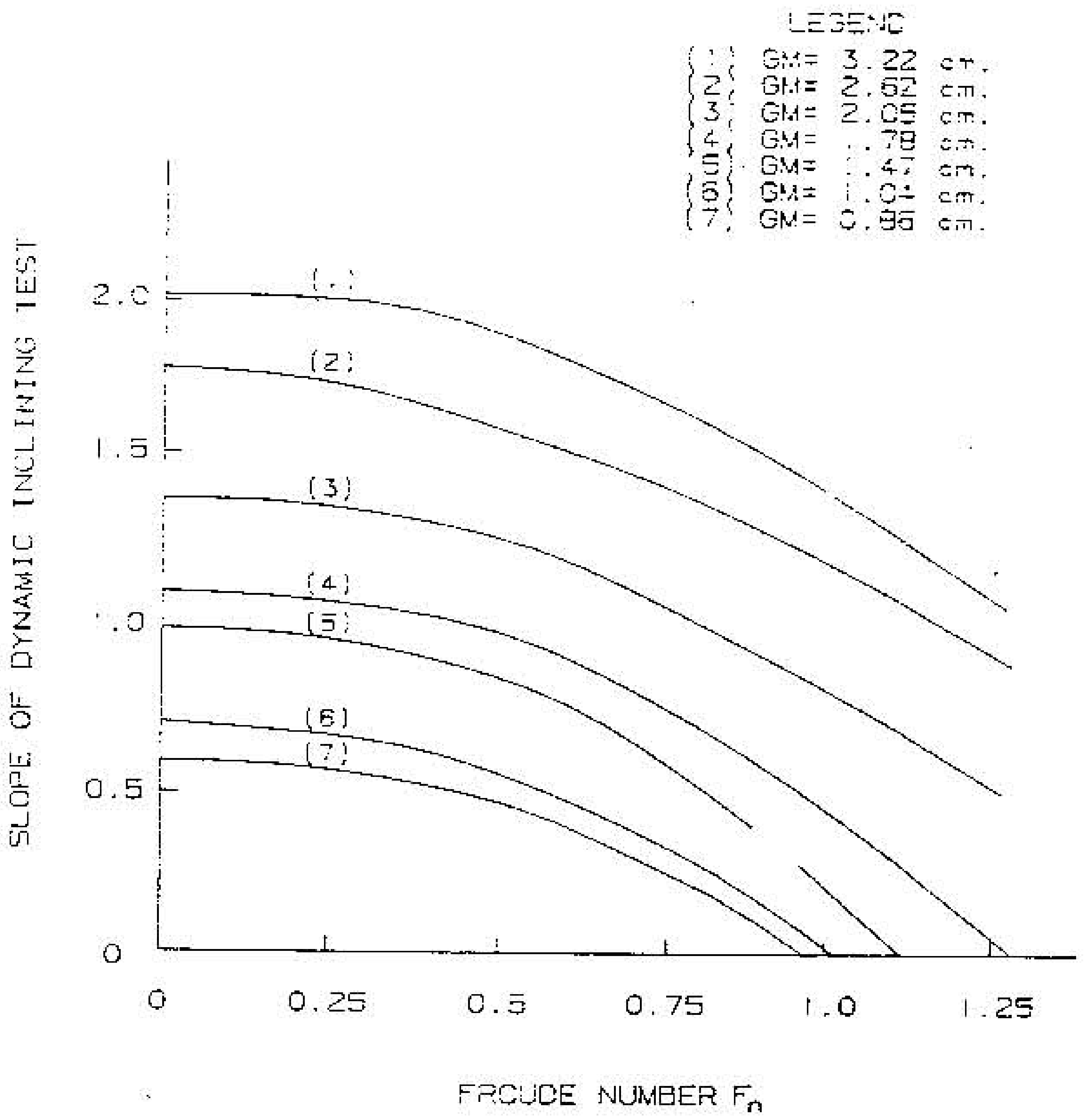


Fig. 7 Decrease in stability with speed

the diving tendency more than does buttock shape, but, at deep immersions, the opposite is true.

It became apparent that at least one of the suspected causes of the phenomenon had already been scientifically investigated, identified as the cause of an instability and, for flying boats at least, removed as an area of concern. It fact, there are enough data in [19] to allow the development of a predictor equation for diving given geometric information about a new flying boat hull. Unfortunately, this equation would not be directly applicable to the planing hull problem because the speeds at which the tests were performed corresponded to a volume Froude number that is roughly twice, and a loading coefficient that is about half, that of a typical planing hull.

The final potential cause of the phenomenon that was found was a coupling of yaw and roll motions. Gill [20] points out that when a high-speed hull experiences yaw, the planing surfaces change their angle of attack and develop a rolling moment. An angle of yaw to port, for example, will increase the angle of attack of the starboard side of the hull and decrease the angle of attack of the port side, resulting in a roll with the port side down. Gill states that some craft are unstable in this mode and that a small angle of yaw can quickly result in a large angle of roll. This is described as similar to an instability that can be developed by aircraft. An estimate is made of the rolling moment associated with a small angle of yaw and is found to be significantly more than that associated with off-center weights or engine torque.

The literature search pointed out, if nothing else, how little is known about the bottom pressures acting on a hull traveling at planing speeds. If the surface in contact with the water is prismatic, the pressures are very well defined. Any practical boat, however, has surfaces that are to a greater or lesser extent curved. What happens to bottom pressures when these are submerged, if only during operations in a seaway, is largely unknown. Additionally, three potential causes of the problem were identified: transverse instability at high speeds caused by the change in pressures under the hull; an instability due to low pressures resulting from some unspecified extreme curvature in the bow, which had in fact been investigated in conjunction with flying boat accidents; and a coupled roll-yaw phenomena. It was then hoped that a test program could be developed and carried out to identify the cause of the instability in the surf rescue boat.

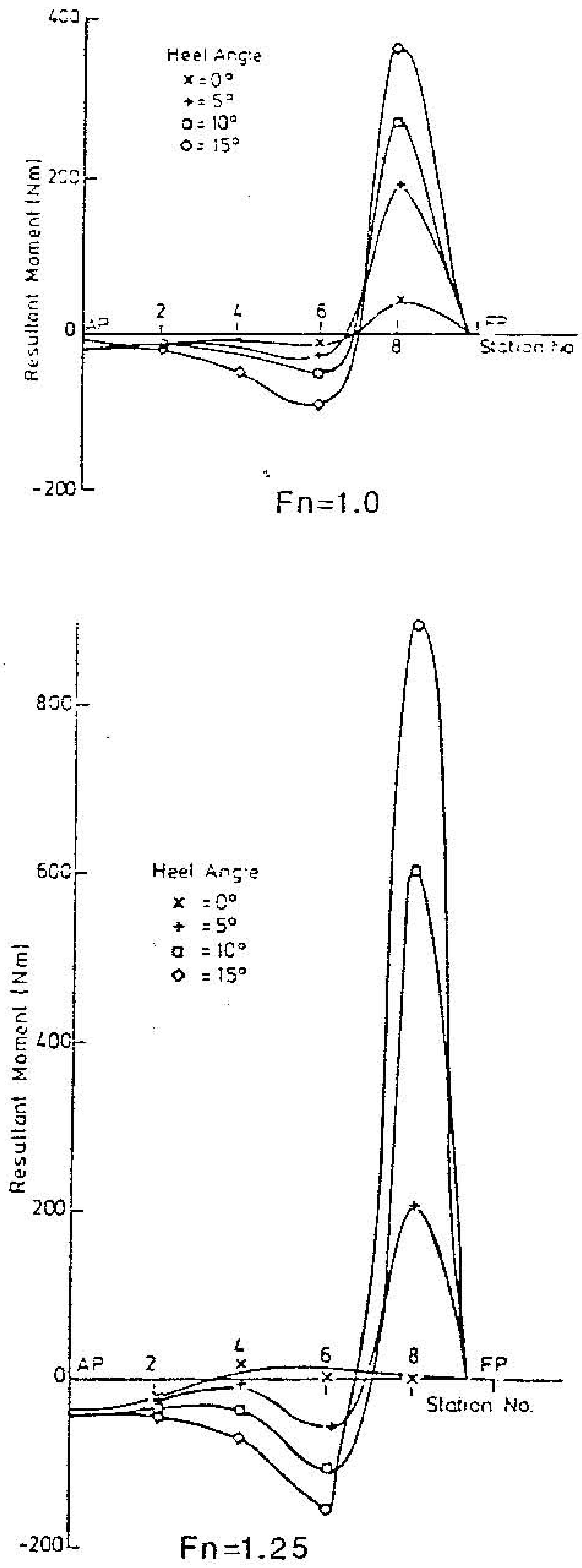


Fig. 8 Righting moment distribution along hull

Test program

Objectives. The objectives of the test program were to measure, document and analyze those dynamic parameters that would provide insight into the cause of the roll instability exhibited by the 30-ft SRB.

Test approach. The test data to be gathered had three basic requirements: (1) allow identification of the instant of time the boat became unstable, (2) show the boat's operating conditions (rudder angle, speed, etc.) prior to and during the instability, and (3) accurately measure the hydrodynamic forces on the hull. Since the time at which the instability would occur was unpredictable, the logical approach was to continuously record all of the test parameters onto a magnetic tape recorder. The

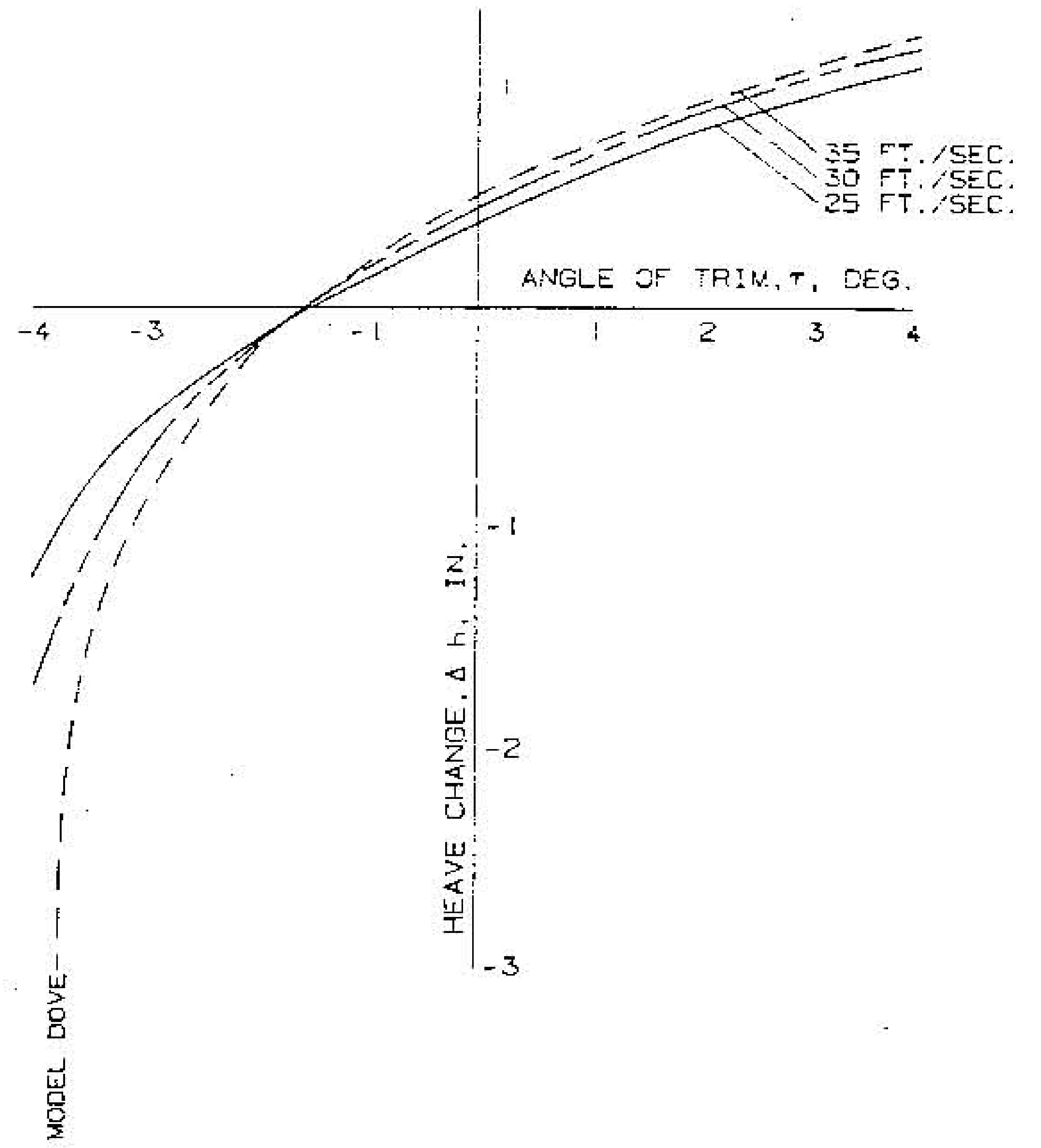


Fig. 9 Variation of heave change with trim and speed

data could then be played back repeatedly at a later time for a detailed analysis.

To identify on the magnetic tape the instant of time the instability occurred, roll and pitch were recorded and the event annotated on a voice channel. The rapid increase in roll rate and high roll angle identified on the recorded data the exact time of the instability. A vertical gyro was used for measuring the roll and pitch angles because of its high accuracy and small size. Also, triaxial accelerometers were mounted on the bow and stern to help identify the exact time the instability started.

To help in reconstructing the operating condition of the boat prior to and during the instability, the rudder angle, propeller shaft torque and rpm, and speed through the water were recorded. The rudder angle was measured using a Sperry rudder angle indicator system. The Sperry system was modified to produce an output signal compatible with the magnetic tape recorder input.

A strain-gage torque telemetry system was used to measure shaft torque. Shaft rpm was measured using a magnetic pickup to sense the frequency of rotation of eight bolts on the shaft's coupling flange. The shaft torque and rpm indicated the engine throttle commands and showed any variations in the propeller loading.

Speed through the water was measured using a Kenyon impeller-type speed transducer. The sensor was accurately calibrated by timing the boat over a measured course at several speeds through out the speed range. This through-the-hull transducer was selected because of its good repeatability, quick response to speed changes and high reliability. The hydrodynamic forces on the hull were measured using flush-mounted pressure transducers distributed along the hull bottom. It was desired to install as many transducers as possible. As it turned out, the number used was governed by their cost ($360 each) and the availability of signal conditioning amplifiers and tape recorder channels. The initial decision was to use 14 pressure transducers. Ten were installed along the port bottom and four along the starboard bottom. Rough-water testing soon showed that the test boat always rolled to port when the instability occurred. An inspection of the pressure data showed no unusually large forces on the starboard bottom at the onset of the instability. The starboard pressure transducers immediately went to atmospheric pressure, indicating that the starboard bottom was out of the water after the instability was initiated. This observation led to the decision to move the starboard pressure transducers to the port side to gain better pressure distribution resolution on the port bottom. A total of 13 pressure transducers were finally installed along the port bottom.

Calm-Water Test. The purpose of the calm-water test was fourfold: (1) to accurately calibrate the Kenyon speed sensor, (2) to measure the steady-state trim versus speed characteristics of the boat, (3) to measure the bottom pressure distribution at various constant speeds, and (4) to measure the natural periods of roll and pitch at rest. To accomplish (1) through (3) the boat was operated and timed over a measured course at incremental rpm settings while the speed signal, trim angle, and bottom pressures were measured. The natural roll and pitch periods were determined dockside by performing roll and pitch decay experiments. The boat was also weighed using a two-point lift, and the location of the LCG was determined.

Rough-water test. The purpose of the rough-water test was to place the boat in the unstable condition while recording the test parameters. The test was conducted near Cape Charles and Cape Henry, Virginia. The wave heights were one to three feet during the testing period.

Instrumentation

A diagram of the installed instrumentation is shown in Fig. 14. As planned, the measured parameters were pitch, roll, bow and stern triaxial accelerations, speed, bottom pressures, rudder angle, shaft torque, and shaft rpm. The magnetic tape recorder used was a Sangamo SABREX11. This recorder has 14 parallel analog channels plus a voice track and is constructed for operation in harsh environments. Since there were 25 channels of data to be recorded, some had to be multiplexed onto one channel of the recorder. The bottom pressure signals and rud-

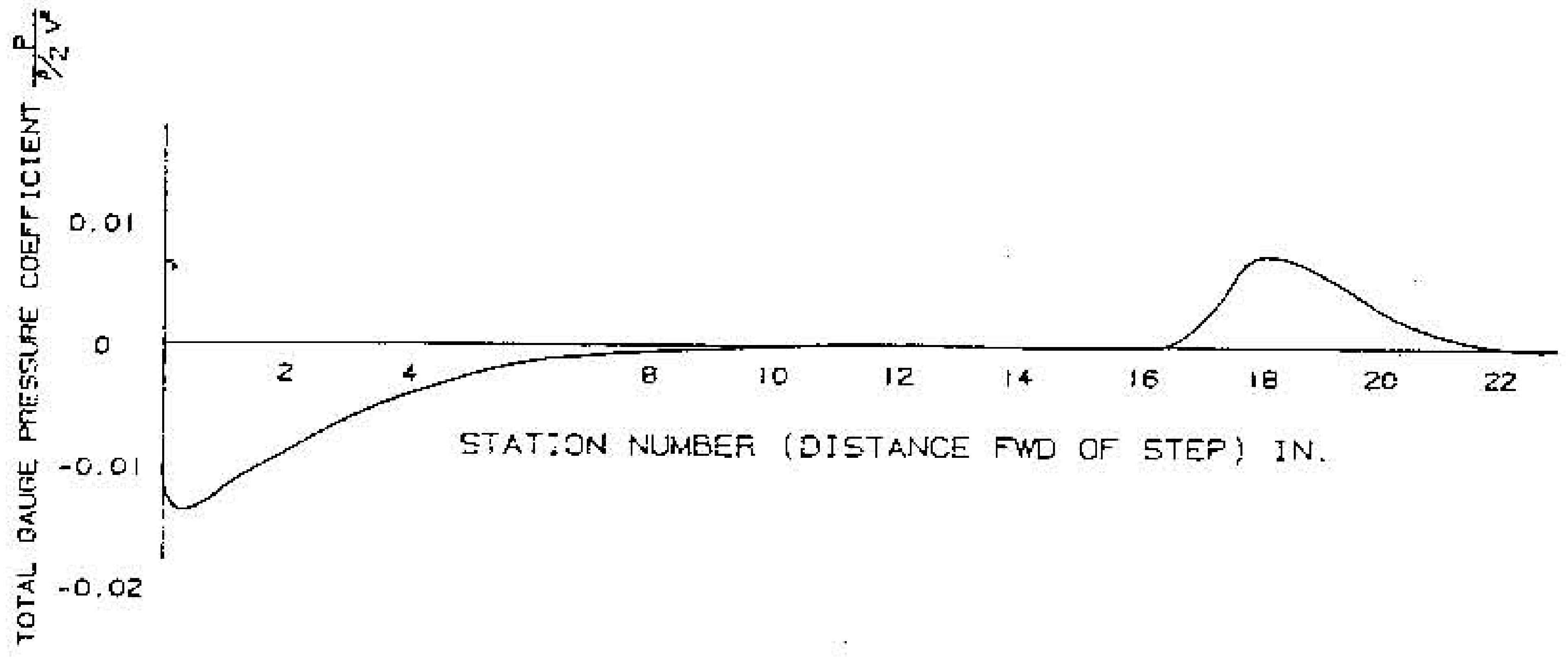


Fig. 10 Distribution of experimental pressure coefficients

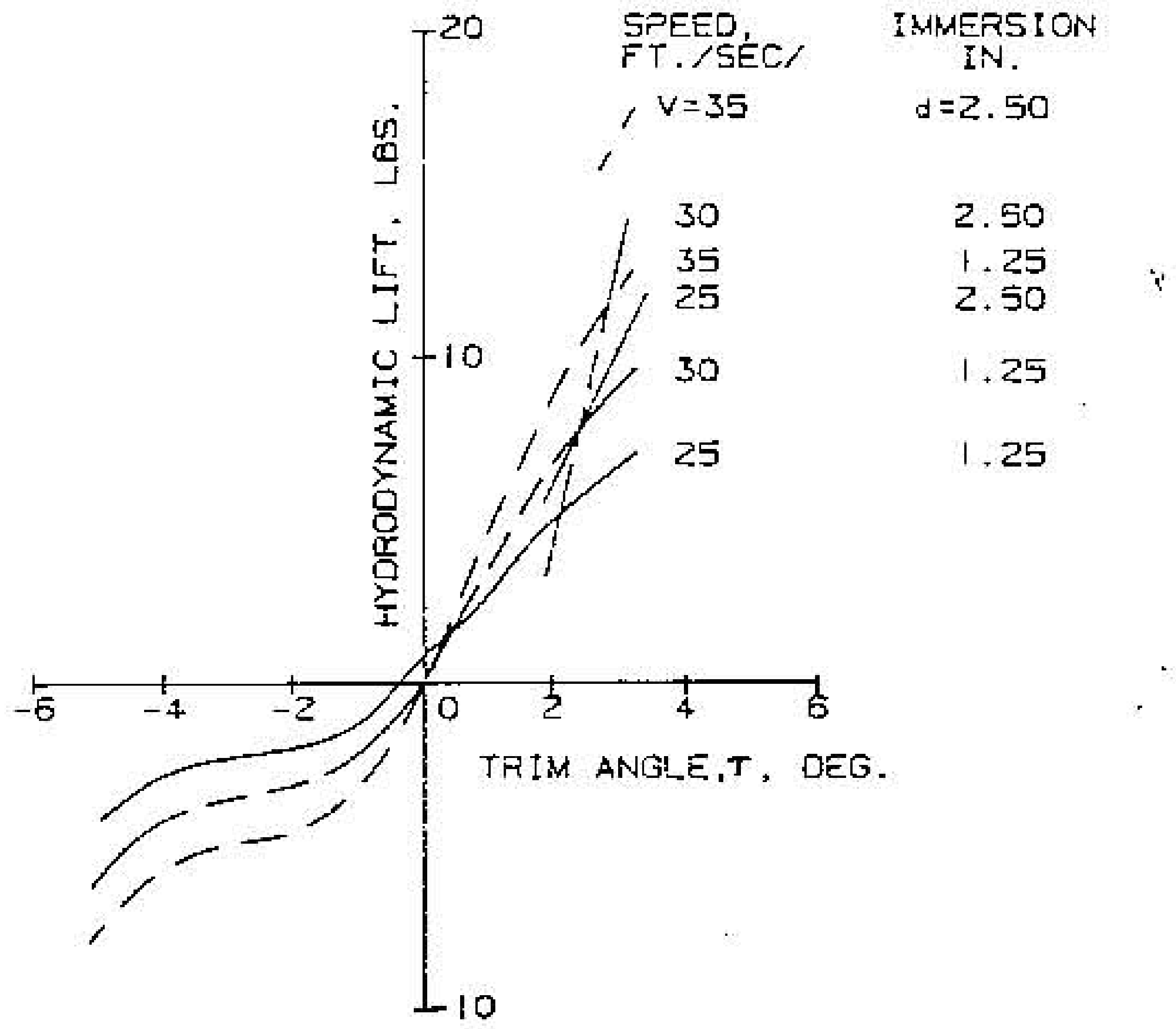


Fig. 11 Variation of hydrodynamic lift with angle of trim

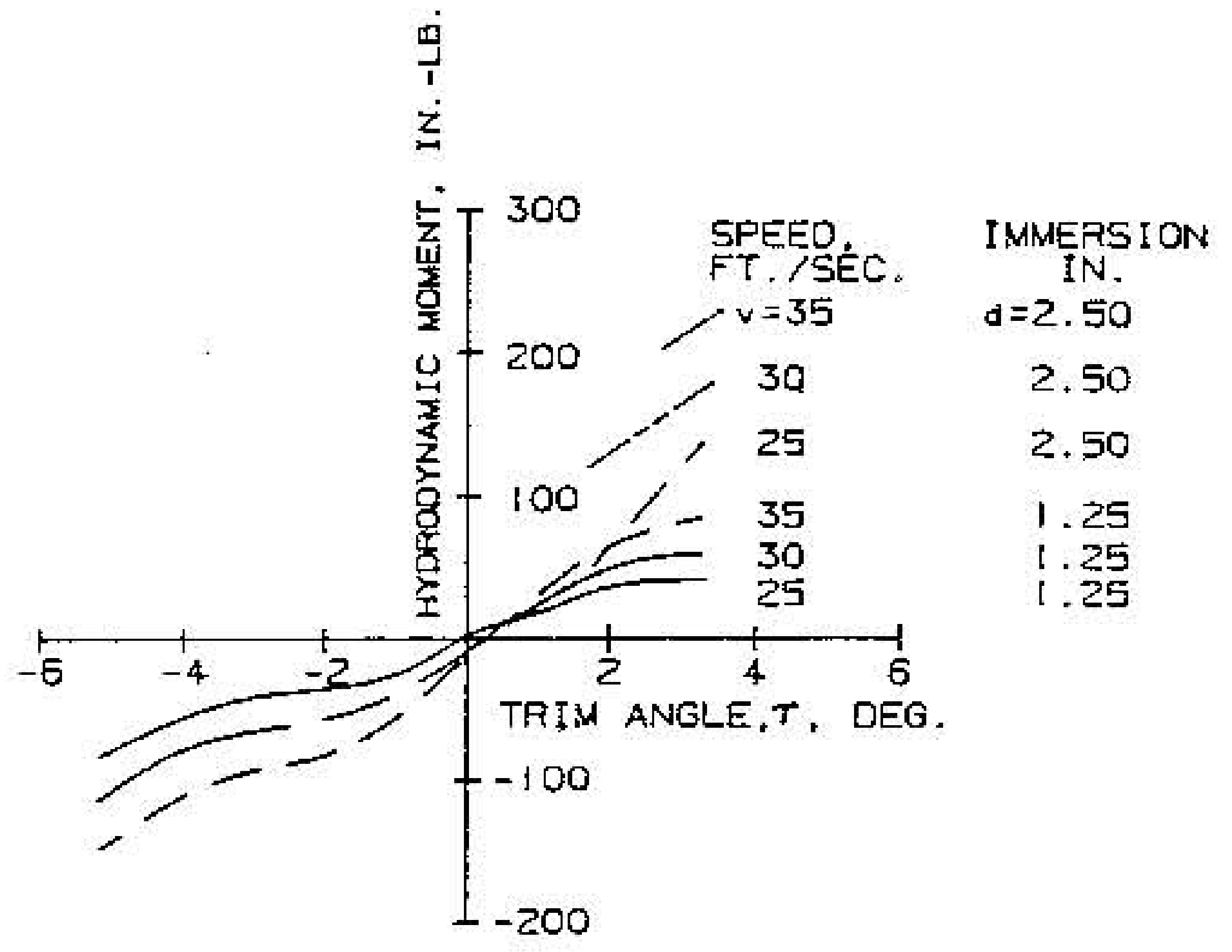


Fig. 12 Variation of hydrodynamic pitching moment with angle of trim

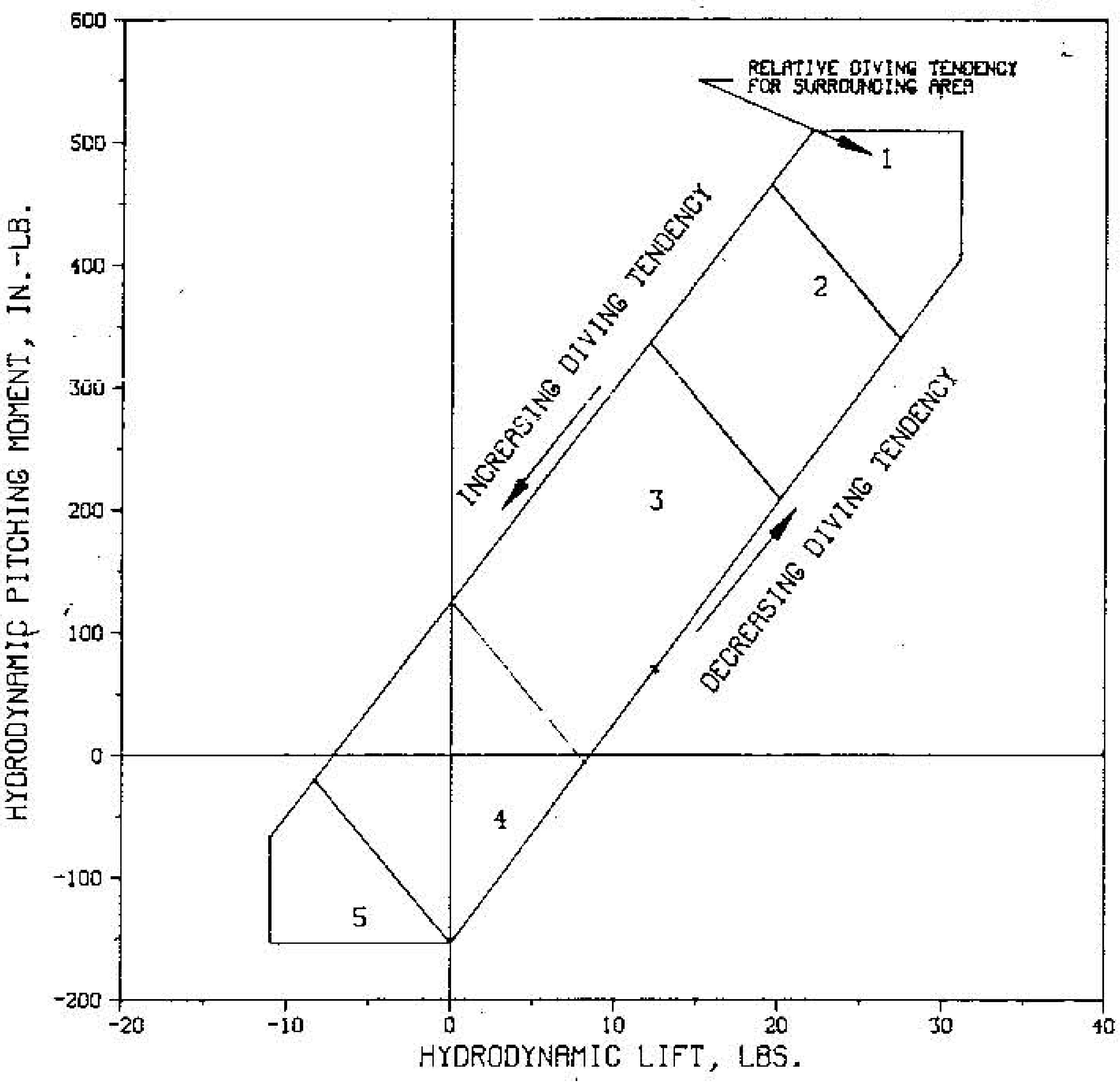


Fig. 13 Range of lift and pitching moment

der angle were multiplexed. The recorder was operated at a speed of 3¾ in./sec, intermediate band. All channels except those multiplexed were recorded using frequency modulation (FM) record modules. This provided those channels with a frequency response of dc to 1.25 kHz. The multiplexed channels were recorded via a "direct record" module and along with the characteristics of the multiplexer provided each multiplexed channel with a frequency response of dc to 60 Hz.

The vertical gyro, recording instrumentation and signal conditioning units were located in the boat's aft compartment to minimize any effects of shock due to bow slamming. Triaxial accelerometers were mounted on the centerline at stations 1 and 9¾. The Kenyon speed sensor was located at station 8 port side. Shaft rpm was measured using a magnetic pickup to sense the frequency of rotation of the eight bolts on the shaft's coupling flange. Shaft torque was measured with a strain-gage telemetry system, and hull bottom pressures were measured with 13 flush-mounted pressure transducers distributed along the port bottom as shown in Fig. 15.

The 12 V electrical system did not have the capacity to operate the craft's normal loads and also power the instrumentation. Therefore, a separate 24-Vdc/115-ac electrical system was added. The system consisted of two 12 V batteries wired in series, a 70-A/24 V engine-driven alternator, and a 115-Vac, 250-W static inverter.

The complete instrumentation list is given in Table 1.

Test results

Calm-water test. The speed-versus-trim characteristics measured during the calm-water test are plotted in Fig. 16. The average bottom pressures at constant speeds are listed in Table 2. The natural roll and pitch periods were found to be 2.3 sec and 1.9 sec, respectively.

Rough-water test. During the rough-water test the boat was maneuvered into the unstable roll condition several times but never predictably. When the waves were steep and close together it appeared as though the bow would not stay down long enough for the instability to occur. Even on days when the sea conditions appeared adequate, it took much maneuvering at high speeds before the instability would unpredictably occur. The instability usually occurred when the boat overran a large wave in a following sea and a port heel condition was initiated using the rudder.

The recorded data show negative pressures developing along the port bow when the instability takes place. Figures 17 through 28 show 40 sec of actual data recorded during which a roll instability occurred and lasted for approximately 5 sec. The following paragraphs give an interpretation of the data and reconstruct the events that occurred prior to, at the onset of, and during the instability. Data from pressure transducers Nos. 9 and 11 are omitted due to transducer failure. Figures 29 and 30 show pictorial views of the bottom pressure distribution at the time the instability occurred. The size of the pressure arrows in Figs. 29 and 30 indicates pressure magnitude. "T1" through "T7" refer to time events labeled on the data plots.

T1 (pre-instability condition). At time T1 on the data plots the boat is traveling at a speed of 24 knots. It has just stopped rolling 17 deg to port in response to an 11-deg left rudder command. The coxswain starts centering the rudder and the roll angle starts decreasing. The pitch data show that the bow has started a downward motion. All pressure transducers forward of pressure transducer No. 8 are at atmospheric pressure, indicating that the bow forward of station 4½ is clear of the water. Pressure transducer No. 8 shows a high pressure (greater than 4 psi), indicating a close proximity to the flow stagnation line. Pressure transducer No. 4 located 2 ft aft of transducer No. 8 shows an increasing pressure, indicating that the center of pressure is moving aft. Immediately after T1 the boat speed increases and the pressure at transducer No. 8 drops to atmospheric, indicating that station 4½ is now clear of the water. Approximately 0.5 sec after T1, pressure transducer No. 4, located at station 5½, also the LCG location, shows pressure increasing to a maximum of 3 psi. The stagnation line is now under the LCG. The boat immediately pitches bow down at a rate of approximately 10 deg per second. Pressure transducers 12 and 13 near the stern show the pressure decreasing to approximately atmospheric pressure as the boat pitches about the LCG.

T2 (start of instability). At time T2 the bow slams into the water, speed stops increasing, and the boat immediately starts rolling back to port at a rate of approximately 25 deg per second. The shaft torque has decreased slightly and shaft rpm starts increasing, indicating that the propeller is unloading due to ventilation. Except for pressure transducers 2, 5, 7 and 10, all bow pressure transducers that were previously out of the water show a high impact pressure for approximately 0.1 sec. Transducers 2 and 5 show an instantaneous negative pressure on impact, then changing to a small positive pressure. Transducers 7 and 10 located above the chine remain at atmospheric pressure.

The impact pressures rapidly dissipate as the bow stops its downward motion and starts back up except at transducer No. 3 located at station 2 near the keel. Transducer No. 3 immediately goes to −1 psi and stays there (see T2+). Approximately 0.25 sec later transducers 2 and 8 also go negative and No. 10 goes positive (see T2++). The positive pressure on No. 10 indicates flow attaching above the chine, starting near the stern.

T3 (throttle decrease). At time T3 the boat has rolled more than 25 deg and shows no sign of stopping. The coxswain pulls back on the throttle. The shaft torque and rpm start decreasing as does the boat speed. However, the boat continues to roll at the same rate. The bow is also rapidly pitching upward. Pressure transducer 7 and 10 are now both positive, indicating a forward movement of the point where the flow attaches above the chine. The pressure at transducer No. 1 (station ¾) is becoming less positive and the pressure at transducers 2 and 3 (station 2) are becoming more negative. The pressures at transducers 4, 12 and 13 are increasing, indicating higher pressures on the stern. The coxswain increases the left rudder angle from 6 to 11 deg.

T4 (roll rate decreases). At time T4 the shaft torque has decreased to zero and goes negative due to propeller windmilling at the time the transmission is unclutched. Speed is at 23 knots and still dropping. The bow is up 3.5 deg. Pressure transducer No. 1 is now out of the water. Transducer No. 2 becomes less negative and No. 3 changes from negative to positive (from −1 psi to +0.7 psi). Pressure transducer No. 8 (station 4½) goes from atmospheric pressure to −2 psi. The roll rate decreased rapidly.

T5 (roll stops). At time T5 the port roll motion stops at a maximum of 47 deg. Boat speed has dropped to 20 knots. The bow is up 4.7 deg. Transducer No. 1 is still out of the water but submerges approximately 0.5 sec after T5. Transducer No. 3 goes slightly negative again and transducers 2 and 8 are more negative. Just prior to No. 1 submerging, Nos. 2 and 3 go slightly positive, then return to a negative value. The coxswain has thrown the throttle forward and the shaft torque and rpm are increasing. The boat stays rolled over approximately 45 deg with the bow up for approximately 1.8 sec.

T6 (negative pressures decrease). At time T6 pressure transducer No. 1 clears water again. The −2.5 psi pressure at transducer No. 8 decreases to −1 psi and the negative pressures at Nos. 2 and 3 start decreasing. The roll decreases from 45 to 21 deg.

T7 (negative pressures dissipate; roll follows rudder angle). At time T7 the negative pressures at transducers 2, 3, and 8 have dissipated and gone positive. Speed is at 18 knots. The

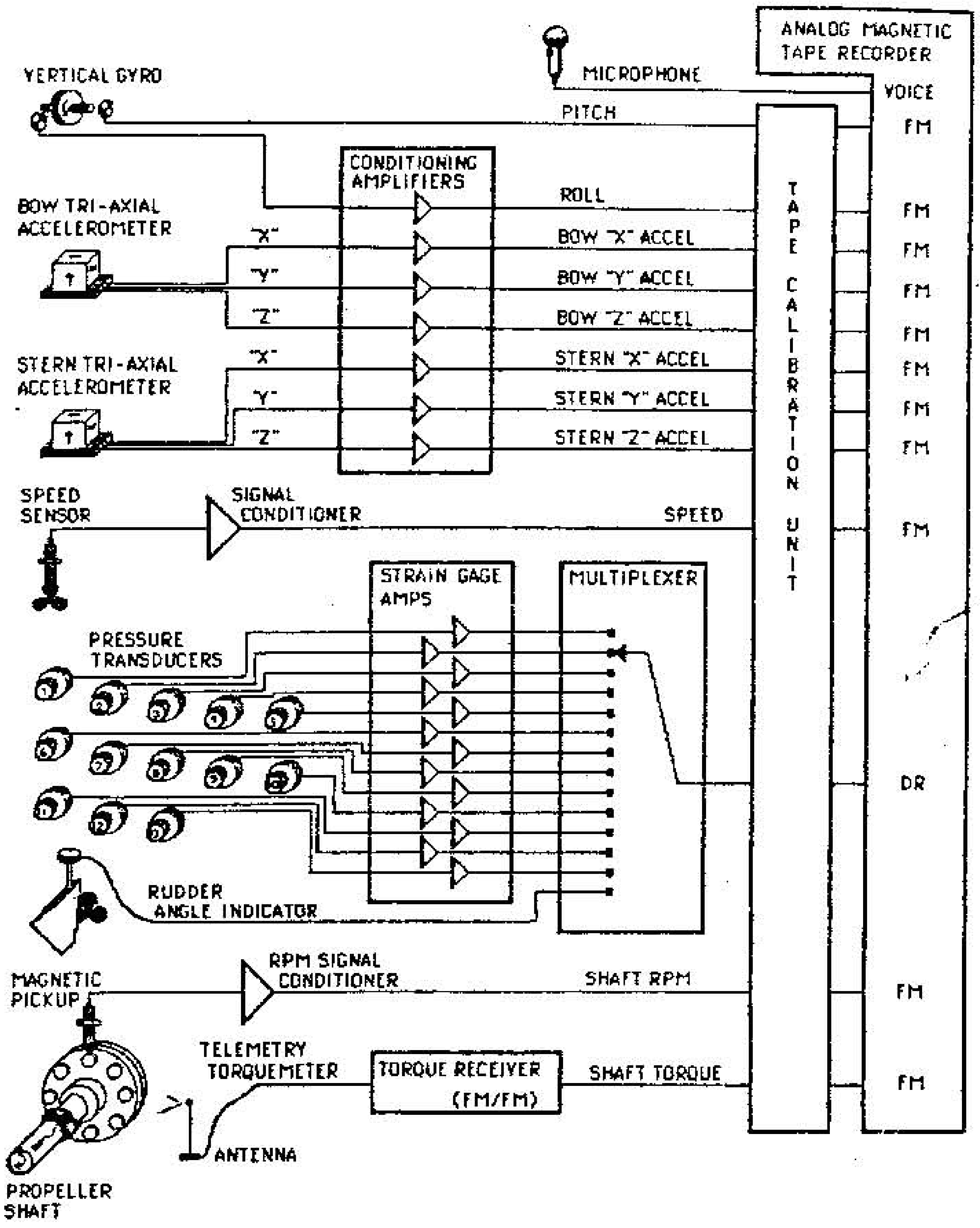


Fig. 14 Diagram of instrumentation hookup

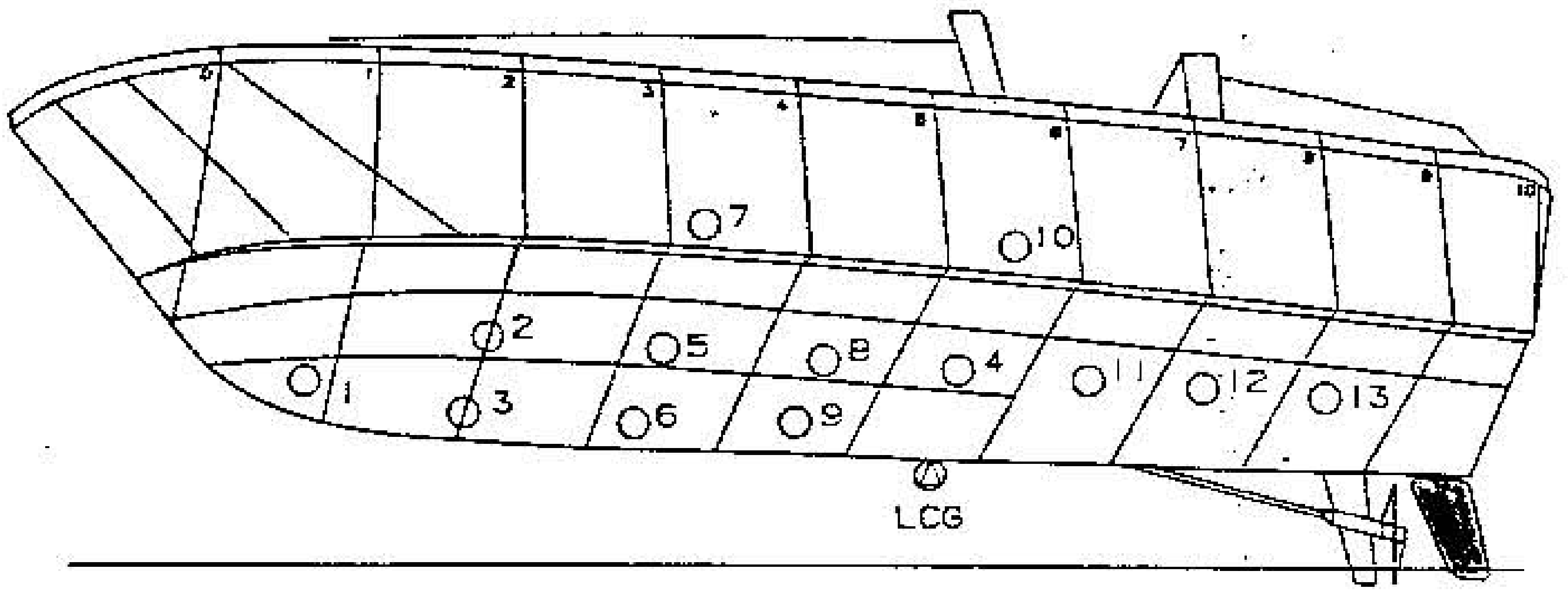


Fig. 15 Location of pressure transducers

Table 1 Instrumentation list

	Quantity
Transducers:	
Singer Kearfott Model C70 4101 023 vertical gyro	1
Sunstrand Model QA1400-AA01 servo accelerometer	6
Kenyon turbine speed sensor	1
Sperry rudder angle indicator	1
Airpax 1-0003 magnetic rpm pickup	1
Physical Measurement Devices, Inc. telemetry torque system	1
Kulite Model HKM-375-10SG pressure transducer	13
Signal conditioning:	
Ectron Model 4001 amplifier/conditioning system	1
Validyne Model MC1-10 amplifier/conditioning system	1
Fairchild Weston multiplexer/demultiplexer	1
Recorder:	
Sangamo SABRE X11 magnetic tape recorder	1
Analyzers:	
Nicolet 442B spectrum analyzer	1
Honeywell TMS 3000	1

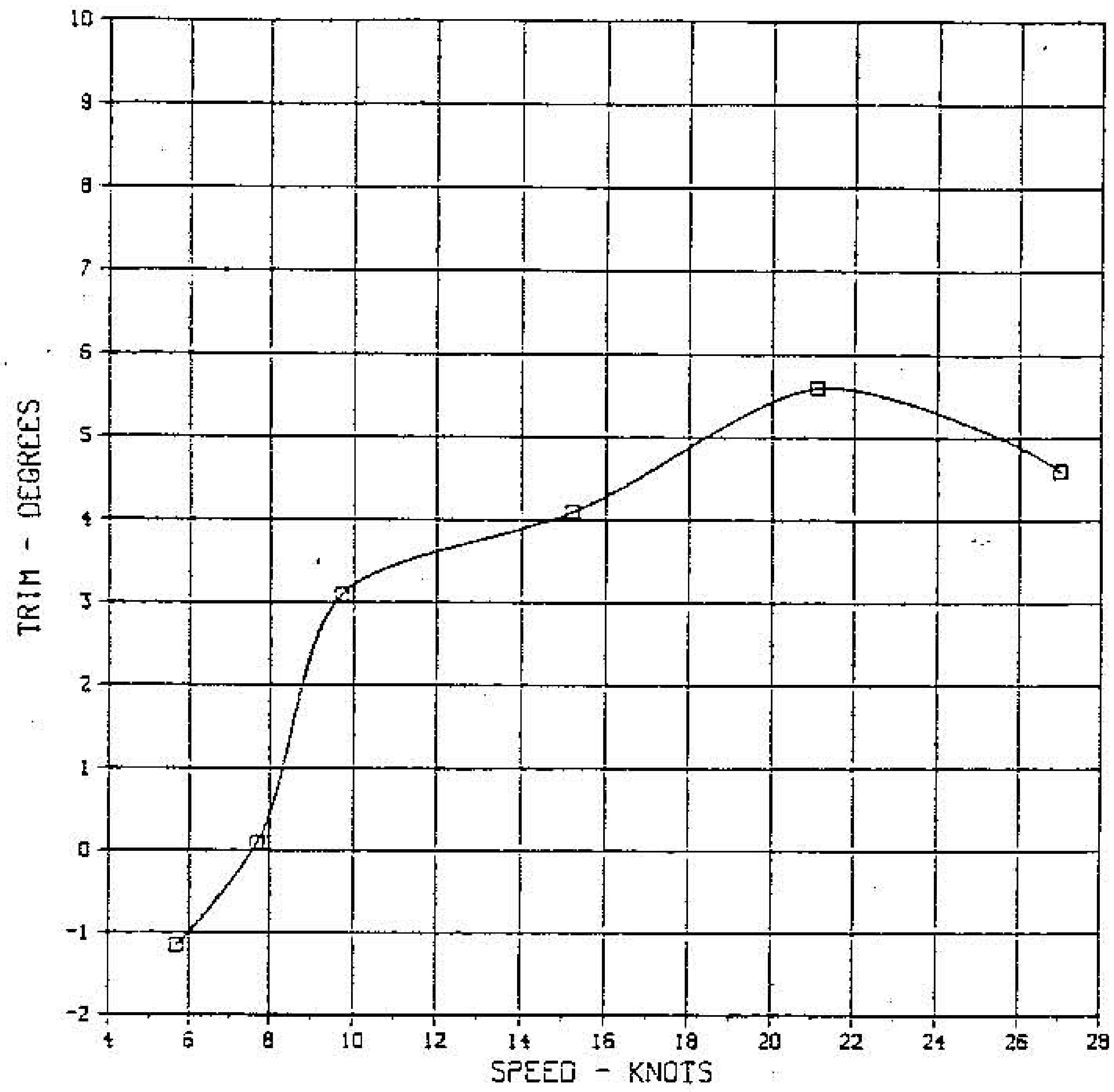


Fig. 16 Plot of trim versus speed

rudder is setting left 13 deg and appears not to be the major cause of the port heel. Roll angle follows the rudder angle for the rest of the data record. The coxswain continues to vary the throttle and rudder angle in an effort to keep the boat in the unstable condition. Pressure transducer No. 8 returns to −1 psi for approximately 5 sec but appears to have little or no effect on the roll.

Mathematical analysis

It was desired to make a limited investigation to see if the bottom pressures in the bow-down, heeled mode could be estimated mathematically. There was only one method available that appeared to be useful and even this was going to be only a very rough approximation to reality.

The technique used was a computerized potential flow model developed at the David W. Taylor Naval Ship Research and Development Center [21–23]. The program evaluates velocities and pressures resulting from completely submerged flow based on potential theory. It was realized that it would take a great stretch of the imagination to apply this to the difficult case of a planing hull, but it was thought that the effort would be worthwhile nevertheless.

To get a feel for the errors associated with using this program, the body of revolution tested in [10] was modeled and the results compared with those for the experiment. Figure 31 summarizes these results. As can be seen, the agreement is surprisingly good, especially for the areas far from the free surface. Most importantly, the model successfully predicted general trends near the forward section of the body.

The hull form of the SRB was modeled for input to the program, in an attitude of 30 deg of heel to port and 1 deg trim, bow down, as shown in Fig. 32. This attitude was approximately that measured while the craft was in the "unstable" mode. This technique was quite tedious since the surface to be modeled has to be divided into discrete areas and the offsets of the corners of these areas found. A total of 192 individual points were input, with the density of points per unit surface greater near the bow. These were then rotated into a coordinte system such that the waterplane corresponded to the *X*-*Z* plane of the model.

The model was exercised both as a single submerged hull and as a body symmetric in the *X*-*Z* plane. The pressure differences between these two calculations were quite small in the area that was of most interest, that is, the port side from the chine to the keel. The results of the pressure calculations in this area are condensed into Fig. 33 and superimposed on experimental pressure measurements taken while the boat was in approximately the same attitude. The results are similar to those for the body of revolution, showing higher pressure regions forward and aft, with a large low-pressure area amidships.

The results of the potential-flow program are presented as a uniform pressure coefficient acting over an area of hull that is defined by the spacing of the input hull points. In addition to having calculated the pressure coefficient, the model reported the magnitude of area over which the pressure acts, as well as the direction vector of the resulting force. A program was written to take this output, add static pressures to it, and integrate the moment of bottom pressures acting about the craft's center of gravity. These results are quite interesting. The transverse moment acting on the boat is positive, tending to right the craft from its 30-deg angle of heel, but is quite small, corresponding to a righting arm of less than one tenth of a foot. The static righting arm at the same angle of heel is over eight tenths of a foot [1]. It appears that the low pressures acting over the wide portion of the boat have significantly decreased the transverse stability. The calculations also indicate that there is no restoring moment in pitch in this attitude. In fact, the moment acting tends to pitch the craft down to a lower trim angle. This is not the case for the static calculations, which would indicate a large restoring moment in pitch.

Realizing the approximations involved in extrapolating this calculation to the complicated physical reality, it seems that some conclusions as to trends are justified given the reasonable agreement found with measured pressures in the body of revolution tests and to a lesser extent from the SRB tests. It appears that the boat, once forced down into the bow-down, heeled

Table 2 Average bottom pressures of 30-ft SRB at steady speeds in calm water

Speed, Knots	Trim, deg	Port, Heel, deg	Average Bottom Pressures, psi — Transducer Locations 1	2	3	4	5	6	7	8	10	12	13
9.7	3.1	3.2	0.20	0.10	0.48	0.63	0.50	0.60	0.20	0.65	0.50	0.53	0.45
15.2	4.1	3.3	0.55	0.40	0.31	0.62	0.55	0.75	0	0.55	0.60	0.60	0.47
21.1	5.6	5.6	0	0	0.95	0.63	1.72	1.25	0	0.84	0	0.63	0.40
27.0	4.6	7.7	0	0	0.80	0.61	1.30	1.90	0	1.10	0	0.65	0.35

NOTES:
1. Trim is referenced to the average buttock line angle from station 5 to station 9.
2. Port trim tab for correcting heel due to propeller torque reaction was not installed.
3. Pressure data from transducers 9 and 11 are omitted due to transducer failure.

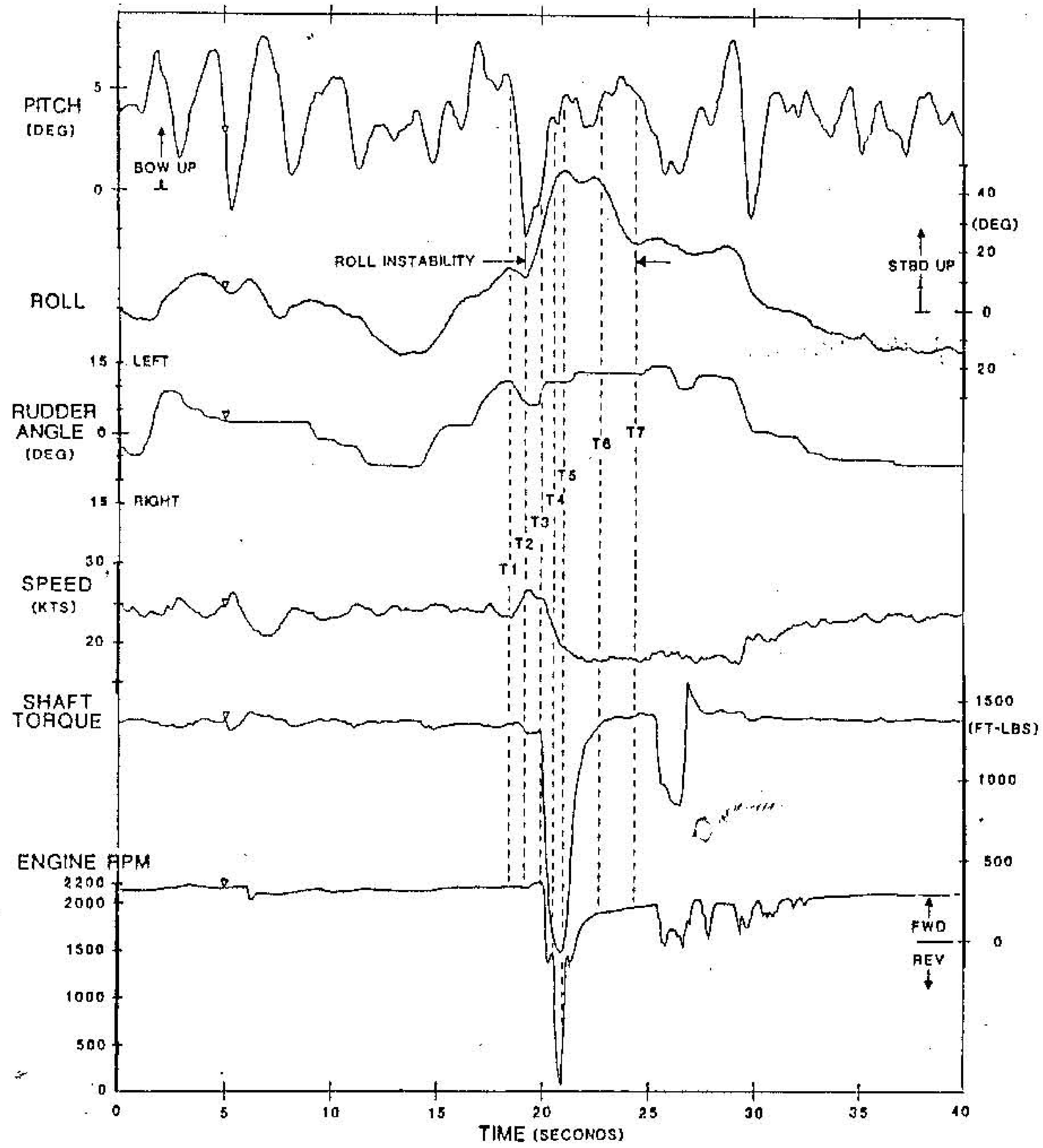


Fig. 17 Recorded data showing roll instability

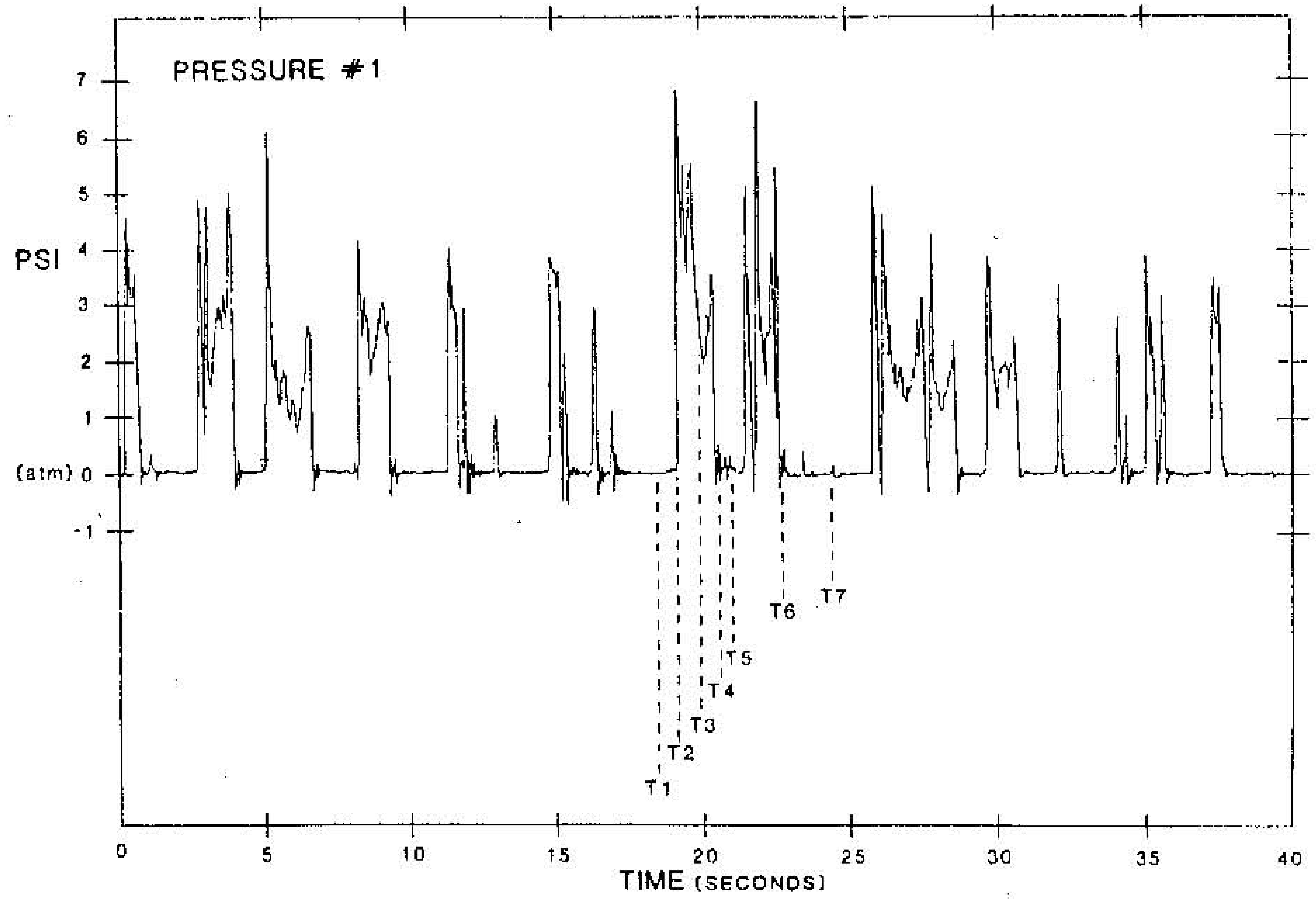


Fig. 18 Recorded data for pressure transducer No. 1

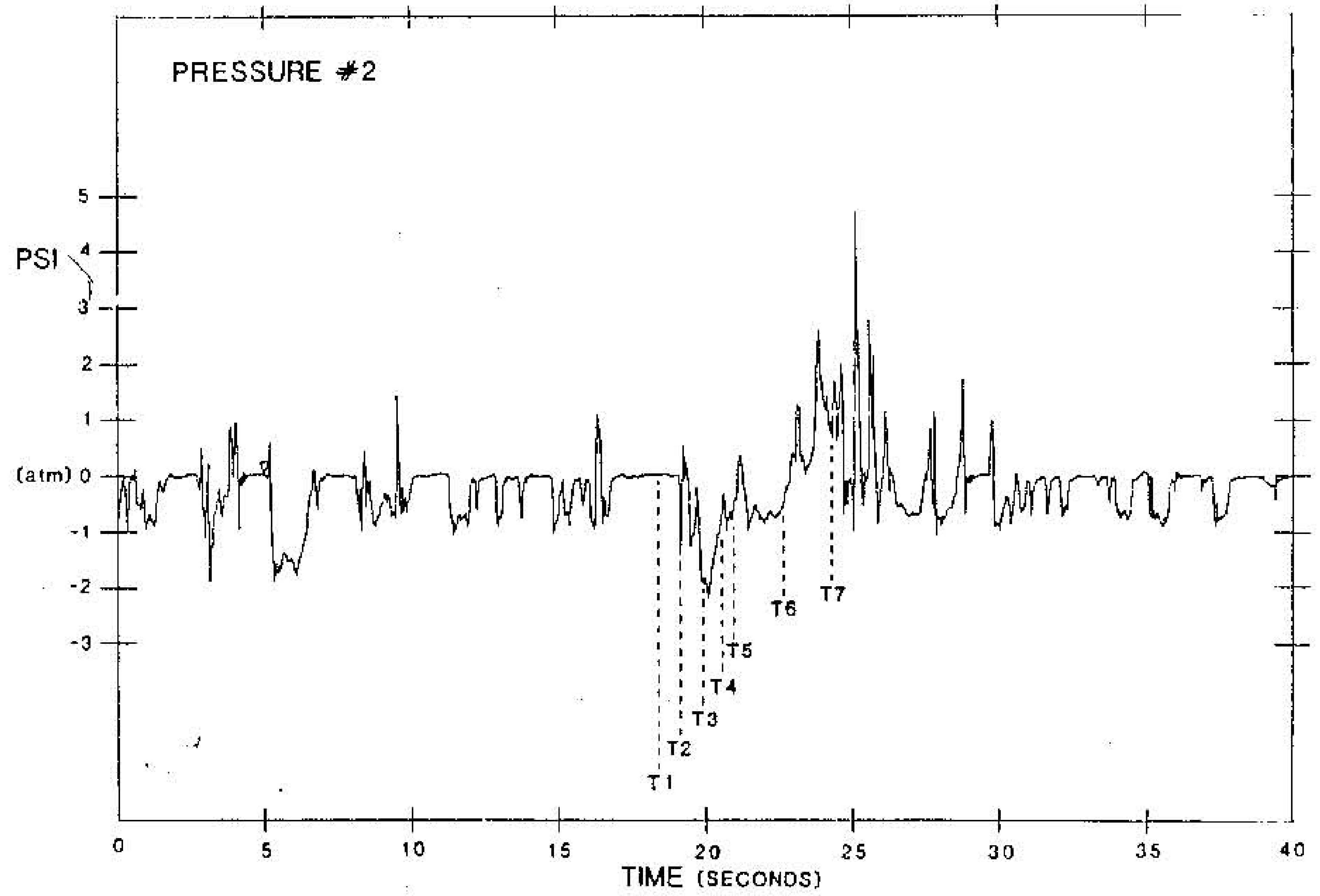


Fig. 19 Recorded data for pressure transducer No. 2

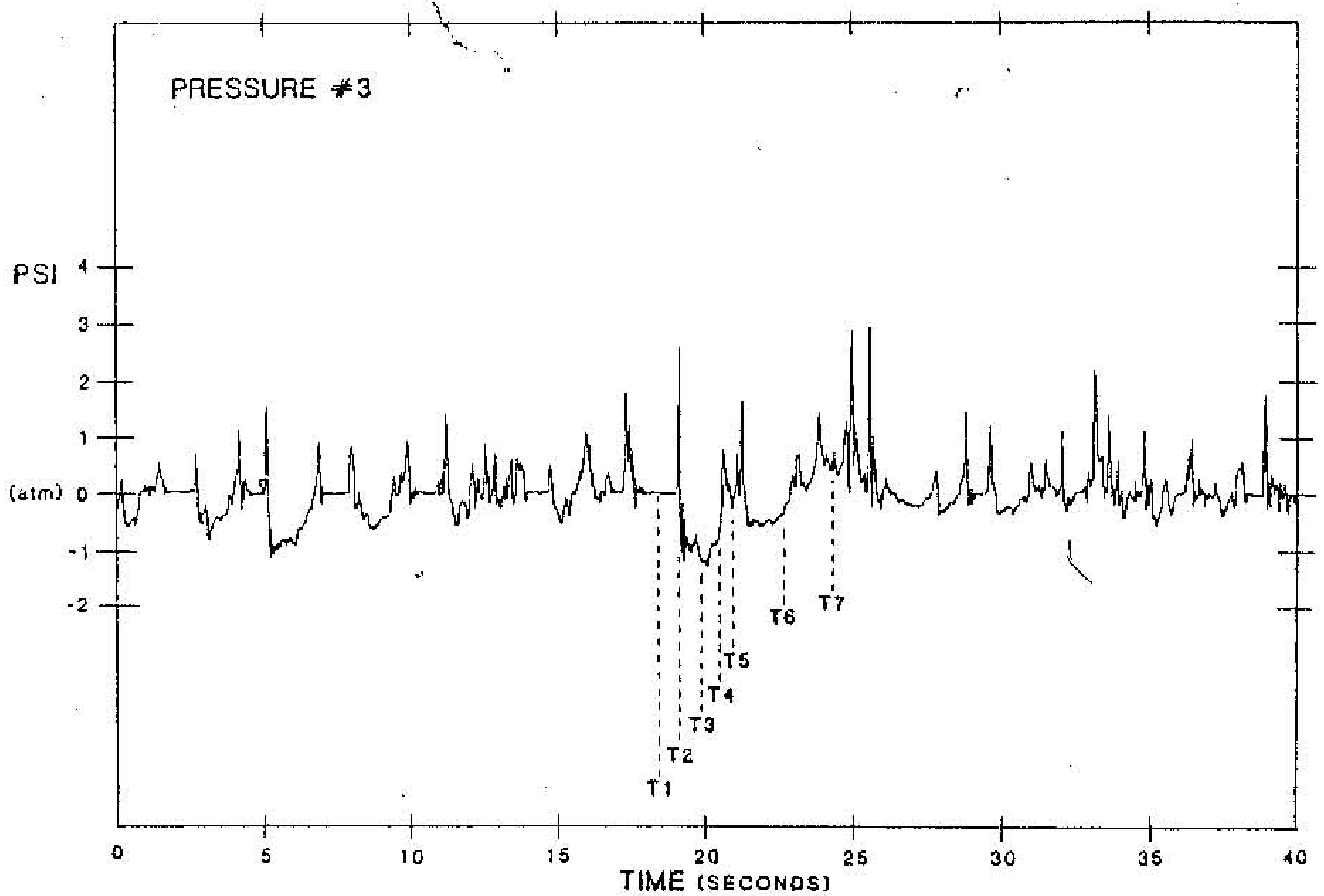


Fig. 20 Recorded data for pressure transducer No. 3

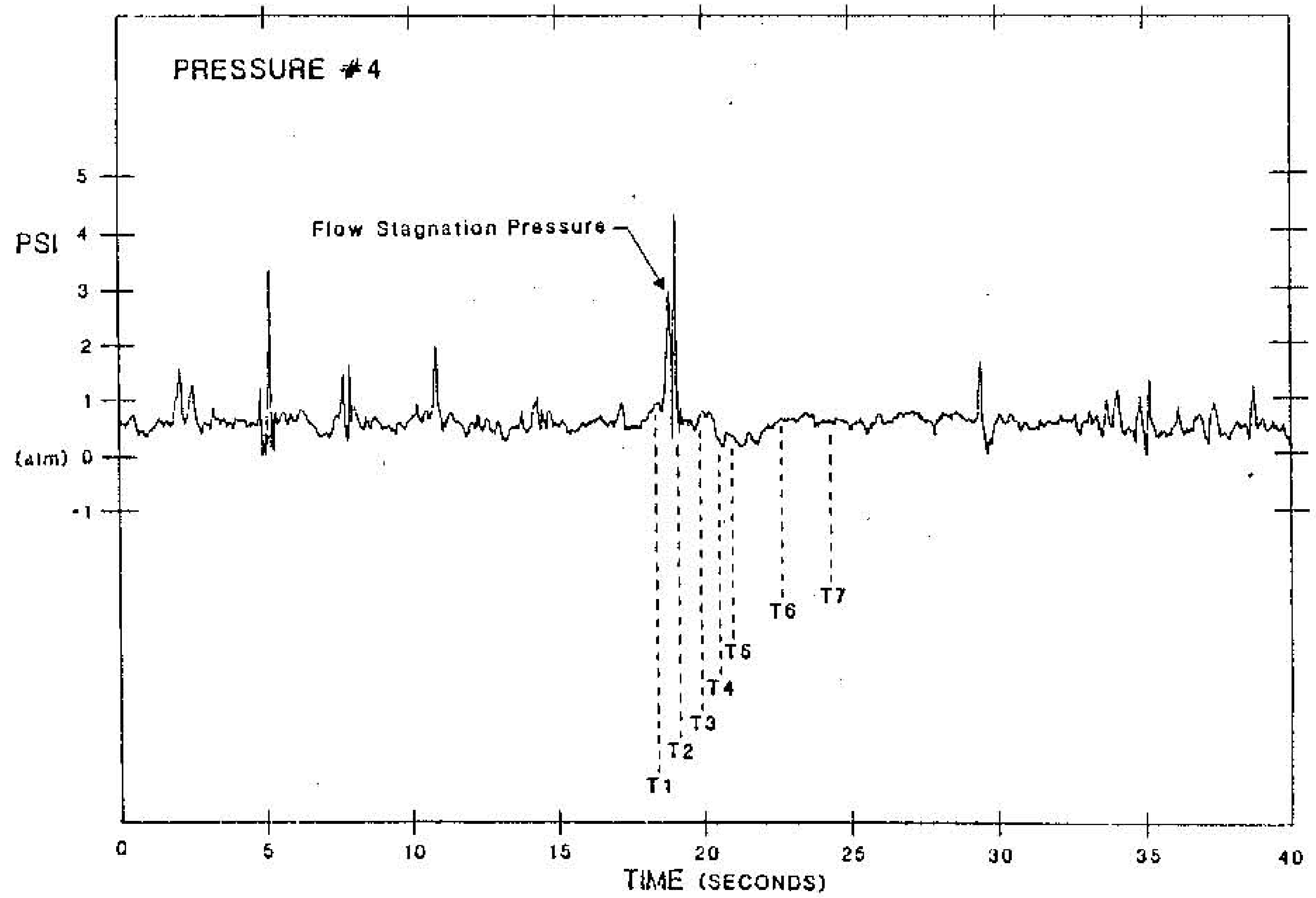


Fig. 21 Recorded data for pressure transducer No. 4

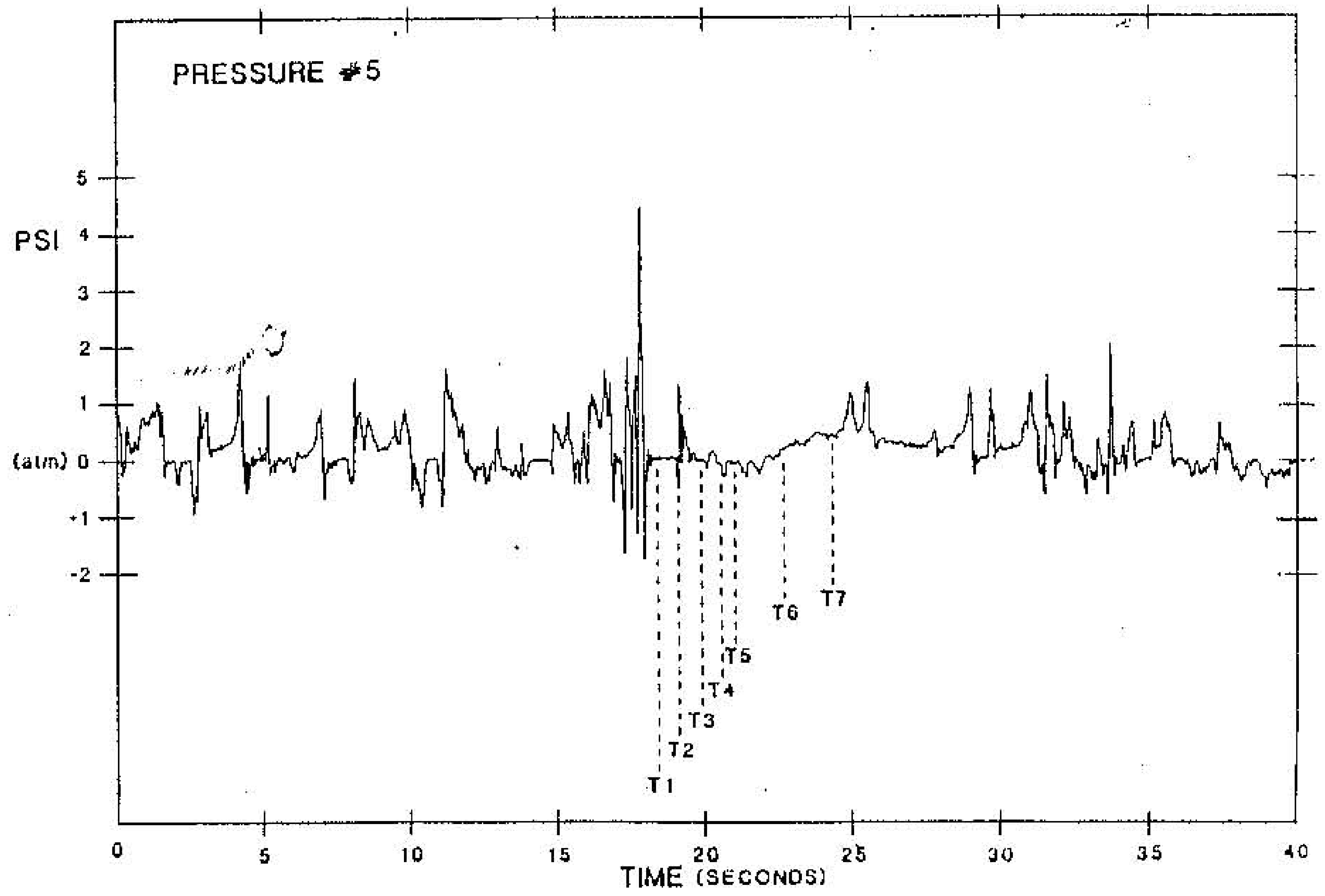


Fig. 22 Recorded data for pressure transducer No. 5

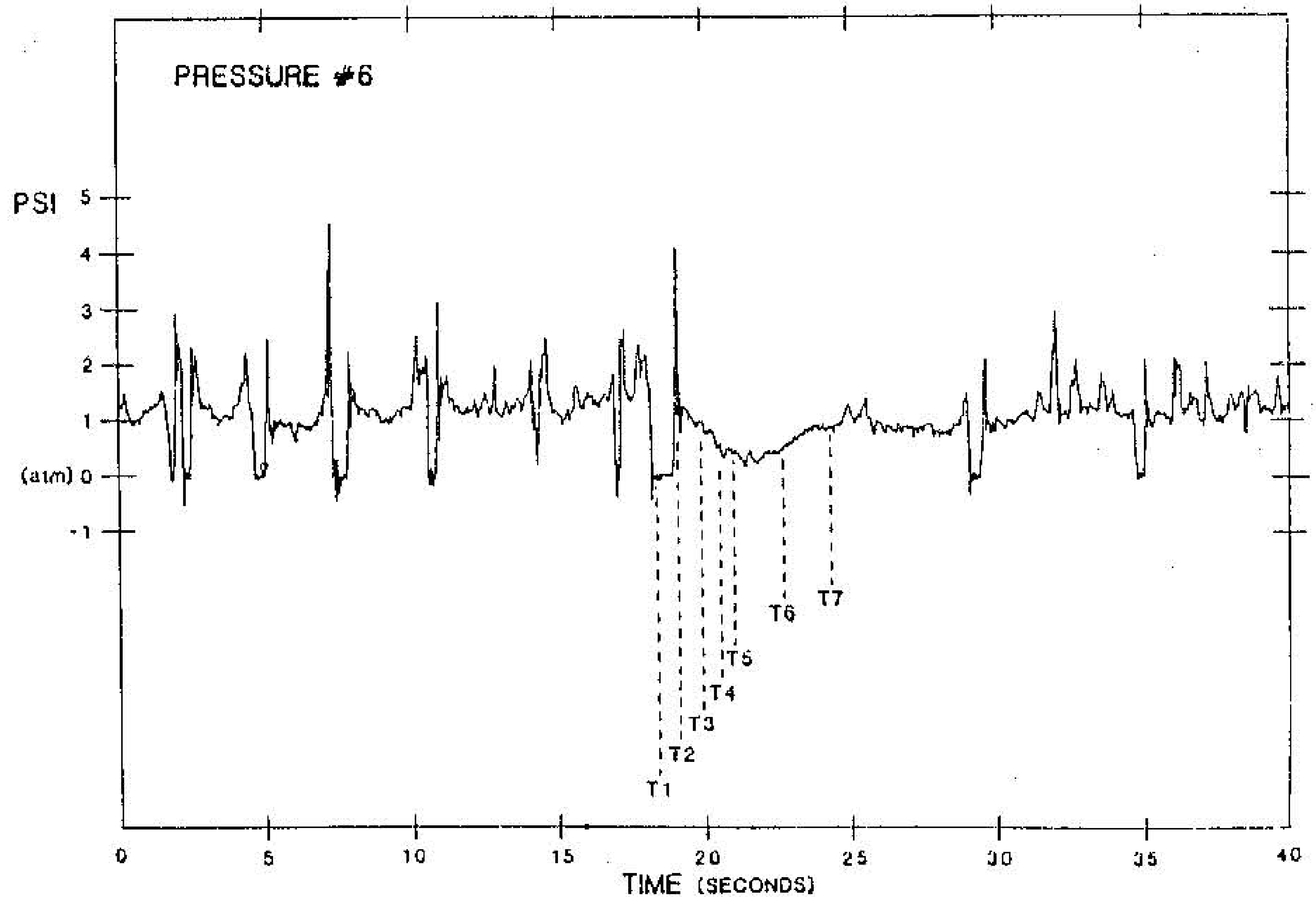


Fig. 23 Recorded data for pressure transducer No. 6

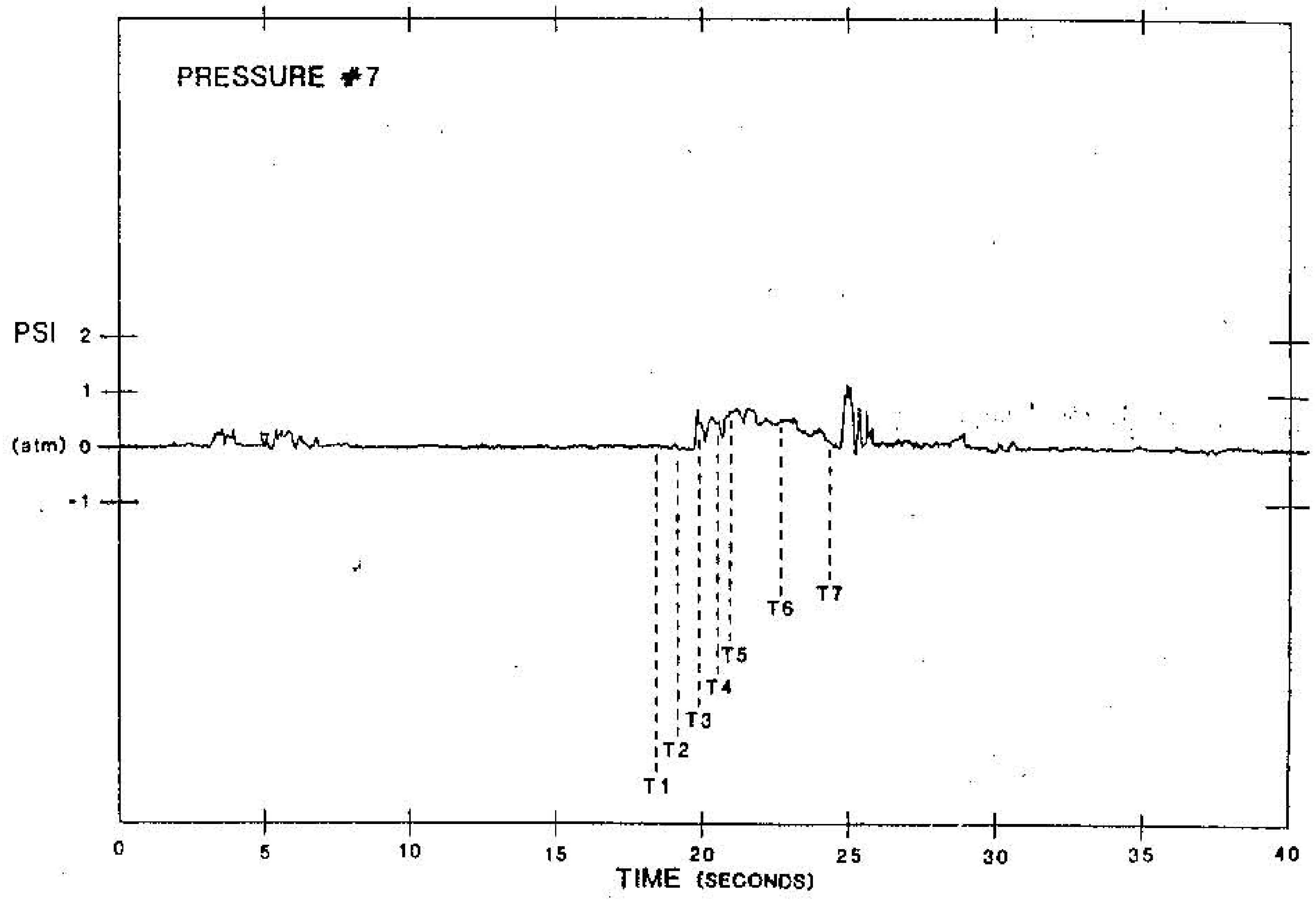


Fig. 24 Recorded data for pressure transducer No. 7

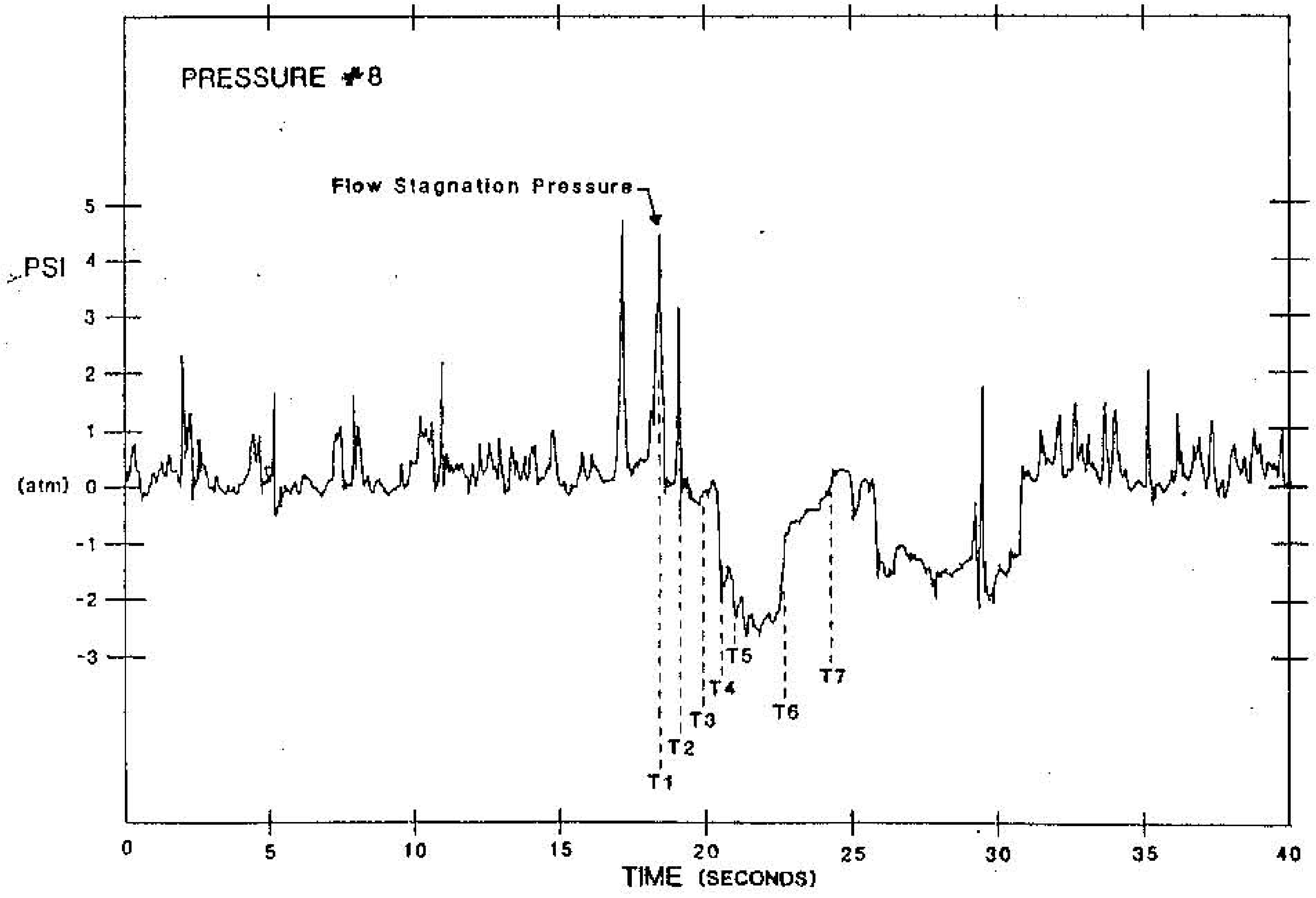


Fig. 25 Recorded data for pressure transducer No. 8

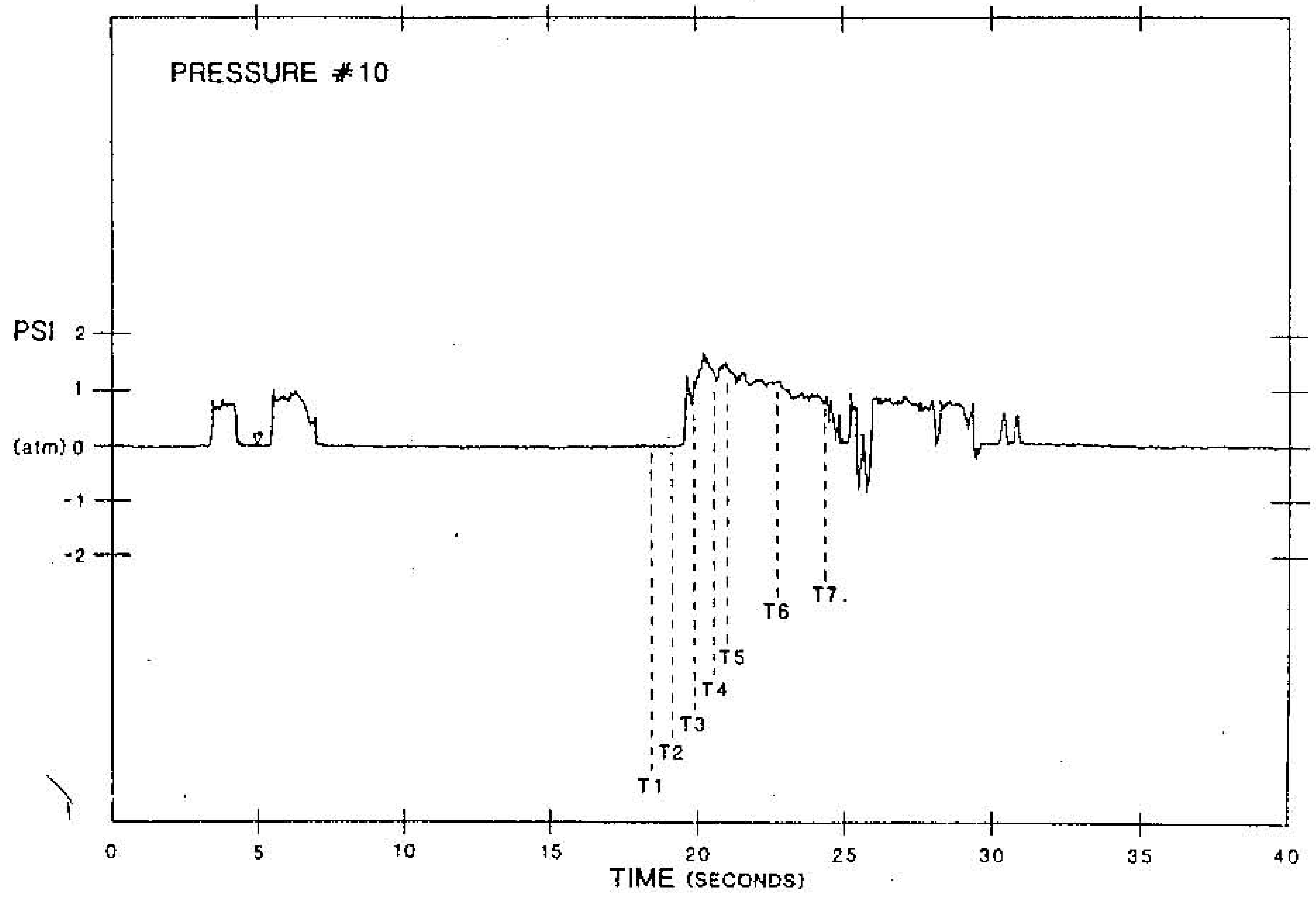


Fig. 26 Recorded data for pressure transducer No. 10

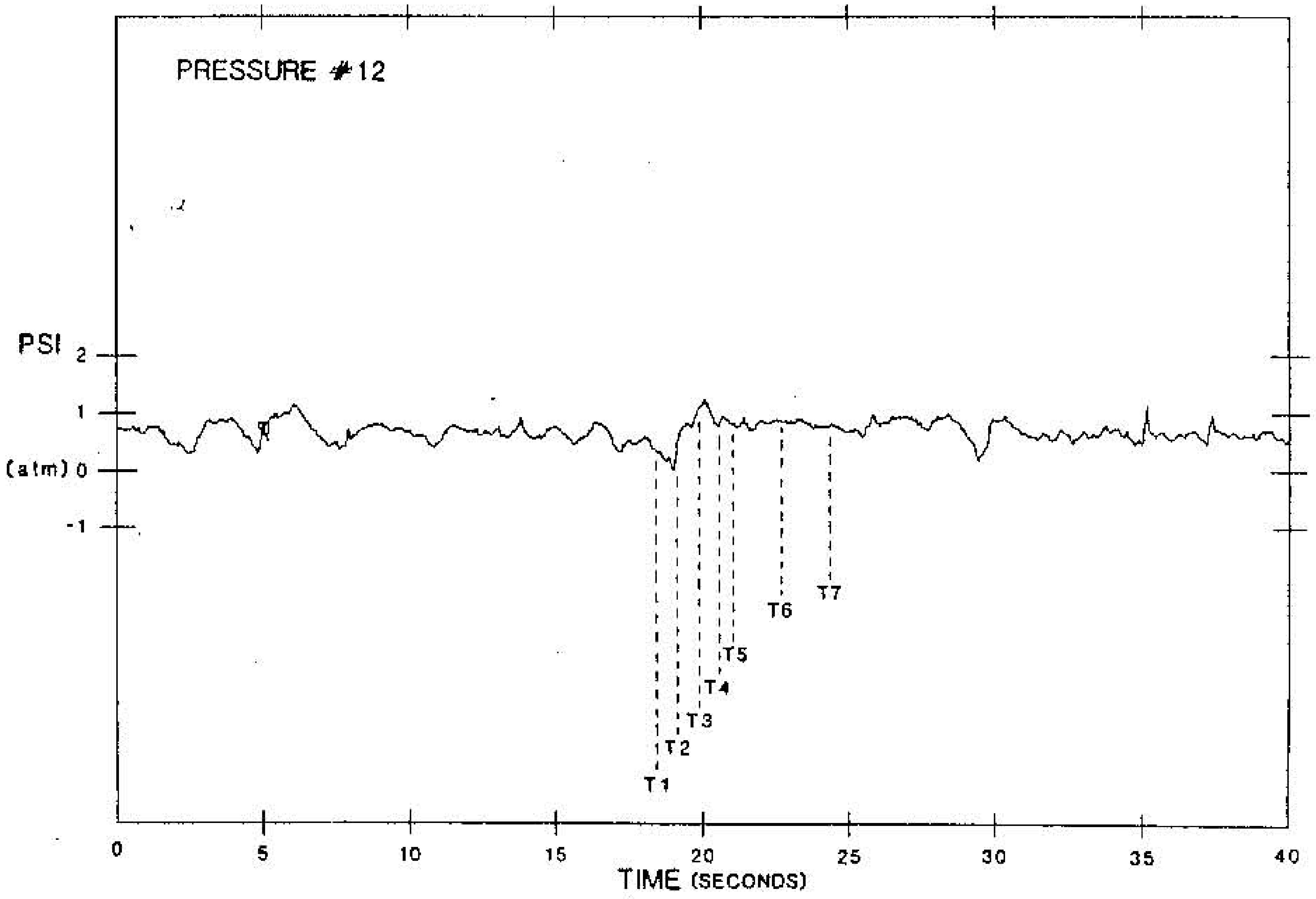


Fig. 27 Recorded data for pressure transducer No. 12

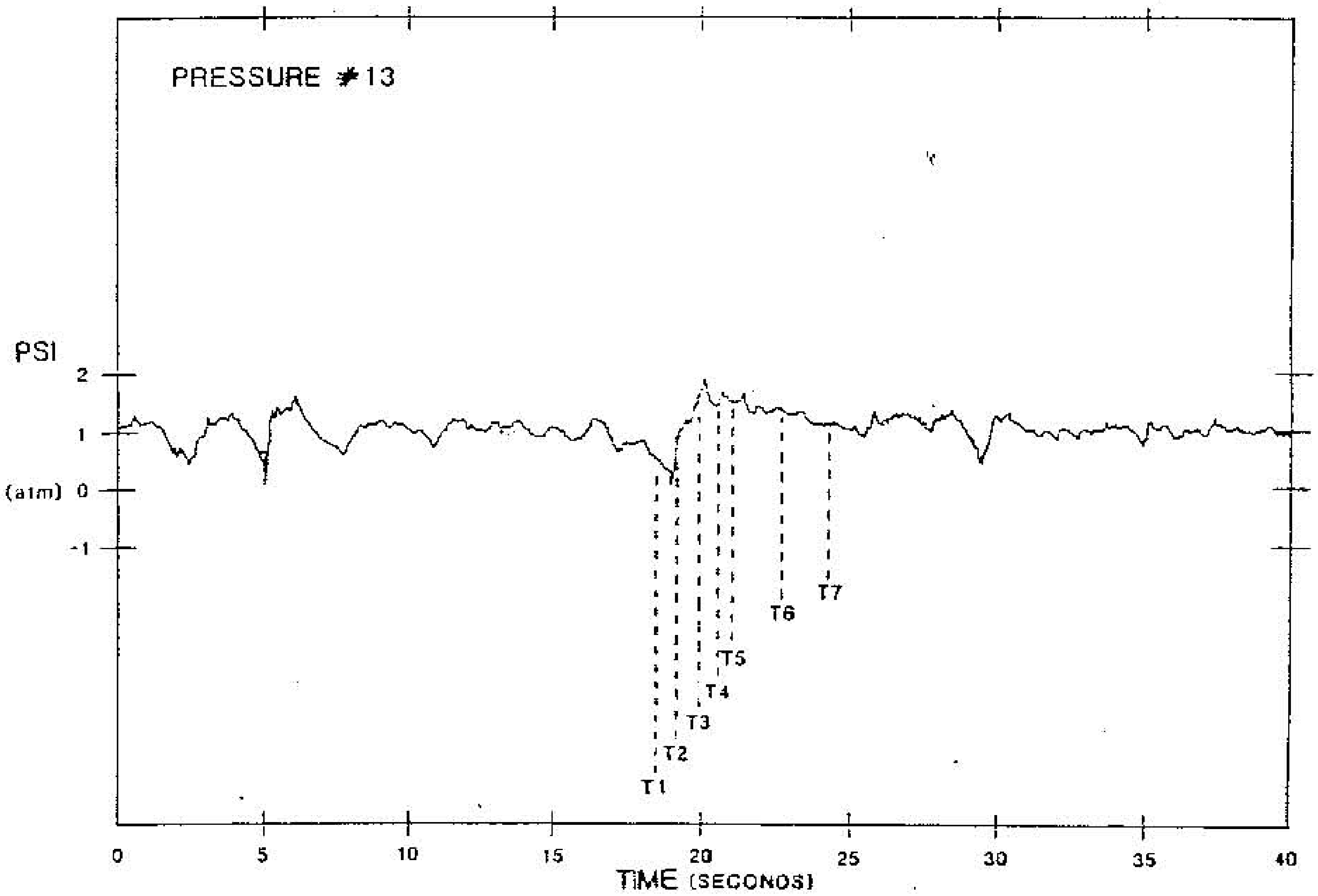


Fig. 28 Recorded data for pressure transducer No. 13

attitude, has no significant righting moments acting upon it in either pitch or roll and is in fact stable longitudinally and transversely in this mode. This is due to the fact that water pressures in the region immediately aft of the bow are very low and in some cases negative as a result of the increased flow velocities caused by the curvature at the bow. There are still positive pressures acting, of course, but these are located at the bow and stern where they have little effect because of the narrowness of the hull and, in the case of the bow, the angle over which they act.

It must be pointed out that this technique has not as yet been applied to any craft other than the SRB due to the tedium of producing the required input. It is not known if other craft that have proven satisfactory in service would show any of the same trends as the SRB.

Other investigations

In the course of our involvement in the test program, it was realized that this dynamic instability phenomenon is exhibited in other craft and we were fortunate in learning of three craft that had similar problems. Two of these were new versions of previously proven designs that resulted in a slightly increased displacement, a slightly farther forward center of gravity, and a little greater speed than the predecessors. The resulting boats both had bottom loading coefficients ($A_p/\nabla^{2/3}$) of around 5.5, an LCG close to the centroid of the projected planing area, and volume Froude numbers of 2.0 and 2.6. (Note that the bottom loading coefficient is "backward"; that is, a numerically small value indicates a highly loaded hull, while a large value represents a lightly loaded hull. A number of 5.5 is typical of a planing workboat or military craft, 6.5 is representative of a high-speed yacht, and a racing hull may be as high as 8.0.) Both of these craft had sufficient transverse stability, but when underway would adopt an angle of heel when disturbed by either the rudder or waves. Each boat had transverse bow wedges installed, similar to those described in [17], which resulted in the complete cure of the problem.

Another craft was a new design that came in significantly overweight. The result has an extremely heavy bottom loading of 4.3, an LCG 1 percent aft of the centroid of the planing area, and a very narrow hull for its size, with a length-to-beam ratio of 4. The static stability of the boat was marginal and the dynamic stability completely unacceptable. The boat ran at a low trim angle of about 1 deg to the mean buttock and would roll rapidly and violently to rudder movements in calm water. When the craft was operating at full speed, it would heel 10 deg in response to an individual walking from one side to the other across the afterdeck. Bow wedges were installed on the boat and resulted in perhaps a slight improvement in handling. An expansion of the planing area by 25 percent resulted in acceptable dynamic stability.

It was also noted that the two boats first described had an unusual trim-versus-speed curve. The trim would dip slightly as speed was increased, and then begin to increase at volume Froude numbers between 0.5 and 1.0. What was unusual was that above a Froude number of 1.25, the trim would drop sharply, then rise to its maximum angle at a Froude number of about 2 and then drop again. This has one more hump in it than the normal planing boat speed-trim curve. Figure 34 illustrates speed-versus-trim curves for a model test of a 25-deg deadrise planing hull drawn from data presented in [24]. An extreme example of this behavior can be seen for the curve of the model with the LCG at the center of the planing area, labeled "0% Lp." The curve labeled "12% Lp" shows what would be considered a normal trim curve. It should also be noted that this first hump in the trim curve is accompanied by large increases in resistance with decreasing trim, just the opposite of what happens at higher Froude numbers.

It is interesting to note that this anomaly in the curves appears only for combinations of forward LCG's and heavily loaded bottoms, not only for this series of tests, but also for those reported by Clement and Blount [25]. The range of variables where this occurs is for a bottom loading coefficient less than 5.5, with LCG at or forward of 4% Lp aft of the centroid of the planing area, and is most severe when both of the characteristics are in the range, as illustrated in Fig. 34.

It is hypothesized that the heavily loaded bottom requires that more of the boat be supported by hydrostatic forces when compared with the same hull form, but more lightly loaded, operating at the same Froude number. This requires that the hull be deeper in the water, exposing more of the curved sec-

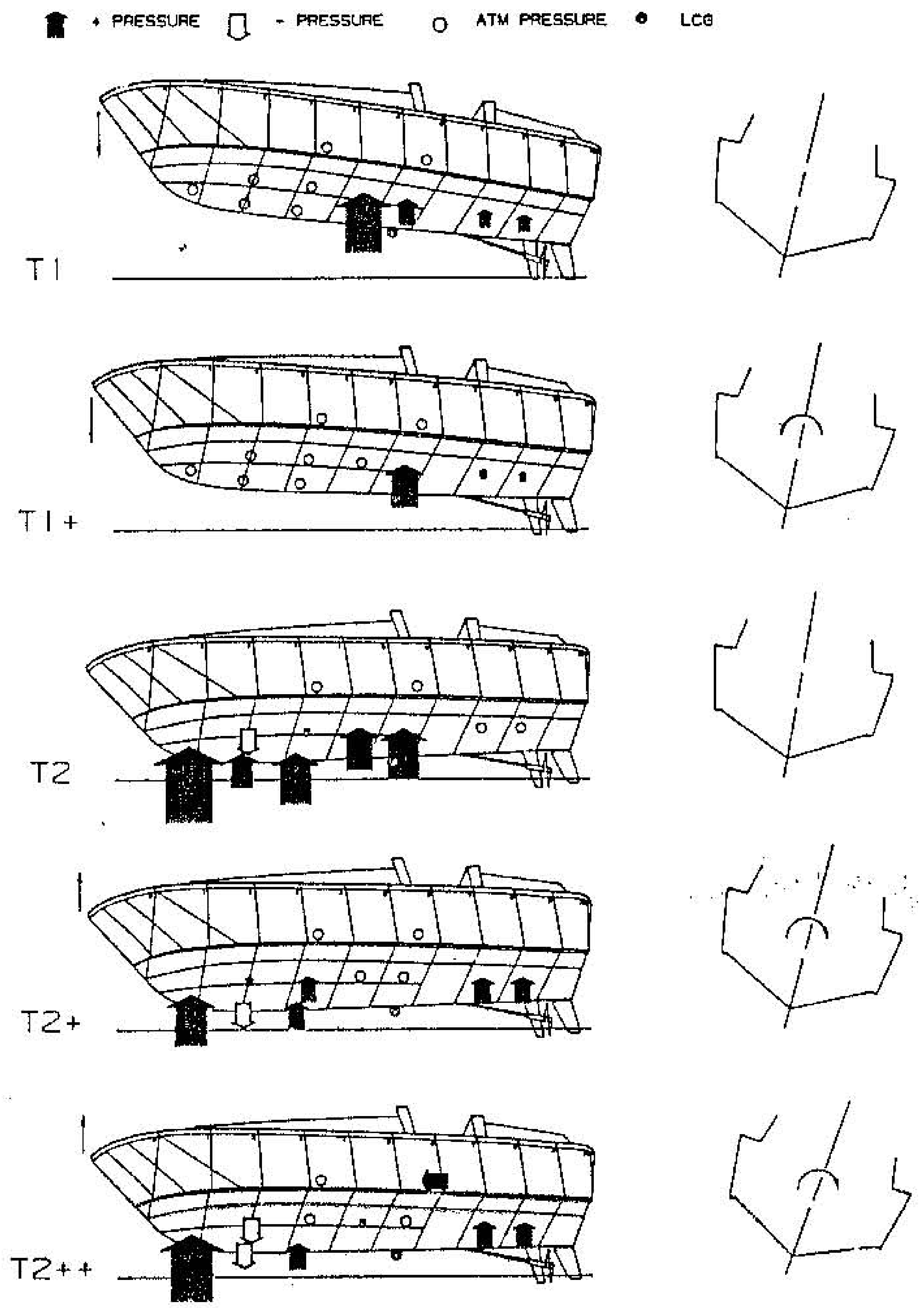


Fig. 29 Pictorial view of bottom pressure at times T1–T2++

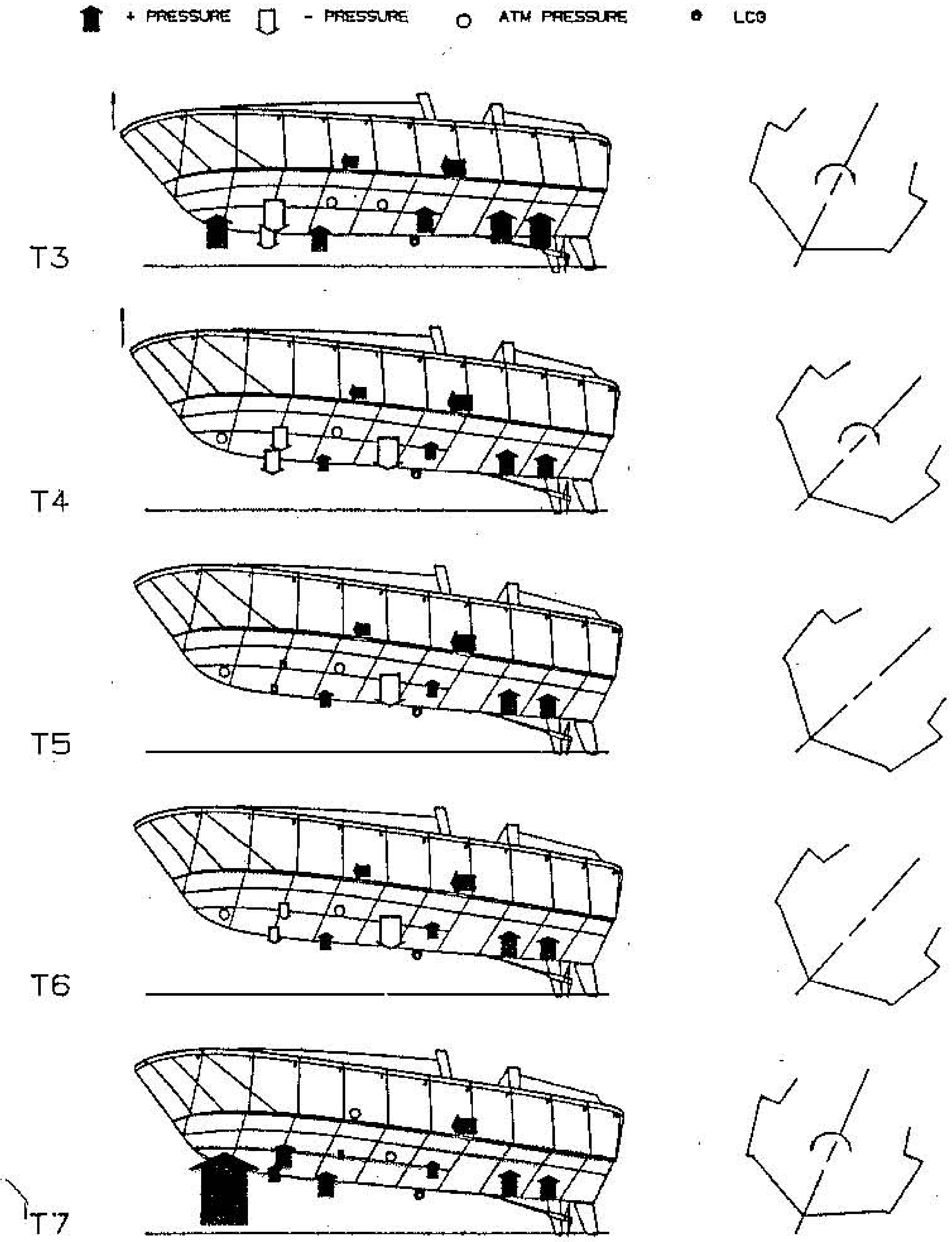


Fig. 30 Pictorial view of bottom pressures at times T3–T7

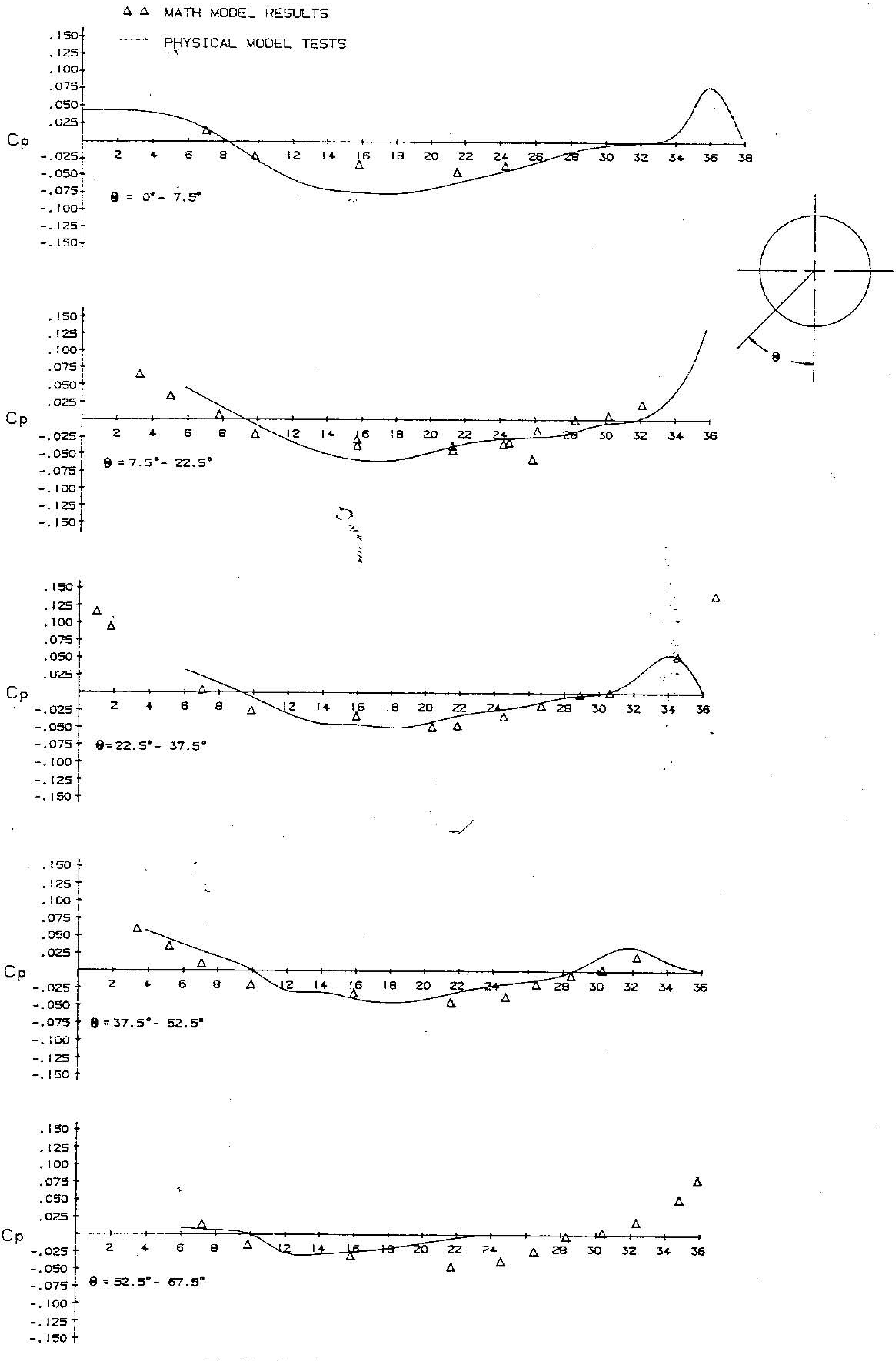


Fig. 31 Results of potential-flow model for body of revolution

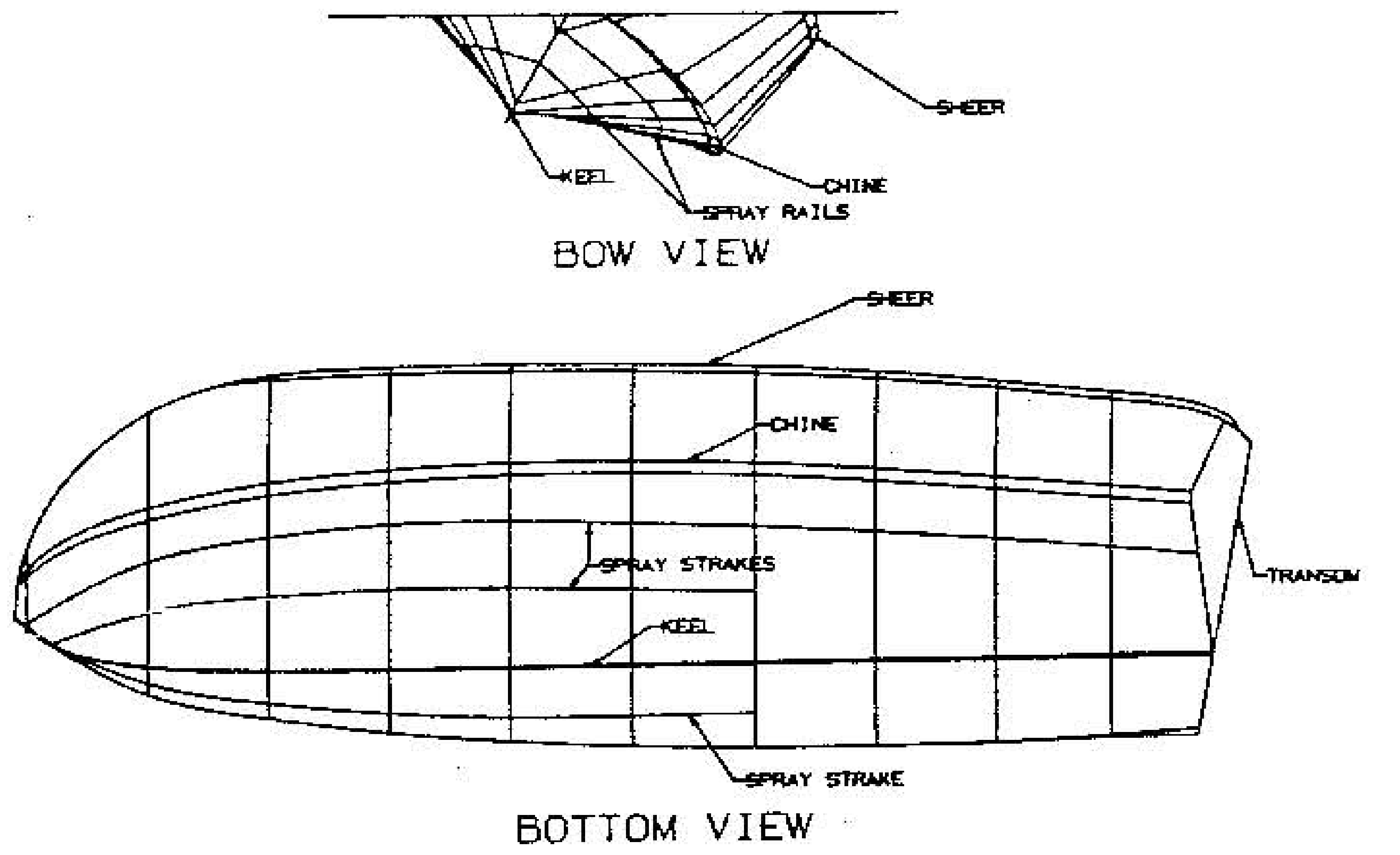


Fig. 32 SRB hull form as modeled for potential-flow model

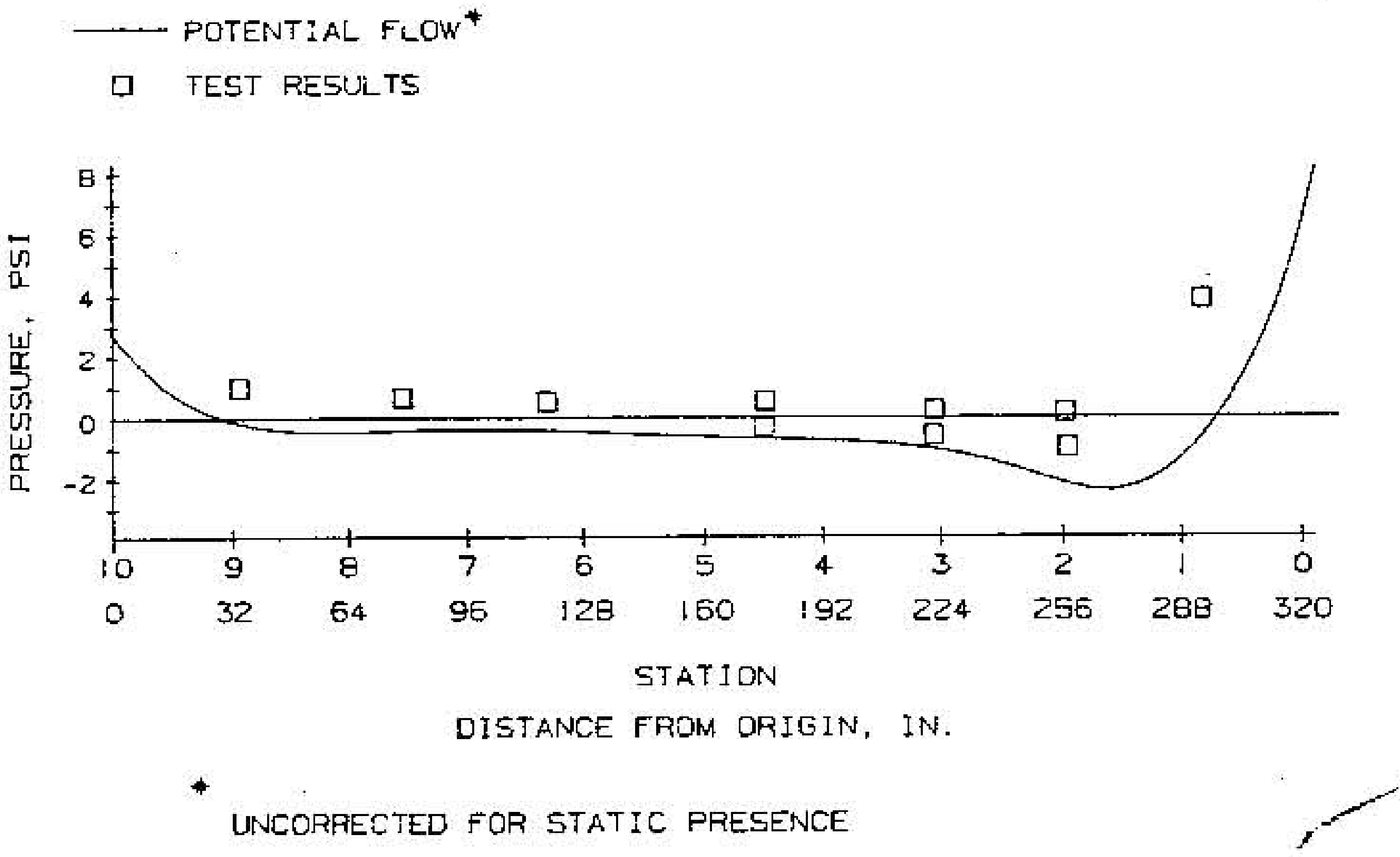


Fig. 33 Results of potential flow model

tions forward to the flow. Negative, or at least less positive, pressures forward pull the bow down and result in the first hump in the curve. As the speed increases, dynamic forces begin to dominate and the bow breaks free, allowing the second hump. The forward LCG contributes to the problem in that it necessitates a greater trimming moment to overcome the low pressures forward due to the lower running trim angle.

The bottom loading coefficient of the SRB is 5.4, the LCG is at the centroid of the projected planing area, and the boat operates at a volume Froude number of 2.6. The trim curve, Fig. 16, does not show a well-defined double hump, but does have a point of inflection at a Froude number of 1.7. The similarity between all of these cases is striking.

Model tests for the SRB have recently been completed at the U.S. Naval Academy Model Basin. The tests were conducted with the model fixed in heave and trim and run at various speeds, displacements, and trim angles. Pitching moment and heave force were measured. The results have not yet been published, but they show that at low trim angles both the heave force and pitching moment reverse and tend to draw the boat deeper in the water and decrease the angle of trim. This is exactly the same effect observed during the flying boat model tests [19].

Evaluation

The conclusion of the investigation is that the SRB's behavior is due to either of two causes, both of which are the result of low pressures being developed just aft of the bow. The curvature forward, which is extreme for a boat operating at such a high Froude number, causes an unstable situation when this area (normally above water) becomes immersed. As the area enters the water a low-pressure area is formed instead of the high-pressure area that would be expected. The low-pressure area causes more changes in attitude, resulting in a larger low-pressure area being formed, until a stable situation is reached. This is the bow-down, heeled-over attitude that the craft can exhibit for quite some time. It is surprising to note that the pressure measurements at transducers 2 and 3 become negative as the boat enters an oncoming wave, as can be seen in Figs. 24 and 25. It appears that the torque of the right-hand propeller biases the roll to the port side. The violent broach that occurs if the roll angle becomes too great is simply the result of a dynamic directional instability while in this attitude.

There is some evidence to suggest that the craft is stable in pitch at two different angles, again as the result of the full bow. The first is the normal running angle of 6 deg bow up, with the second at an angle of about 1 deg, also bow up. In this lower trim angle, however, the craft is transversely unstable and will not remain upright. This is brought out by two pieces of evidence. First is that examination of the videotapes of the instability will occasionally show the boat's trim dropping noticeably before

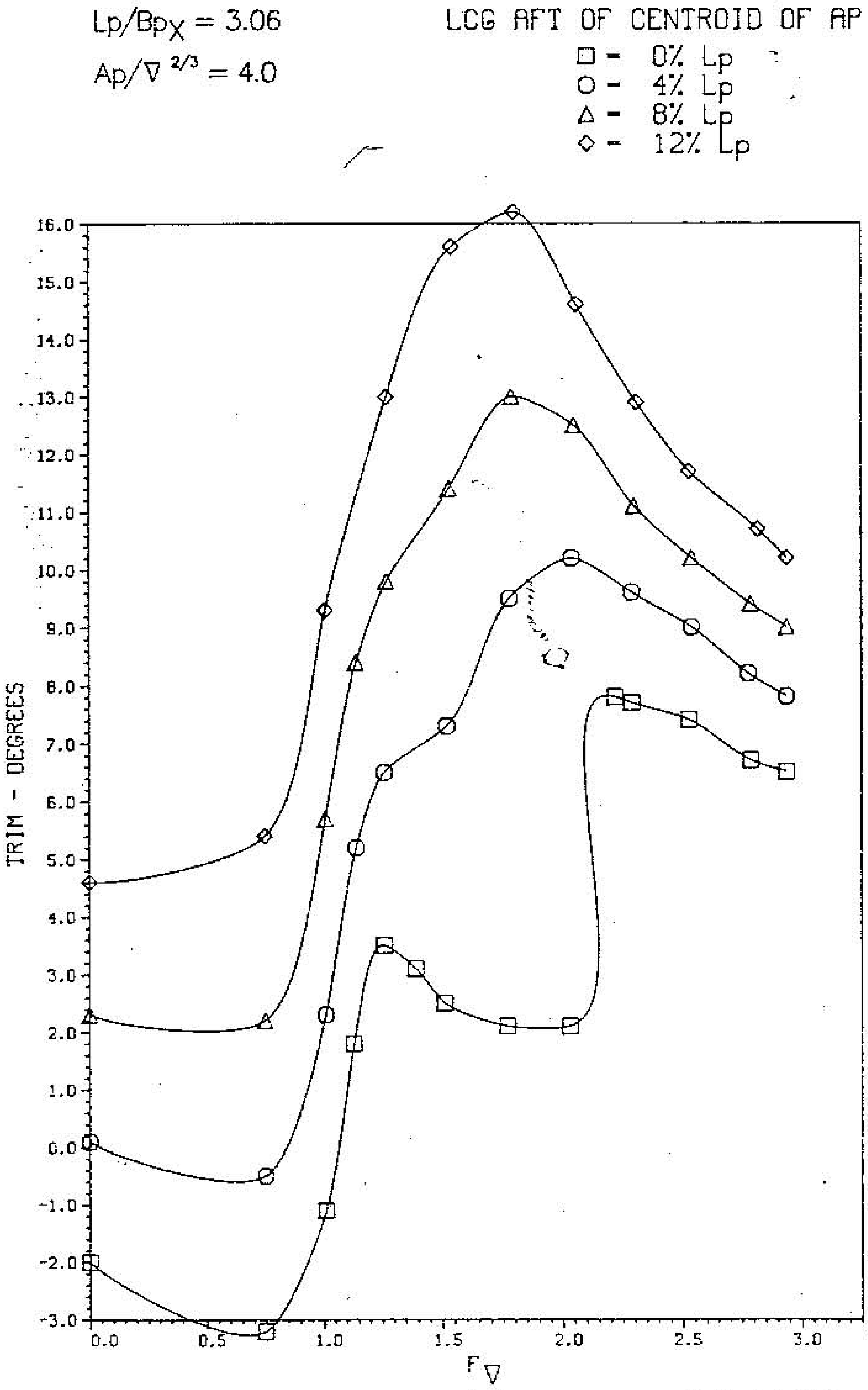
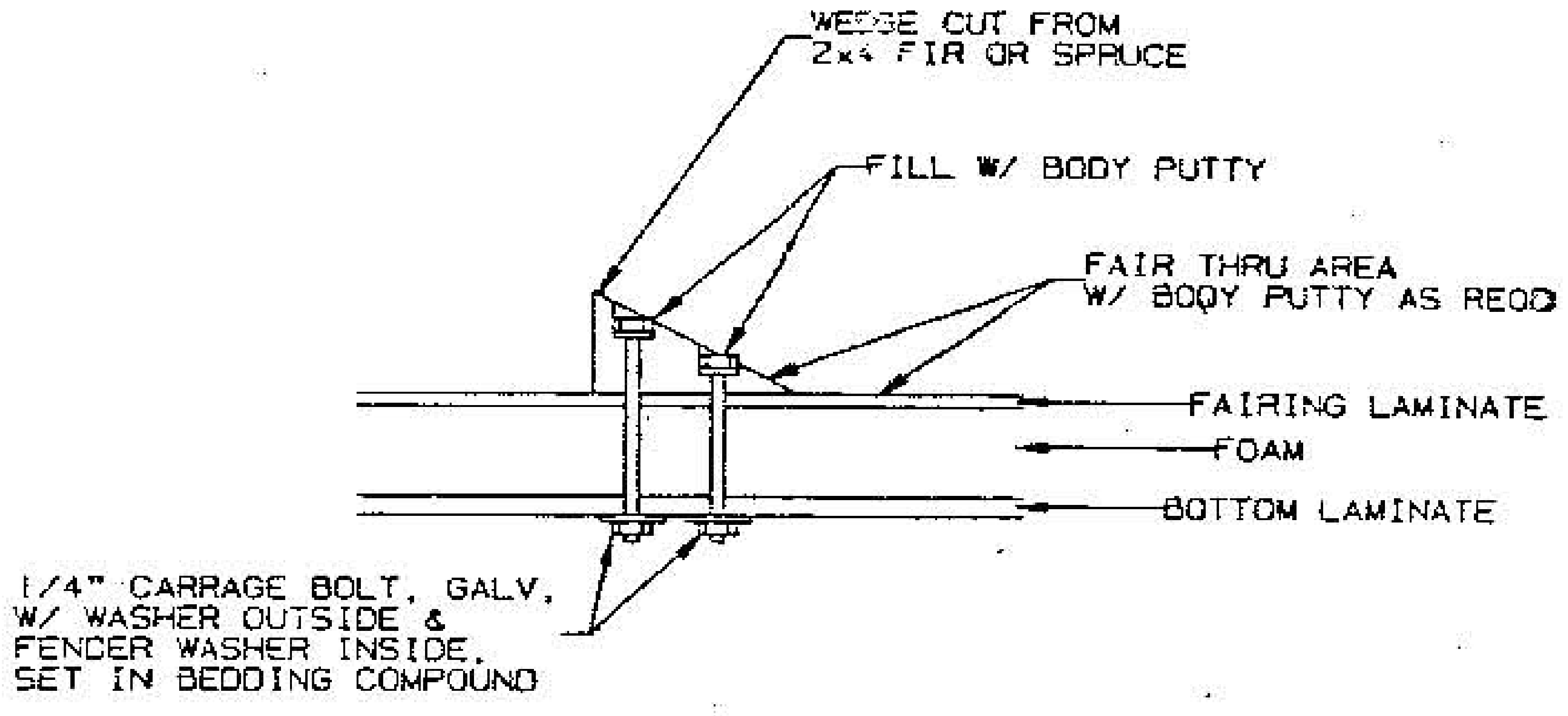
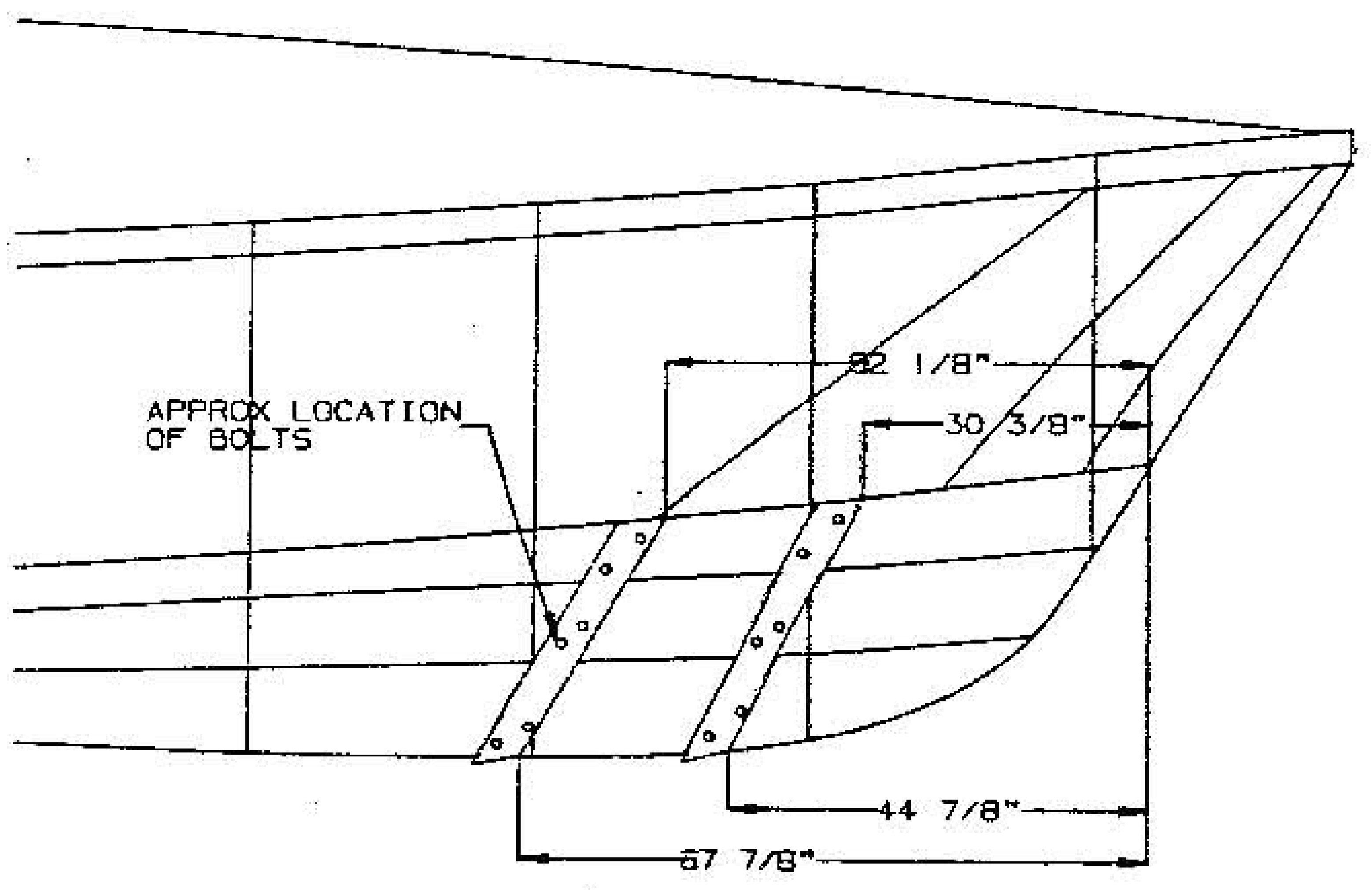


Fig. 34 Series 62 (25-deg deadrise) trim versus speed, Model 187



INSTALLATION DETAIL



LOCATION

Fig. 35 Wedge installation

the rapid roll to port. This is accompanied by large amounts of spray being thrown forward and precedes the roll by a few seconds. The second piece of evidence was obtained during a discussion with one of the more experienced coxswains. He informed us that he was able, on one occasion, to cause a boat to enter the bow-down trim angle attitude and was able to drive it for about 12 miles without either rolling over or rising to the normal trim angle. This coxswain has an extremely good feel for the boat, and it is hypothesized that he was able to keep the boat upright with corrections on the rudder.

It is interesting to note that the results of the potential-flow model indicate negative pressures which would destabilize the boat acting over the widest portion of the hull. The positive pressures regions are forward and aft, the narrowest areas on a hull that is unusually narrow for its size and speed. The chines are also calculated to be an area of positive pressure and so exert a righting moment on the boat. This agrees with the conclusions of reference [13].

What triggers this behavior is still unknown. There are three events that were all present when the boat was forced into the bow-down attitude during the test program: operation in waves, usually pitching down while going downwind, roll of the boat forced by a port rudder angle and high-speed operation. It is not known why one period of recorded data will be essentially identical to another, but at the end of the second period the craft will enter the unstable mode. There is certainly something that was not recorded affecting the onset of the phenomenon. The best explanation thus far is that the range of stability at the low trim angle is very small, and the boat will return to its normal operating mode if disturbed by a wave before the angle of heel rapidly increases.

The only proposed, feasible, solution to the problem has been the installation of bow wedges similar to those that were used previously to cure dynamic transverse instability problems. At this point, the tests are inconclusive. One installation was done at the National Motor Lifeboat School at Cape Disappointment, Washington. Three rows of wedges were installed forward, but were fitted between existing spray strakes. Tests showed no difference in behavior of the craft in that handling was the same and the boat could still be forced into its unstable mode. A significant difference was that, with the wedges installed, the rudder had control over the boat while unstable. Small changes in rudder angle, to either port or starboard, would return the boat to its normal operating mode. Without the wedges the rudder had an erratic effect. Small rudder angles had no effect, while large angles would turn the boat in the direction of the helm, against it, or not at all.

It was suggested that the presence of the spray strakes might be degrading the effect of the wedges. A modified design, Fig. 35, was installed on the test craft, which had the spray strakes glassed in during a previous attempt at a cure. The results, though not fully tested, have been encouraging. In one day of running in 2- to 3-ft waves, the boat could not be forced into the unstable mode and generally had a much more stable feel. For example, small rudder angles previously resulted in fairly large angles of heel. With the wedges, these heel angles were smaller. An unexplained phenomenon is that the turning radius is much smaller than without the wedges, particularly to port. As a result, it is possible to bury the bow on an extremely hard turn, with an accompanying large angle of heel. This will also occur in calm water and results in pressure distribution that closely resembles that obtained when the boat enters the unstable mode without wedges. Recovery is immediate without any action required on the part of the operator. It is expected that the test boat will be transferred to a station where operation in surf is routine, for a more thorough evaluation.

Some solutions that suggested themselves were not considered feasible for an existing design. These include extending the bow of the craft forward to reduce the curvature forward and moving the centroid of the planing area forward when referred to the LCG. Shifting the center of gravity aft will also improve the situation. This could be done by installing the engine aft and utilizing a V-drive to turn the propeller.

Greatly expanding the planing area by adding large, wide spray strakes should also have a positive effect, though at a great detriment to seakeeping performance.

Recommendations

This investigation has been one that has uncovered more questions than it has answered. It is apparent that a large amount of research has yet to be done before the naval architect has the information needed to rationally design a planing hull so that its dynamic performance will be satisfactory. The rules of thumb have proven workable for conventional hulls but, as was demonstrated in the SRB's case, even seemingly minor departures from previous experience can have tremendous consequences on the craft's performance. However, some guidelines can be given as a result of our research and full-scale tests.

The naval architect should avoid a high-speed, round-bilge boat with any appreciable amount of deadrise. It has been shown that it will become transversely unstable if driven fast enough. Reference [12] has excellent data on the reduction in righting arm that can be expected with increasing speed.

Likewise, hard-chine planing hulls can also become unstable at speed. A highly loaded bottom hull forces the designer to carry a large amount of curvature forward to support the hull statically. This will result in low pressures being developed that can lead to unstable behavior.

There is evidence to suggest that an LCG that is forward when compared with the centroid of the planing area will also result in low pressures being developed. This probably is from two effects. First is that the forward LCG forces a forward longitudinal center of buoyancy (LCB) from hydrostatic considerations, leading to full shapes forward. The second is simply the fact that the further forward the LCG is on a given hull form, the more likely it is to develop a bow-down pitching moment in a seaway as the center of bottom pressure shifts fore and aft.

All of these effects are a function of speed and displacement. It is apparent that an acceptable hull form at one speed or displacement may not be suitable at an even slightly higher speed or increased displacement. Until more definitive research can be done, it is recommended that references [24] and [25] be consulted and that combinations of coefficients that lead to a double hump in the trim-versus-speed curve be avoided.

More research has to be done before quantitative guidelines can be developed to aid in the hull form design. It is highly recommended that a test program similar to that for the flying boat hull forms be undertaken. This would require six, or perhaps nine, models and a relatively simple test program. The results of these tests would give the naval architect the empirical information required to avoid at least one form of the dynamic instability problem.

There would seem to be a correlation that can be made between the hull shape forward and the probability of the craft exhibiting unstable behavior, but as yet nothing conclusive has been found. An investigation will soon be conducted to try to correlate the three-dimensional stagnation line shape with the double hump reported in model test trim curves.

The real answer, of course, is to develop a way to evaluate the bottom pressure distribution on an arbitrary planing hull form, and to use this information to evaluate the stability of the craft in various attitudes. In the meantime, the available potential flow model will be exercised for other hull forms to see if a more positive correlation can be made between it and boats of known performance.

An attempt should be made to develop a method of numerically evaluating the transverse stability of a planing hull. This should be possible to do at least for the simplified case of a prismatic hull form.

Finally, we have amassed a huge quantity of data in the course of this test program, very little of which have been analyzed at this point. One of the obvious uses for these data would be a correlation of measured bottom pressures with boat accelerations. This would be the most extensive verification to date of the design guidelines used for the structural design of planing hull bottoms.

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Metric Conversion Factors

1 ft = 0.3048 m
1 in. = 25.4 mm
1 psi = 6.894 757 kPa
1 mph = 1.6 km/h
1 gal = 3.785 412 L
1 lb = 0.453 592 kg