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Dynamic Stability of Planing Boats

Donald L. Blount[1] and Louis T. Codega[1]

High-speed craft have been known to lose stability while underway even though they possess adequate static stability. Dynamic instabilities have been reported in roll, pitch and yaw, and include porpoising, chine walking, loss in running trim (diving), bow steering, progressive heeling to port or starboard, or a combination of motions. Instabilities can result in structural damage, loss of control, and crew injury. The problem is not well understood and accepted guidelines do not exist which will ensure adequate dynamic stability. The authors report data for boats which exhibit nonoscillatory dynamic instabilities and suggest quantitative criteria which may result in development of dynamically stable planing boats. Experimental procedures are presented to indicate the potential for nonoscillatory instabilities for expected operating conditions.

Introduction

EVER-INCREASING demands for speed in marine surface craft have expanded the interest in vessels having some part of their weight supported by dynamic forces. As planing monohulls, catamarans, stepped hulls, and others have supplanted displacement hulls, some accepted engineering techniques based on displacement technology have become stretched beyond their intended application. As an example, static stability criteria are based on technology that does not consider pressures generated by fluid velocity relative to the hull form.

The emphasis on speed results in a large increase in production cost for propulsion machinery and development of hydrodynamically efficient, lightweight and safe hull forms. Thus a carefully conducted engineering assessment is important to make reduced risk decisions relative to the design, development and production of a boat intended for high-speed service. Prior to producing tooling for a large production run or building a large high-speed custom yacht, very detailed design and engineering attention is required to ensure success. It is the intent of this paper to focus on approaches, as part of a balanced design process, to assist in the development of planing boats which may avoid nonoscillatory dynamic instabilities.

General discussion of stability

The stability of a boat or any dynamic system is defined as the ability of the boat or system, once in equilibrium, to return to the same state following a small disturbance. The behavior of a system may be described as stable, neutral, or unstable depending on its reaction to a small disturbance. A positively stable system returns to the predisturbance equilibrium. A neutral system settles into an equilibrium different from the original. The unstable system does not reach equilibrium at all and continually diverges from, or oscillates about, the original equilibrium.

Two terms closely related but not synonymous with stability are often confused. First, *range of stability* defines the maximum displacement from which a system will return to its predisturbance equilibrium when the disturbance is removed. Second, *stability margin* is excess restoring energy above a minimum required value. This provides a margin for inaccuracies in predicting the upsetting forces and stability characteristics for the system in its expected operating environment.

To demonstrate stability as it applies to boats, consider the case of static stability in roll. A stable boat returns to an upright position when a small heeling moment is applied and then removed. An unstable boat rolls over when disturbed and does not return upright; it may, however, become stable at some angle of loll. A neutrally stable boat (an unlikely phenomenon) can be illustrated by a submerged cylinder. It has no resistance to roll related to geometric form and continues rolling so long as a heeling moment is applied. There is no preferred angle of heel and the angle assumed, for this case alone, is a function of the length of time that the moment is applied.

Fundamentally, stability depends solely on the location of the craft's center of gravity and all of the forces and moments resulting from bottom pressures as the orientation of the boat changes. At low boat speeds, these forces and moments are essentially the same as for the hydrostatic case, but at high speeds these forces and moments differ significantly.

Dynamic stability

High-speed craft can exhibit unstable characteristics that are speed dependent. While these instabilities can take many forms, some are commonly known as chine walking, bow steering, bow diving, chine riding and porpoising. All of these behaviors are speed related and only occur when dynamic forces are significant when compared to buoyant forces; thus, they are generally referred to as dynamic instabilities.

The severity of these instabilities varies. In some boats, it is a minor annoyance that can be easily corrected. In other boats the most dedicated corrective efforts are unsuccessful and the instabilities result in hull damage or crew injury. The true cause of the aberration is often suspected only after an extended time in service when customary explanations such as improper seamanship or wave conditions are no longer plausible. Very little is known about the fundamental causes, and no guidelines presently exist to ensure adequate dynamic stability.

Types of instabilities

Outward manifestations of dynamic instability are varied and depend at least upon speed, displacement, weight distribution, hull form, and appendage design and location. Not all

[1] Donald L. Blount and Associates, Inc., Norfolk, Virginia.

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boats display instabilities; some display one type, others suffer from multiple instabilities. While the exact relationship between the various forms of instability is not known with any certainty, Table 1 taken from [1][2] provides an assumed relationship based on Froude number (*Fn*). At rest, stability is governed entirely by hydrostatics. As the Froude number increases, hydrodynamic effects come into play as hull pressures change. The first speed-related effects are caused by wavemaking and lend themselves to hydrostatic approximations. As speeds increase, dynamic bottom pressures dominate, and calculative procedures are far more complicated. In these speed ranges, instabilities can be characterized as being oscillatory and nonoscillatory.

Nonoscillatory instabilities usually occur at speeds lower than those associated with oscillatory instabilities and generally are found on relatively heavily loaded craft traveling at moderately high speeds. Unstable behavior can occur about the yaw, pitch, and roll axes typified by a loss in running trim, progressive heeling, bow steering, or a combination of rotations. These motions may result in a new stable orientation; the craft often can be operated with some degree of control for an extended period in this new attitude. Even though the instabilities occur at moderate speeds, they are particularly dangerous as the onset may be rapid and without warning, particularly when the instability is initiated in a seaway. There also may be secondary results, such as broaching or unpredictable steering response. Finally, they may be found on craft which would not otherwise require a high degree of operator skill. As a result, these instabilities often create concern among designers.

Oscillatory instabilities include roll oscillations (chine walking), and pitch and heave oscillations (porpoising). There are some common factors in these aberrations: both are typically associated with high-speed, hard-chine planing craft; the amplitude of oscillation is related to boat speed; the oscillations occur without any apparent excitation from environment or operator. In some cases, the oscillations increase while the craft is at a constant speed. Design guidelines [2, 3,4] have proven to be effective in predicting and avoiding porpoising. No accepted guidelines are available for predicting the conditions which result in chine walking.

Typically, oscillatory instabilities occur on boats that require a high degree of operator skill and attention. Except in rare cases, they gradually increase in severity; as a result the operator has an opportunity to adopt corrective measures. For example, a boat that porpoises under a given operating condition will always do so, allowing the operator to become familiar with and anticipate the oscillation.

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

Design factors

Hull shape

The underwater hull shape has a profound effect on the tendency toward nonoscillatory dynamic instabilities. The shape of the buttocks of the planing surface is especially significant since aft of the stagnation line the water flow follows the buttocks. A literature search leads to vague references about instabilities in boats [5,6] that are described as full in the bow, having wide waterlines or excessively curved buttocks, and the like. Nowhere can there be found quantitative guidelines as to the effect of shape on stability.

Clement [7] demonstrates the effect of shape more clearly than is found elsewhere. A high-performance craft demonstrated instability in roll at high speeds. It was hypothesized that unfairness of the aluminum shell plating where it was welded to frames was causing local low pressure areas as the boat heeled or encountered a wave. Instead of high pressure areas which would have produced an expected restoring moment, a heeling moment was being formed. Adding wedges in way of the unfairness ensured a high pressure area, and the instability was removed.

Consider the simple case of a fast, flat-bottom boat with buttocks shaped like the bottom half of an airfoil. With the boat running at its usual angle of trim, only the aft, relatively flat portion of the airfoil is immersed. As weight is shifted forward or when a wave strikes the bow, the more highly curved forward sections become immersed. These forward sections are not necessarily at a positive angle of attack, and hence do not necessarily develop higher than static pressures. They may, in fact, develop pressures lower than static. Instead of supporting the bow, the forward areas contribute to further bow-down trim. As pressures forward drop, the pressures aft must increase to compensate for the support of the total boat weight, further shifting the center of pressure aft. Thus a dynamic instability can be initiated.

If we look at pressure data from a family of standard airfoils that vary only in thickness/chord (t/c) ratio [8], we find that higher t/c sections develop lower local pressures at low angles of attack than do lower t/c sections. The extension of the

Table 1 General types of instabilities

	HYDROSTATIC ⟵⟶ HYDRODYNAMIC			
	DISPLACEMENT	SEMI-DISPLACEMENT		PLANING
	INCREASING FROUDE NUMBER ⟶			
TRANSVERSE	TRANSVERSE HYDROSTATICS $GM_T \leq 0$	LOSS OF GM_T DUE TO WAVE EFFECT	ROLL INSTABILITY NON-ZERO HEEL NON-OSCILLATORY	"CHINE WALKING" DYNAMIC ROLL OSCILLATION
LONGITUDINAL	LONGITUDINAL HYDROSTATICS $GM_L \leq 0$	LOSS OF GM_L DUE TO WAVE EFFECT	TRIM INSTABILITY BOW DROP NON-OSCILLATORY	"PORPOISING" DYNAMIC PITCH-HEAVE OSCILLATION
COMBINED	COMBINED $GM_T \leq 0$ $GM_L \leq 0$	COMBINED WAVE EFFECT (WAVE CREST)	BROACH NON-OSCILLATORY	"CORKSCREW" PITCH-YAW-ROLL OSCILLATION

analogy suggests that highly curved underwater buttocks are more prone to developing local low pressure areas with the accompanying destabilizing moments than are less curved buttocks.

A vee-bottom hull can be thought of as having buttocks shaped like two airfoil sections joined at the keel, Figure 1. Any asymmetric port and starboard wetted surface or a change in trim, caused by shift in weight or sea state, changes the pressure distribution. A boat with highly curved buttocks, the equivalent of an airfoil with a high thickness-to-chord ratio, is more prone to develop the local low pressure areas that lead to instabilities.

Speed

As mentioned previously, dynamic instabilities are speed dependent. Regardless of manifestation, the common and sometimes only cure is to reduce the speed of the craft. Dramatic changes are sometimes made with relatively small speed decreases. In at least one case [9] a reduction in speed from 28 to 25 knots was enough to change a dynamically unstable craft into a completely operational one.

The airfoil analogy again provides insight. Consider a flat-bottom boat with an airfoil section bottom. If fixed in a bow-down attitude, but without forward motion, the bottom pressures may be calculated by hydrostatics. With forward speed, the local pressure is the sum of the hydrostatic pressure and the dynamic pressure. The hydrodynamic contribution becomes more significant with increasing speed. If this contribution is at less than static pressure, the local pressure will drop. At some speed, local pressures may well become less than atmospheric. The extreme dependence on speed is clear, especially since dynamic pressure is a function of speed squared.

Appendages

Any source of rapidly changing pressure distribution under a hull, including ventilation of a portion of the hull bottom and/or appendages, may lead to a dynamic instability. Ventilated propellers will lift the stern of a boat and a ventilated off-centerline rudder or strut will induce a roll moment. One or more ventilated rudders and/or struts will also induce stern lift. Thus, asymmetrical port or starboard heel angle, or undesirable running attitude, may be induced by ventilation.

These conditions can occur predictably if craft design details result in easy air paths. In other cases, ventilation caused instabilities are unpredictable if, for example, the air path depends on a particular loading condition, sea state, or rudder maneuver.

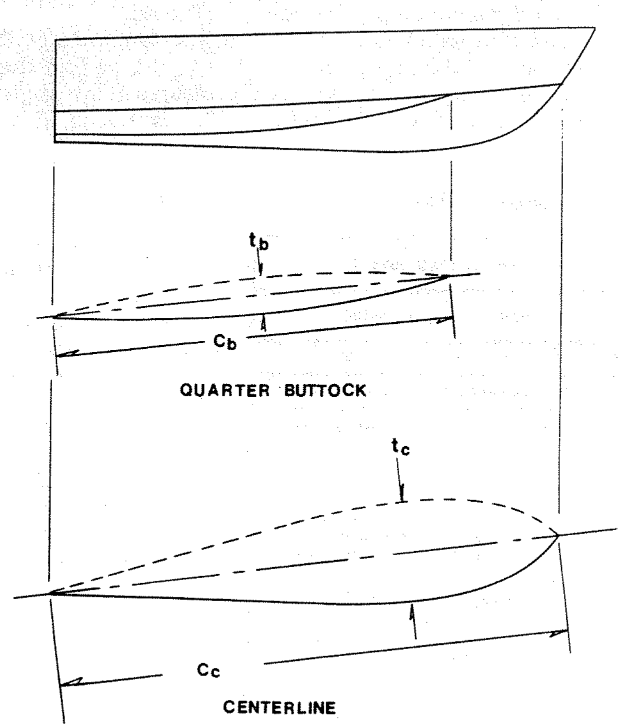

Fig. 1 Wing section analogy

Experimental information

Round bilge model tests

Millward, Wakeling and Sproston [10,11] report on stability tests performed on a series of high-speed, round bilge models. Inclining experiments were conducted with models fixed in the design condition of trim and heave with and without water flowing past the hull. The inclinings were repeated with the boat fixed in its high speed heave and trim angle with and without water flowing under the hull. The static inclinings showed that 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 effects of heave and trim were small.

The results obtained from dynamic inclining tests at various speeds were significantly different. The tests clearly showed increasing dynamic transverse instability (DTI) with increasing speed, all other conditions being constant, Fig. 2. At some speeds, the models became unstable without a heeling moment and took an angle of loll. Pressure measurements taken at two stations, one forward and one aft, showed that the instability at higher speeds was apparently caused by low pressures being developed near the stern, particularly near the turn of the bilge, as seen in Fig. 3.

Mathematical investigations

Codega and Lewis [9] performed a limited mathematical investigation of bottom pressures as part of a test program on a dynamically unstable boat. This craft, once disturbed at high speed, became stable at 36 deg of heel and 1 deg of trim. A potential-flow model [12] was used to approximate dynamic bottom pressures on the boat in this position. The calculated bottom pressures and their vectors were then integrated to find the moments acting about the craft's center of gravity.

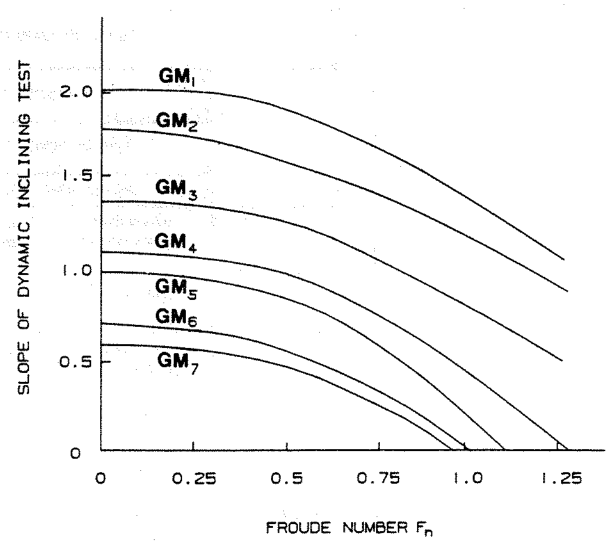

Fig. 2

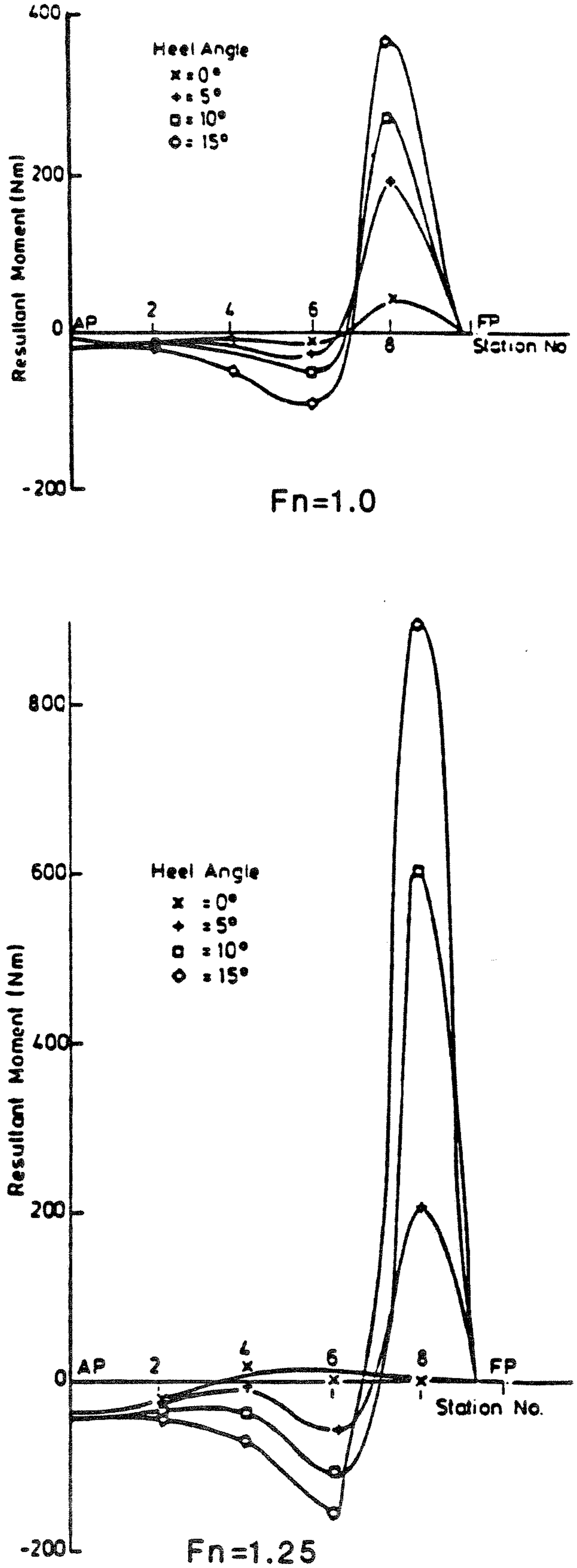

Fig. 3 Righting moment along hull

There was a large area of low pressure acting on the midbody which apparently decreased the transverse stability. The dynamic moment tending to right the craft from the angle of heel was found to be positive but very small, equivalent to a righting arm of less than one tenth of a foot. The static righting arm at the same angle of heel was over eight tenths of a foot. There was a negative restoring moment in pitch, tending to rotate the craft to lower trim angle. This was not the case for the static calculations which indicated a large restoring moment.

This approximation of dynamic pressure confirmed that the boat once in the bow down, heeled attitude had no significant righting moments acting upon it, in either pitch or roll. The boat was in fact stable longitudinally and transversely in this new heel and trim position when operating at high speed.

Trim versus speed curve

Trim versus speed curves for a planing hull with four different LCG's are shown in Fig. 4 [13]. The upper curves exhibit a slight negative trim at low speeds as compared to static trim. At that point they show steadily increasing positive trim until a volume Froude number of about 2 beyond which the trim gradually decreases. It is the authors' experience that many boats exhibiting a dynamic instability have an

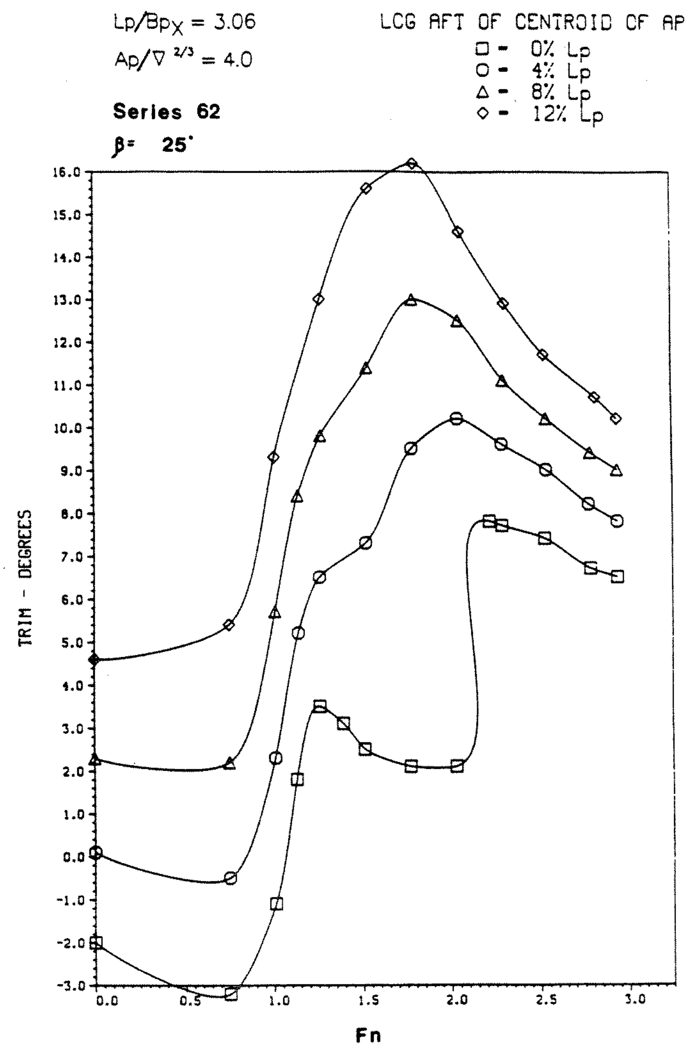

Fig. 4 Trim versus speed

inflection in their trim-speed curve at volume Froude numbers between 1 and 2, as seen in the lower curve of the figure.

This figure also illustrates the effect of longitudinal center of gravity (LCG) on dynamic stability. As the LCG is moved forward and the running trim is decreased, the trim curve develops the characteristic inflection point.

Proposed design guideline

It has become apparent to the authors that hull loading, that is, heavy or light displacement relative to hull dimensions, and LCG location have important influences on potential instability. The full-scale tests reported by Codega and Lewis [9] provide experimental evidence leading to this analysis; the wide range of model hull loading and LCG locations reported in references [13,14] provide additional technical insight.

The development of the proposed design guideline necessitates a dimensionless hull loading parameter and a dimensionless LCG parameter. The two most frequently used hull loading parameters utilized in planing technology literature [14,15] are:

$$A_p/\nabla^{2/3}$$

$$C_\Delta = \nabla/B_{px}^3$$

Both of these hull loading parameters are given in Table 2. However, $A_p/\nabla^{2/3}$ is preferable because both chine length and beam have significance while C_Δ only considers the importance of chine beam. The dimensionless LCG parameter is taken as the difference between the center of the planing surface and the LCG which is normalized by the projected length of the planing bottom. The definitions of planing hull parameters utilized for this paper are shown in Fig. 5.

The data from Table 2 in Fig. 6 demonstrate that the "problem" boats are all more heavily loaded than $A_p/\nabla^{2/3} = 5.8$ and LCGs are no more than 3 percent L_p aft of the centroid of A_p. (Note that the hull loading parameter $A_p/\nabla^{2/3}$ has a small numerical value for a proportionally heavy boat.) The proposed design criteria can be seen in Fig. 6 to include a bandwidth for margin reflecting the authors' experience. Furthermore, the criteria indicate that the speed versus trim curves of high L_p/B_{px} hulls are more likely to have reverse slope/inflection points between $1.0 \leq Fn \leq 2.0$ than low L_p/B_{px} hulls. This relationship may be seen in Fig. 7. It is suggested that until an adequate fluid flow model is developed, the criteria in Fig. 6 offer an engineering approach to avoiding nonoscillatory instabilities.

Boat test program

It is possible to evaluate a hull design with either a full-scale or model program which tests for potential dynamic instability for a variety of operating conditions. As discussed elsewhere in this paper, the likelihood of instability increases as the hull becomes heavier, the LCG moves forward, and the speed increases. It is for this reason that full-scale testing is important, particularly when installing additional horsepower in an existing boat since increased speed may take the vessel beyond a condition of dynamic stability.

The authors have adopted successfully two test procedures, a speed-trim test and a dynamic inclining test. Either one may be conducted with models in a towing tank during the design stage. However, it is recommended that they be part of a full-scale testing plan for prototype and/or first hull production boats. The test conditions should focus on heavy displacements and LCGs representing expected conditions as outfitted and operated by future boat owners. In addition, conditions of weight and LCG for the fully outfitted boat, without fuel when the tanks are aft of the LCG, also should be evaluated.

Whether for a new boat or a conversion, operational testing by several experienced captains is important to evaluate the "feel" of the resulting craft at different loading conditions and environments.

Trim-speed test

The purpose of the speed-trim test is to determine if low dynamic pressures which may develop at the bow of the hull will generate a bow-down moment resulting in a potential problem. The results of the dynamic pressure are evaluated indirectly by measuring the change in dynamic trim of the

Table 2 Boats with and without dynamic instability

Boat	L_p/B_{px}	Fn	$A_p/\nabla^{2/3}$	C_Δ	CA_p/L_p, %	LCG/L_p, %	$\frac{[CA_p - \text{LCG}]}{L_p}$, %
BOATS *with* OBSERVED DYNAMIC INSTABILITY							
1	3.58	3.72	4.78	0.524	44.0	42.5	1.5
2	3.31	3.36	5.50	0.353	43.6	43.6	0.0
3	3.57	2.98	5.53	0.397	44.0	40.8	3.1
4	4.21	1.84	4.85	0.538	43.5	42.1	1.4
5	2.99	2.78	5.00	0.339	43.4	41.8	1.6
6	3.03	3.42	5.17	0.337	42.5	41.7	0.8
7	3.24	2.06	4.47	0.457	44.2	44.0	0.2
8	3.14	1.50	5.80	0.249	42.0	43.4	−1.4
9	3.12	2.26	5.38	0.321	44.7	45.2	−0.5
BOATS *without* OBSERVED DYNAMIC INSTABILITY							
A	3.53	3.74	6.15	0.379	43.7	39.6	4.1
B	3.32	3.87	5.55	0.319	42.1	40.1	2.0
C	3.76	3.04	6.52	0.324	42.7	39.1	3.6
D	3.14	1.50	5.90	0.249	43.0	43.0	0.0
E	4.13	4.62	9.16	0.219	41.5	32.1	9.4
F	4.13	4.76	9.18	0.218	41.5	29.3	12.2
G	4.13	4.36	8.43	0.248	41.5	33.1	8.4
H	4.13	3.48	8.43	0.248	41.5	30.7	10.8
I	4.30	6.98	6.01	0.450	37.7	33.8	3.9
J	4.59	2.70	5.70	0.539	43.8	39.5	4.3

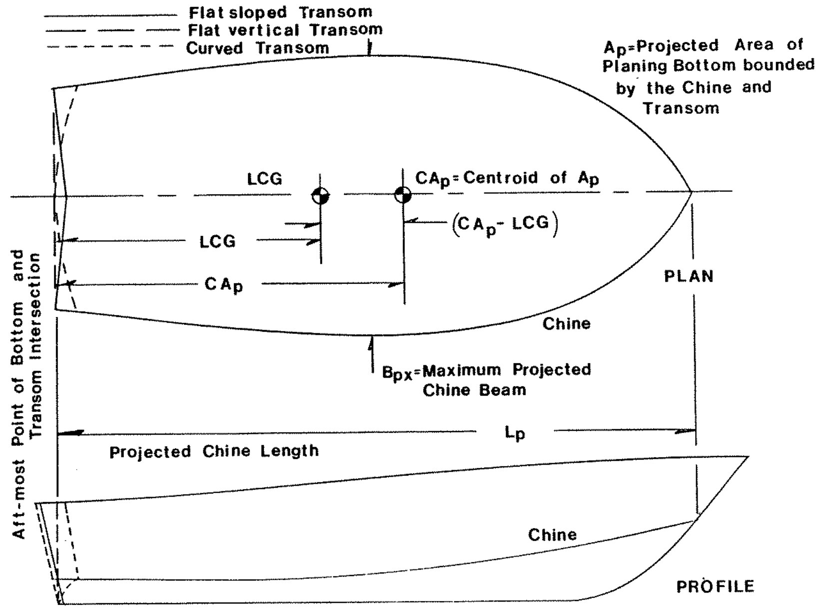

Fig. 5

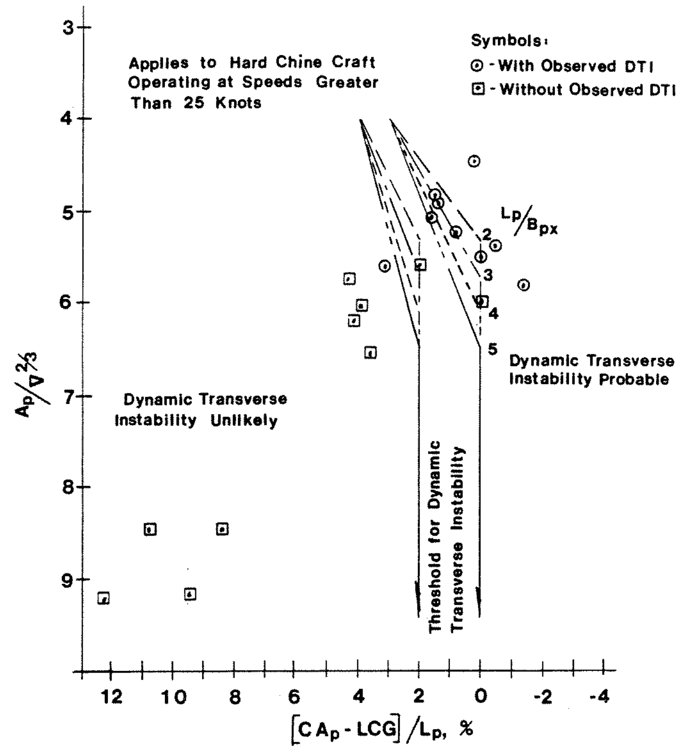

Fig. 6

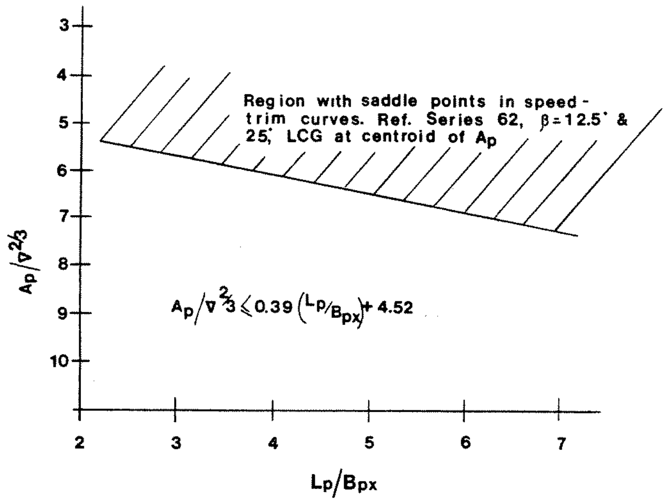

Fig. 7

boat as the speed increases rather than measuring the dynamic pressure distribution over the hull surface.

Figure 4 is an example from model tests of trim versus speed. The condition indicated by "squares" is for the LCG at the centroid of A_p and depicts a trim curve with a negative slope between $1.2 \leq Fn \leq 2.0$, indicating that low dynamic pressures resulted in a bow-down moment.

Figure 9 describes the results from full-scale trials. The trim versus speed condition indicated by "circles" were measurements made during a test program undertaken to correct the boat's operational problems. These included:

1. The boat was sensitive to transverse movement of people especially at speeds indicated by arrow "B."
2. The boat was difficult to steer when it heeled to either port or starboard.
3. With no off-center load, the boat at random would heel to either port or starboard 10 to 15 deg and remain in that position until corrective action was taken.

The trim-speed test showed an inflection in the curve indicated at arrow "A." It is the authors' experience that a zero or negative slope at the trim-speed curve in the range of $1.0 \leq Fn \leq 2.0$ indicates that bow-down moments are sufficiently large that a dynamic instability problem can be anticipated at higher speeds.

It is very important that speed, trim, LCG and displacement be measured accurately. In order to conduct these tests, it is critical to begin with low speeds and to increase the speed in small increments, obtaining a variety of speeds in the range of $1.0 \leq Fn \leq 2.0$ to define the slope of the trim curve. It is an incorrect test procedure to begin at high speed and then decrease speed in small increments since bow wetting

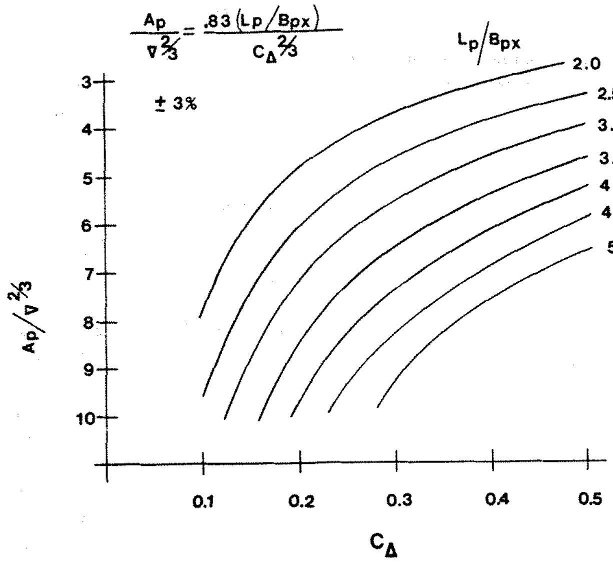

Fig. 8

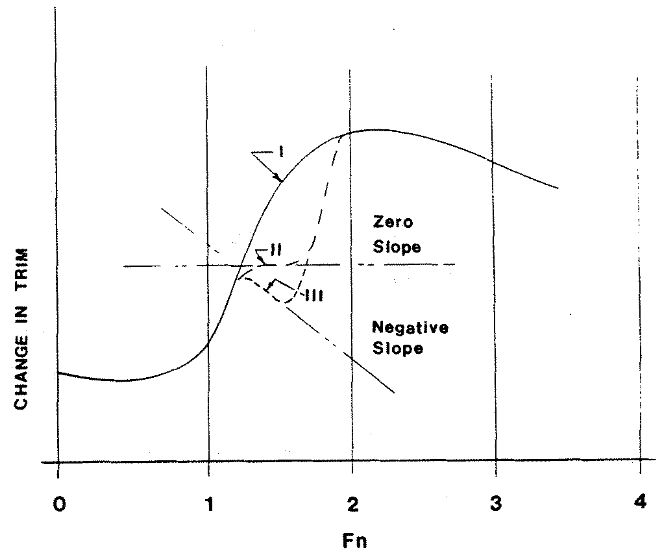

Fig. 10

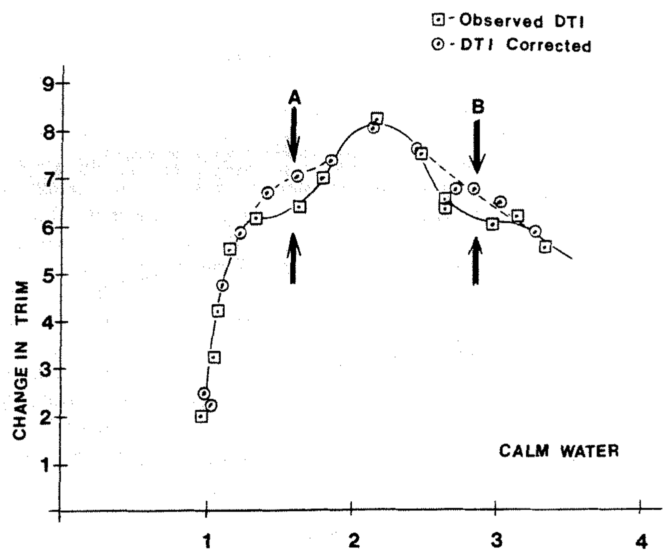

Fig. 9

occurs differently for $1.0 \leq Fn \leq 2.0$ depending on acceleration or deceleration. The trim measure of interest is the change of trim with speed. Thus, the trim gage may be set at zero when the boat is at zero speed.

Figure 10 depicts a generic trim curve to indicate the criteria for dynamic instability potential using change of trim versus volume Froude number (dimensionless speed) from full-scale and/or model test results. In the region of $1.0 \leq Fn \leq 2.0$, the curves marked II and III, zero slope and negative slope respectively, indicate that there is potential for a dynamic instability problem at higher speeds.

Dynamic inclining test

The purpose of the dynamic inclining test is to determine if the heel angle caused by an off-center weight will change as speed increases from zero to maximum speed. The dynamic pressures are measured indirectly by measuring the change in dynamic roll with change in speed rather than measuring the dynamic pressure distribution over the hull surface. Figure 2 shows results from model tests and reports the change in slope of the inclining curve rather than heel angle as the authors suggest. It is very important to measure all data accurately; a digital trim gage is recommended to measure roll angle. The boat should be statically inclined to determine the vertical center of gravity (VCG) in trial conditions.

The test procedure begins with a symmetrical loading condition and measurement of the change in roll at increasing speeds. A weight is then offset to produce a heeling moment which results in an angle of 3 to 5 deg to starboard. The roll angle is measured at increasing speeds throughout the speed range of the craft. The test is then repeated with the heeling moment to port. A zero-degree rudder angle must be maintained so as to not induce any roll moment by rudder action. As a result, these tests must be conducted in calm, open water free of hazards and risks to other boats.

The critical indicator is the pattern of change with speed for the difference between the angle of heel caused by the heeling moment and the angle of heel without the heeling moment. A dynamic instability is indicated when this heel angle difference increases with speed. It is vital to investigate this throughout the craft's expected loading condition and full speed range. Figure 11 depicts generic roll-versus-speed curves for boats with asymmetric rotating propulsors and symmetric rotating propulsors. Single-screw boats or boats without counterrotating propulsors are expected to exhibit asymmetrical hull roll as a reaction to propulsor torque.

Design considerations

Bow steering, diving or chine riding may result when the forward curved portions of the buttocks become wetted at high speeds. (The definition of high speed in this context is for speeds in excess of 25 knots.) This can occur as the result of several different design and operational scenarios as given in Table 3.

The operational problems with the boat in Fig. 9 were corrected by adding bow wedges (a concept installation is shown in Fig. 12) and incorporating rocker at the stern. The bow wedge causes flow separation while providing an air path at its base which ventilates the low dynamic pressure area on the hull. (Note: In locating these bow wedges, do not introduce air which might enter the seawater intakes.) "Squares" and the dotted curve in Fig. 9 demonstrate that the zero slope in

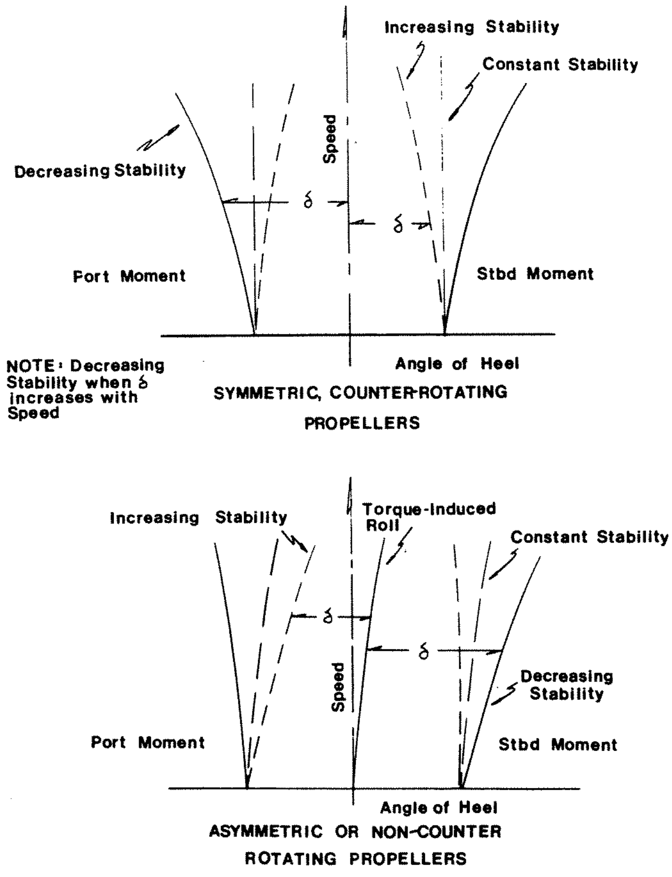

Fig. 11

Table 3 Design and operational scenarios

Action	Result
1. Modifying existing boat design	
A. Shifting static LCG forward	Running trim is reduced
B. Increasing horsepower without shifting LCG aft	Above hump speed, the dynamic trim reduces as speed increases
C. Adding or increasing trim tab size or angle	Increasing dynamic bow down trim moments are developed
2. New boat design	
A. Locating consumable loads, that is, fuel and/or water, aft of the optimum LCG	When planing at constant boat speed, reducing displacement (dynamic lift coefficient) results in decreasing dynamic trim for equilibrium. In addition, a bow down trim moment results as the consumable load is reduced from aft of the LCG
B. Locating the design LCG too far forward	The center of dynamic lift may result in wetting of curved buttocks
C. Too little bottom area relative to the design full load	Both static and dynamic draft increase resulting in wetting of curved buttocks

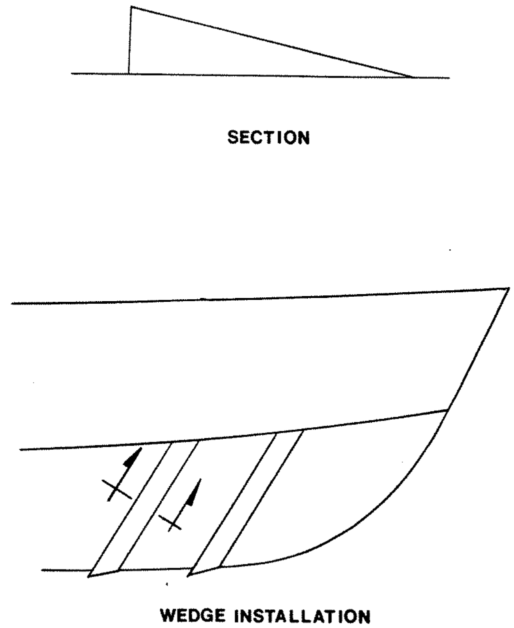

Fig. 12

the region of arrow "A" no longer exists and the trim curve at arrow "B" is typical of planing boats.

It must first be determined that the boat has adequate static stability in the case of roll instabilities. If that is the case, dynamic roll instabilities have been cured by increasing the running trim with aft shift of LCG, adding a rocker to the aft planing bottom and with wedges affixed forward on to the running surface in a location which assures a restoring moment in roll. Experimentation is usually needed to determine the optimum size and location of these wedges.

Ventilation related problems are easily diagnosed with underwater photography. Once the source of ventilation and the affected appendages are identified, it is usually a comparatively easy matter to correct the problem. Changes must be made so that the air path is closed off to the problem area.

The cavities typically found behind rudders or struts should be reduced through relocation, improved appendage shapes or fairings. Where possible, appendages should be deep in the water to increase the local hydrostatic pressure. Rudders can be modified by removing the upper trailing edge, or by adding a horizontal surface near the top. With more difficulty, they can be put further forward under the hull, or the hull bottom can be extended aft with the same effect if it does not move the centroid of the A_p to a risky position relative to the LCG. Caution should be used when incorporating design features such as spray strakes. If added with the intent to improve performance, they should not align with propellers, rudders or seawater intakes since they could supply a ready path for ventilating air resulting in unanticipated problems. Vortices caused by appendage shape or constricted flow will also provide a path for ventilating air and so the suspect source should be eliminated.

Course-keeping instabilities may succumb to increasing the running trim with rocker aft or a center-of-gravity shift. Skegs and larger or more efficient rudders will improve the situation only if low dynamic hull pressures are not present at the bow. Adding hull wedges forward may improve course-keeping when low dynamic hull pressures at the bow are the source of the problem.

For high-performance boats, the operators need to be aware of the capabilities and limitations of the craft so they may recognize and compensate for instabilities such as shifting load items by making dynamic trim adjustments or reducing to a speed below which dynamic instability occurs.

Conclusion

Criteria based primarily on hull loading and LCG are offered to assist designers/builders to develop boats which have dynamic stability for their expected operating conditions. In addition, several experimental approaches are described which may be utilized to assess nonoscillatory instabilities. The proposed criteria can now be evaluated by the marine community. It is the authors' expectation that the quantitative technology for dynamic stability will grow from this beginning.

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