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Sinkage and Trim of a Fast Displacement Catamaran in Shallow Water

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A theoretical method is put forward for predicting the sinkage and trim of a fast displacement catamaran in shallow water. Special emphasis is placed on the transcritical speed range, where sinkage and trim reach a maximum and the risk of grounding is at its highest. Results are condensed into simple formulas for estimating maximum sinkage and trim of a fast displacement catamaran through the transcritical speed range.

Keywords: catamarans; hydrodynamics (hull form); safety

1. Introduction

SINKAGE AND TRIM in shallow water are important issues for large monohull ships, such as bulk carriers and containerships, since these vessels often operate at small underkeel clearances. Because of their enormous size, such vessels are displaced downward by a significant amount when underway, even at low speed. Much research has been directed at accurately predicting the sinkage and trim of these vessels, in order to avoid grounding in shallow waterways (see PIANC 1997 for an overview).

By contrast, the vertical displacement typically experienced by large catamarans is small at low speeds, due to the much smaller displacement of even the largest catamarans compared to large bulk carrier and containership monohulls. However, unlike these monohulls, some large displacement catamarans are able to travel at and above the "critical speed" in shallow water. The critical speed is given by $\sqrt{gh}$, where g is the acceleration due to gravity and h is the undisturbed water depth. This speed is accompanied by large resistance in shallow water, so that sustained travel at the critical speed is normally avoided. However, a vessel accelerating to "supercritical" speeds, or decelerating back down to low speeds, must pass through the critical speed.

The sinkage and trim of a monohull through the transcritical speed range has been studied both experimentally (Graff et al. 1964, Millward & Bevan 1986) and theoretically (Mei 1976, Chen & Sharma 1995, Gourlay & Tuck 2001). A monohull traveling at just below the critical speed will tend to experience a large midship sinkage, accompanied by a large stern-down trim, so that it may be at risk of grounding at the stern in shallow water.

Abbott (1998) and Dand et al. (1999) have performed experimental studies on transcritical sinkage and trim of fast displacement catamarans. These results have also shown large midship sinkage and stern-down trim for vessels passing through the critical speed so that the stern is at risk of grounding in shallow water. Unfortunately, these studies are not suitable for theoretical comparison due to the narrow tank width of the Abbott (1998) experiments, and the lack of information publicly available from the Dand et al. (1999) experiments.

Sinkage and trim of a catamaran is analogous to the case of a monohull moving close to a vertical channel wall (neglecting wall friction), with the channel wall representing the centerplane between the catamaran demihulls. The monohull problem has been studied extensively at low speed (King & Tuck 1979, Norrbin 1985) from the point of view of bank effect, in order to calculate and measure the sway force and yaw moment on the hull. The same case has been studied less extensively with regard to sinkage and trim (see Chen & Sharma 1994 for a theoretical treatment and McDonnell 2003 for an experimental study). However, due to the low speeds and vastly different hull shapes considered in bank effect studies, this analogy has limited relevance.

We shall here use slender-body theory to calculate the sinkage and trim of a fast displacement catamaran at subcritical, transcritical, and supercritical speeds in shallow water, using linear superposition of the flow fields due to each hull. Simple expressions will be developed for the maximum midship and stern sinkage

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likely to be experienced by a catamaran passing through the critical speed, so that grounding may be avoided for ships accelerating to supercritical speeds or decelerating back down to low speeds.

2. Theoretical method

We use slender-body shallow-water theory, including the leading-order dispersive term so as to allow transcritical flow. The basic method is as described in Gourlay and Tuck (2001), but modified to allow transom sterns. The waterplanes of the catamaran demihulls, and body-fixed (*x,y*) coordinate system, are shown in Fig. 1. The demihulls' waterline length is L and spacing between centerlines is w.

The theory used has no time dependence and is valid only for ships traveling at constant or slowly varying speed. Unsteady effects on sinkage and trim, which are not considered here, may be important for ships that are rapidly accelerating or decelerating.

2.1. Single hull

The velocity potential ϕ for flow in the positive x direction past a single slender hull lying along the x axis can be shown (Mei 1976) to satisfy the equation

$$(1 - F_h^2)\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{h^2}{3}\frac{\partial^4\phi}{\partial x^4} = 0 \tag{1}$$

subject to the boundary condition

$$\frac{\partial\phi}{\partial y} = \pm\frac{U}{2h}\frac{dS}{dx} \qquad \text{on} \qquad y = 0_{\pm} \tag{2}$$

where

h = water depth (assumed constant)
U = ship speed (= free stream speed in body-fixed reference frame)
g = acceleration due to gravity
$F_h = U/\sqrt{gh}$ = depth-based Froude number
$S(x)$ = hull cross-sectional area to static waterline

The boundary condition at infinity is that the flow should either tend to the free stream solution or behave like an outgoing wave.

Solution by Fourier transform gives

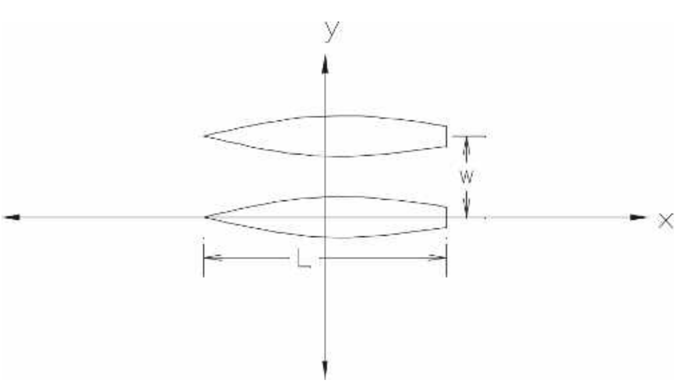

Fig. 1 Coordinate system

$$\phi(x, y) = \frac{-U}{4\pi h}\int_{-\infty}^{\infty}\frac{\overline{S_x}(k)}{\lambda}\, e^{-ikx}\, e^{-\lambda|y|}\, dk \tag{3}$$

with

$$\lambda = \begin{cases} \sqrt{(1-F_h^2)k^2 - \frac{h^2}{3}k^4}, & (1-F_h^2)k^2 - \frac{h^2}{3}k^4 > 0 \\ -i\sqrt{\frac{h^2}{3}k^4 - (1-F_h^2)k^2}, & (1-F_h^2)k^2 - \frac{h^2}{3}k^4 < 0 \quad \text{and} \quad k > 0 \\ i\sqrt{\frac{h^2}{3}k^4 - (1-F_h^2)k^2}, & (1-F_h^2)k^2 - \frac{h^2}{3}k^4 < 0 \quad \text{and} \quad k < 0 \end{cases} \tag{4}$$

and the Fourier transform of the sectional area derivative defined by

$$\overline{S_x}(k) = \int_{-L/2}^{L/2}\frac{dS}{dx}\, e^{ikx}\, dx \tag{5}$$

The above solution is given in a more original form than that in Gourlay and Tuck (2001), which required the section area to vanish at the stern, and so was valid only for cruiser rather than transom sterns. The above solution is based on the derivative of the section area rather than the section area itself and is equally valid for transom sterns. In this case the flow past the transom is modeled as that past an infinitely long cylinder extending downstream from the transom, with cross-section identical to the transom. This method for modeling transom sterns is similar to that used in Tuck et al. (2002) for calculating wave resistance of slender ships.

The hydrodynamic pressure $p(x)$ is defined as the excess above hydrostatic pressure; this is constant in the vertical and can be found from the linearized Bernoulli equation to be

$$p(x, y) = \frac{-\rho U^2}{4\pi h}\int_{-\infty}^{\infty}\frac{ik\,\overline{S_x}(k)}{\lambda}\, e^{-ikx}\, e^{-\lambda|y|}\, dk \tag{6}$$

The above treatment assumes that the weight of the hull is almost entirely supported by buoyancy forces. Therefore, the method is invalid for planing or semiplaning hulls. In this article we shall be concentrating on large fast displacement catamarans, for which the demihull length/beam ratios vary from around 12 to 22 (Lamb 2004, pp. 45–33). Also, because of their large length/draft ratios, when underkeel clearance is small, these vessels tend to pass through the critical speed ($F_h = 1$) at a fairly low value of the ship length-based Froude number F_n (e.g., $F_n < 0.4$). At these length-based Froude numbers, planing effects are minimal (see, e.g., Müller-Graf 1995). However, the theory will lose validity at large supercritical speeds, when $F_n > 0.6$.

One situation in which dynamic lift does become important for large, fast vessels operating at low F_n is when stern flaps or wedges are used. These provide dynamic lift at the stern (Savitsky & Brown 1976) and hence decrease the vessel's trim by the stern. The effect of stern flaps or wedges is not considered in this article but should be added to the sinkage and trim results calculated here at the appropriate value of F_n.

2.2. Extension to catamarans

Flow around catamaran demihulls differs from flow around monohulls in several important respects:

Asymmetric flow. Whereas flow around a monohull at zero drift angle in open water is port-starboard symmetric, asymmetries exist for catamarans due to the flow around each demihull affecting the other demihull. For example, Miyazawa (1979) observed cross-flow velocities beneath each demihull, in deep water, of 5% to 7% of the ship's speed, being outward near the bow and inward near the stern.

Transverse lifting effect. Due to the asymmetric flow around each demihull, lifting effects occur. These cause sway forces and yaw moments on each demihull. Methods have been developed by Chen & Sharma (1994) for modeling flow around a monohull with cross-flow and circulation in shallow water. Care must be taken in applying a suitable Kutta condition at the transom stern, which is treated as a sharp trailing edge, similar to airfoil theory. Extension of these methods to catamarans (Chen et al. 2003) has focused on supercritical wave reduction rather than open-water sinkage and trim.

Nonlinearity. The superposition of bow waves between catamaran demihulls can result in large waves being produced between the hulls. Insel (1990) reported large breaking waves forming between demihulls at model scale in deep water. Gourlay et al. (2005) reported a large one-dimensional breaking bore wave spanning between demihull bows at certain supercritical speeds in shallow water.

Large and steep free surface elevations, such as those leading to breaking waves, are clearly nonlinear in nature. The constricted flow between demihulls increases the effects of nonlinearity, so that the linear assumption is expected to introduce more error for catamarans than for monohulls. This effect is moderated, however, by the extreme slenderness of the catamaran demihulls.

In this article, we shall use linear superposition to calculate the combined flow around two catamaran demihulls, by adding the velocity potential for flow around each hull. This method allows asymmetry and resulting cross-flows to occur beneath each hull, although it does not apply the Kutta condition at the demihull sterns. Also, the method will not capture local nonlinearities, such as wave breaking between the hulls. Despite these localized deficiencies, the theory is still expected to be adequate for estimating overall quantities, such as sinkage and trim.

As shown in Fig. 1, the catamaran considered has one demihull with centerline on $y = 0$ and the other with centerline on $y = w$. Flow about the demihull with centerline on $y = 0$ is given by equation (3). To this is added the velocity potential of an identical hull with centerline on $y = w$, giving for the combined velocity potential

$$\phi(x, y) = \frac{-U}{4\pi h} \int_{-\infty}^{\infty} \frac{\overline{S_x}(k)}{\lambda} e^{-ikx} \left(e^{-\lambda|y|} + e^{-\lambda/y-w/}\right) dk \tag{7}$$

The linearized Bernoulli equation gives the combined pressure field as

$$p(x, y) = \frac{-\rho U^2}{4\pi h} \int_{-\infty}^{\infty} \frac{ik\, \overline{S_x}(k)}{\lambda} e^{-ikx} \left(e^{-\lambda|y|} + e^{-\lambda|y-w|}\right) dk \tag{8}$$

In a similar manner to Gourlay and Tuck (2001), the upward vertical force F and bow-up trim moment M (about midships) on each demihull are found by integrating the combined pressure field over the length of the hull; hence,

$$F = -\frac{\rho g F_h^2}{4\pi} \int_{-\infty}^{\infty} \frac{ik}{\lambda} \overline{S}_x(k)\, \overline{B}^*(k)\, (1 + e^{-\lambda w}) dk$$

$$M = \frac{\rho g F_h^2}{4\pi} \int_{-\infty}^{\infty} \frac{ik}{\lambda} \overline{S}_x(k)\, \overline{xB}^*(k)\, (1 + e^{-\lambda w}) dk \tag{9}$$

In terms of the local waterline beam $B(x)$, the conjugate Fourier transforms are defined by

$$\overline{B}^*(k) = \int_{-L/2}^{L/2} B(x) e^{-ikx}\, dx$$

$$\overline{xB}^*(k) = \int_{-L/2}^{L/2} xB(x)\, e^{-ikx}\, dx \tag{10}$$

Midship sinkage s and bow-up trim angle θ can then be found by solving the hydrostatic relations

$$F = -\rho g \int_{-L/2}^{L/2} (s + x\theta)\, B(x)\, dx$$

$$M = \rho g \int_{-L/2}^{L/2} (s + x\theta)\, xB(x)\, dx \tag{11}$$

For a given hull and water depth, equations (9) and (11) now allow sinkage and trim to be computed over the complete range of Froude numbers from subcritical to supercritical flow. The numerical method uses Filon quadrature (Abramowitz & Stegun 1965) to calculate the Fourier transforms. Simpson's rule is used to perform the k integrations in equation (9), excepting the singularities when $\lambda = 0$, which are integrated analytically.

3. Results

3.1. Catamaran/monohull comparison

Sinkage and trim have been calculated for a catamaran with NPL High Speed Round Bilge Displacement Hull series demihulls (Bailey 1976) using the methods described above. These demihulls have the characteristics shown in Table 1.

In this standard series, variations on the parent hull were made by a geometric stretching of the hull, which changes the L/B and B/T ratios, while keeping all the values in Table 1 constant. For these results, we shall use the NPL parent hull geometrically stretched to $L/B = 14.0$ and $B/T = 1.5$ for each demihull, which is representative of modern large high-speed passenger/vehicle catamaran ferries (Lamb 2004, pp. 45–33).

The centerline spacing/waterline length ratio has been chosen to

Table 1 Particulars of NPL high-speed round bilge displacement hull series demihulls

Block coefficient, c_B	0.397
Prismatic coefficient, c_P	0.693
Maximum section area coefficient, c_M	0.573
LCB	6.4% of waterline length aft
LCF	8.4% of waterline length aft

be $w/L = 0.20$, while the water depth/waterline length ratio has been chosen to be $h/L = 0.10$.

Figure 2 shows midship sinkage of the catamaran, over a range of depth Froude numbers from subcritical to supercritical. The sinkage of a single demihull operating alone is also included for comparison.

We see that at low speeds the midship sinkage is very small, being less than 0.1% of the waterline length up to $F_h = 0.6$. This equates to less than 0.1 m midship sinkage for a catamaran with 100 m waterline length.

At higher subcritical speeds, the midship sinkage rises sharply and reaches a maximum at around $F_h = 0.97$, for both the catamaran and the single demihull. For a 100 m waterline catamaran, this maximum is around 0.84 m, compared to 0.47 m for the single demihull.

As the catamaran passes into the supercritical regime ($F_h > 1.0$), the sinkage drops sharply back toward zero, and at low supercritical speeds the vessel rises in the water. This effect is due to the center of buoyancy being located aft of amidships; it is not predicted for fore-aft symmetric hulls. The very sharp peak at low supercritical speeds is most likely spurious. It is expected that inclusion of nonlinear terms in the governing equations would smooth out this peak slightly.

Figure 3 shows the predicted stern-down trim for a catamaran through the transcritical speed range, with a single demihull included for comparison. Again, we see that hydrodynamic trim is very small for $F_h < 0.6$. Over most subcritical speeds this vessel, which has its LCB forward of its LCF, tends to trim down slightly by the bow. However, as the ship approaches $F_h = 1$, the critical flow pattern occurs, with a large free surface height near the bow, large depression near the stern, and waves spanning out almost transverse to the ship.

This critical flow pattern causes a large stern-down trim of a single hull operating independently. However, with a catamaran, the effect is increased still further. Because the bow peak and stern trough due to each demihull span out a long way transverse to the hull, this adds to the bow peak and stern trough produced by the other demihull. The resulting bow free surface elevation and stern free surface depression are almost doubled as compared to a single demihull. Therefore, the stern-down trim of the catamaran is almost doubled, as compared to a single demihull.

As stated previously, trim calculations made here do not include any dynamic lifting effects. If stern flaps or wedges are present, these will provide dynamic lift at the stern and hence decrease the stern-down trim. This effect should also be included when calculating trim in particular.

The maximum trim occurs at $F_h = 0.99$, which is slightly higher than the speed at which the maximum midship sinkage occurs.

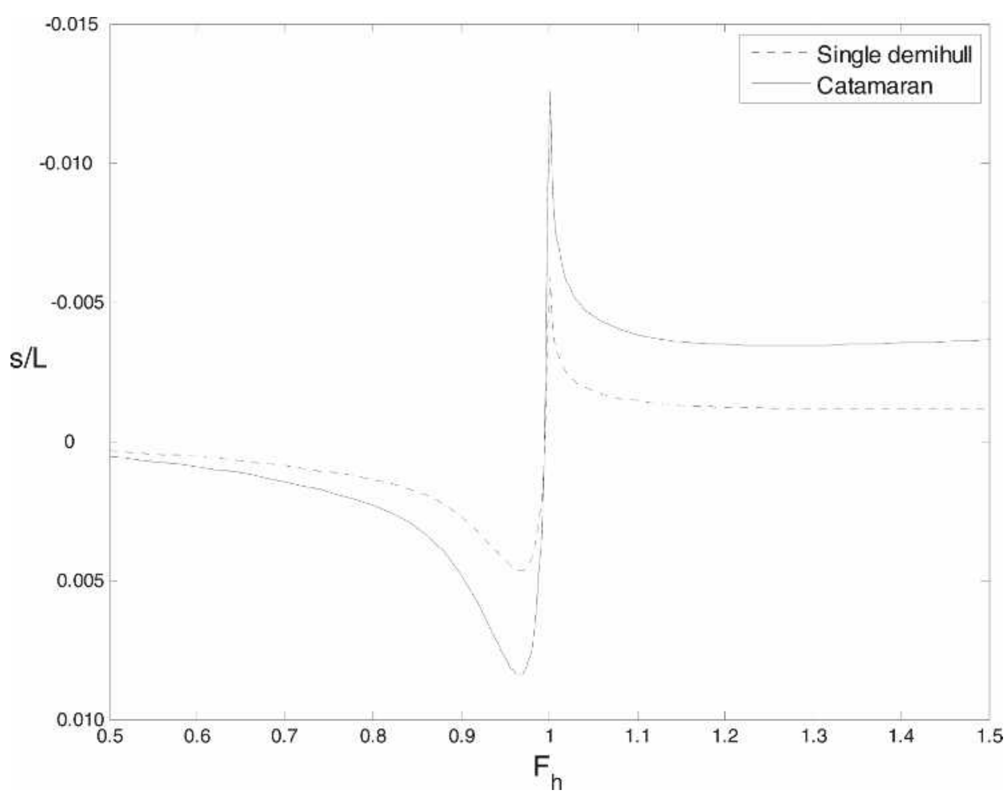

Fig. 2 Midship sinkage, scaled against waterline length, of NPL demihull and catamaran at $h/L = 0.10$

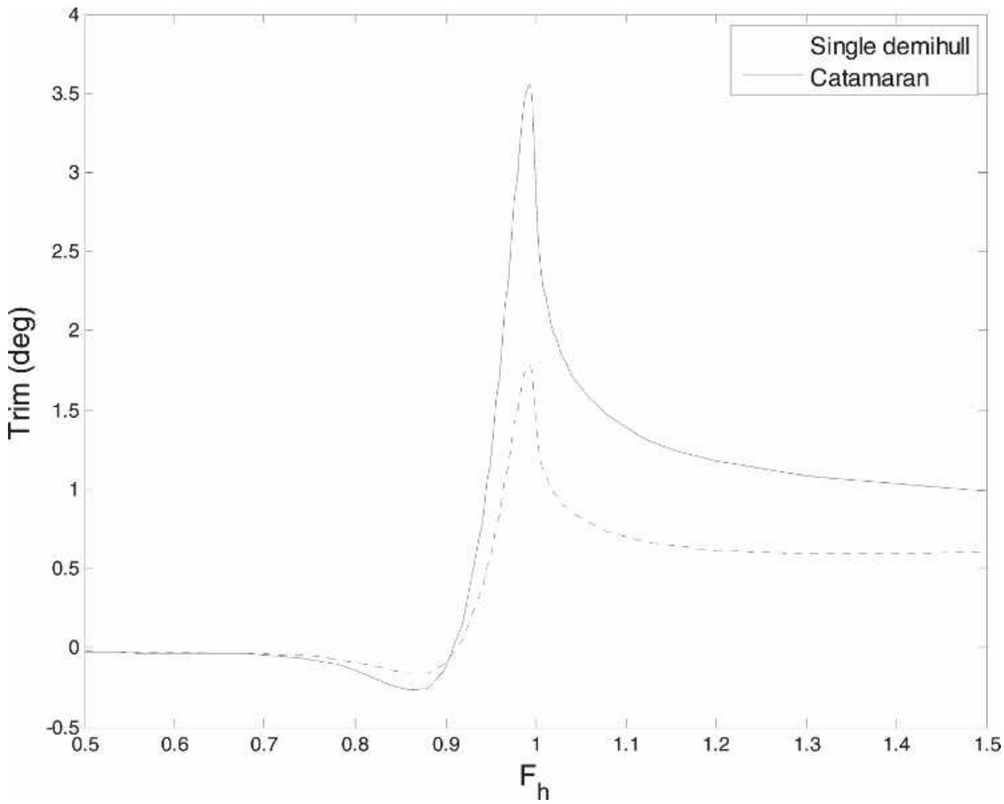

Fig. 3 Stern-down trim, in degrees, of NPL demihull and catamaran at $h/L = 0.10$

Figure 4 shows the stern sinkage for a catamaran and a single demihull. Because of the large stern-down trim through the critical speed range, the stern is the point on the ship's hull most vulnerable to grounding. As for trim, the stern sinkage of a catamaran is almost double that of a single demihull.

For a 100 m waterline hull of the type considered here, the stern sinkage is predicted to reach 1.8 m for the demihull operating by itself, or 3.5 m for the catamaran. This is a large sinkage, which must be taken into account when passing through the critical speed in shallow water, in order to avoid grounding.

3.2. Effect of centerline spacing

Figures 5 and 6 show the midship sinkage and trim of the NPL catamaran, for a range of different centerline spacings.

We can see that demihull centerline spacing has very little effect on the maximum midship sinkage, and almost no effect on the maximum trim. Therefore, the maximum stern sinkage, and hence grounding risk, will be affected very little by changing the centerline spacing.

Centerline spacing does have an important effect on trim at higher supercritical speeds, when the bow wave pattern sweeps back at an increasing angle. In this case a larger centerline spacing allows the elevated bow wave, sweeping back from each demihull, to meet the other demihull closer to the stern, and hence decrease the trim of the catamaran as a whole.

4. Maximum sinkage of catamarans

We have seen in the preceding section that away from the critical speed, catamaran midship and stern sinkage are small. This means that squat-related grounding is not a significant risk for catamarans that are not traveling near the critical speed.

However, catamarans traveling at close to the critical speed can have moderate midship sinkage and significant stern-down trim so that they risk grounding at the stern in shallow water.

Therefore, the most important output of a catamaran squat investigation is the ship's maximum sinkage. If this maximum sinkage is known and allowed for, then the ship can safely accelerate through to supercritical speeds, and decelerate back down to low speeds, without fear of grounding in shallow water.

Here we shall derive simple formulas for estimating the maximum sinkage of a catamaran, following the method outlined in Gourlay (2006) for a monohull. In that case, it was shown that the maximum midship sinkage $s_{max\_midships}$, trim θ_{max}, and stern sinkage s_{max_stern} of a monohull can be nondimensionalized by

$$s_{max\_midships} = \frac{\nabla}{Lh} C_{max\_midships}$$

$$\theta_{max} = \frac{\nabla}{L^2 h} C_{max\_theta}$$

$$s_{max\_stern} = \frac{\nabla}{Lh} C_{max\_stern} \tag{12}$$

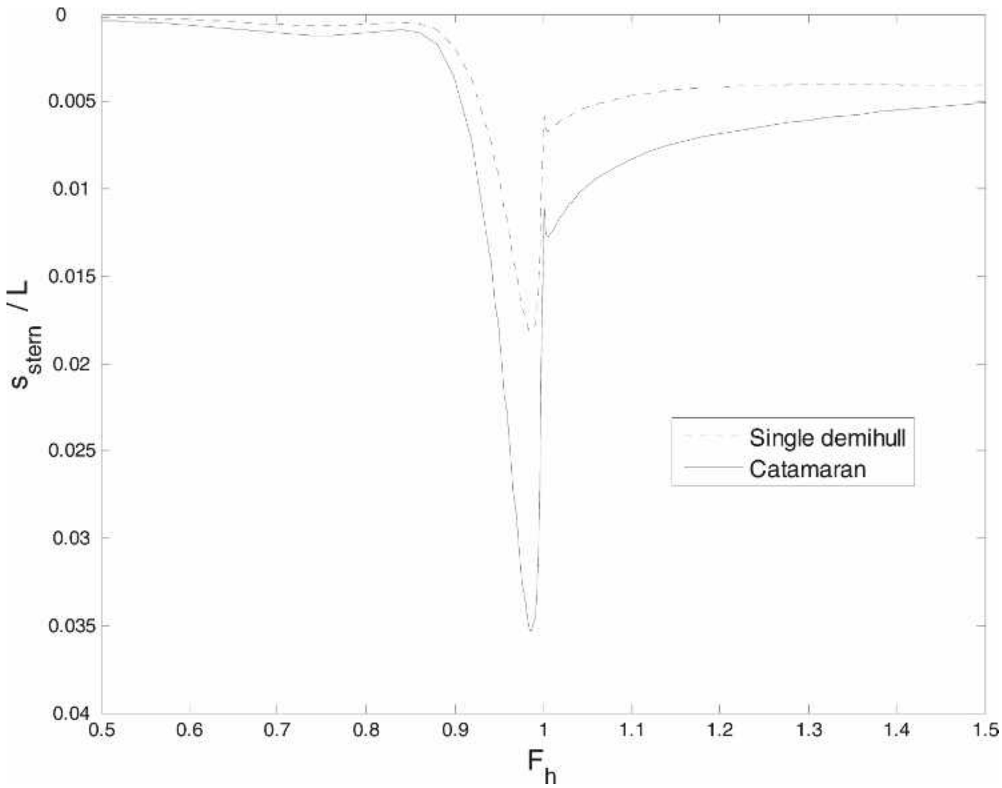

Fig. 4 Stern sinkage, scaled against waterline length, of NPL demihull and catamaran at h/L = 0.10

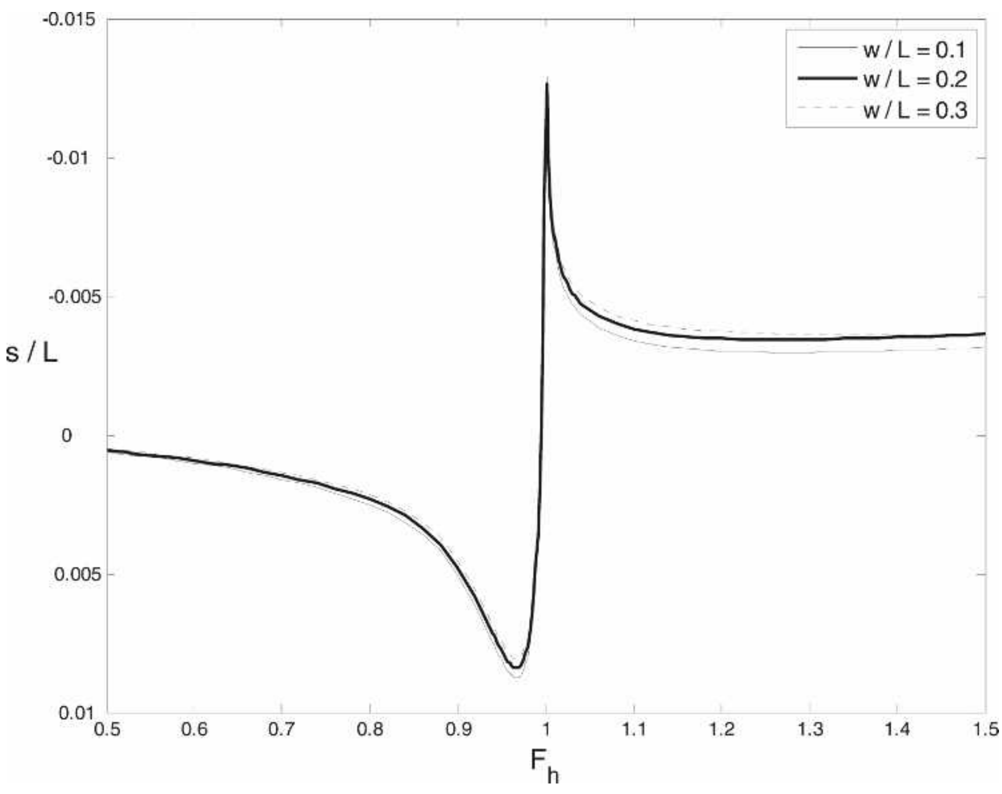

Fig. 5 Midship sinkage, scaled against waterline length, of NPL catamaran at h/L = 0.10, for different centerline spacings

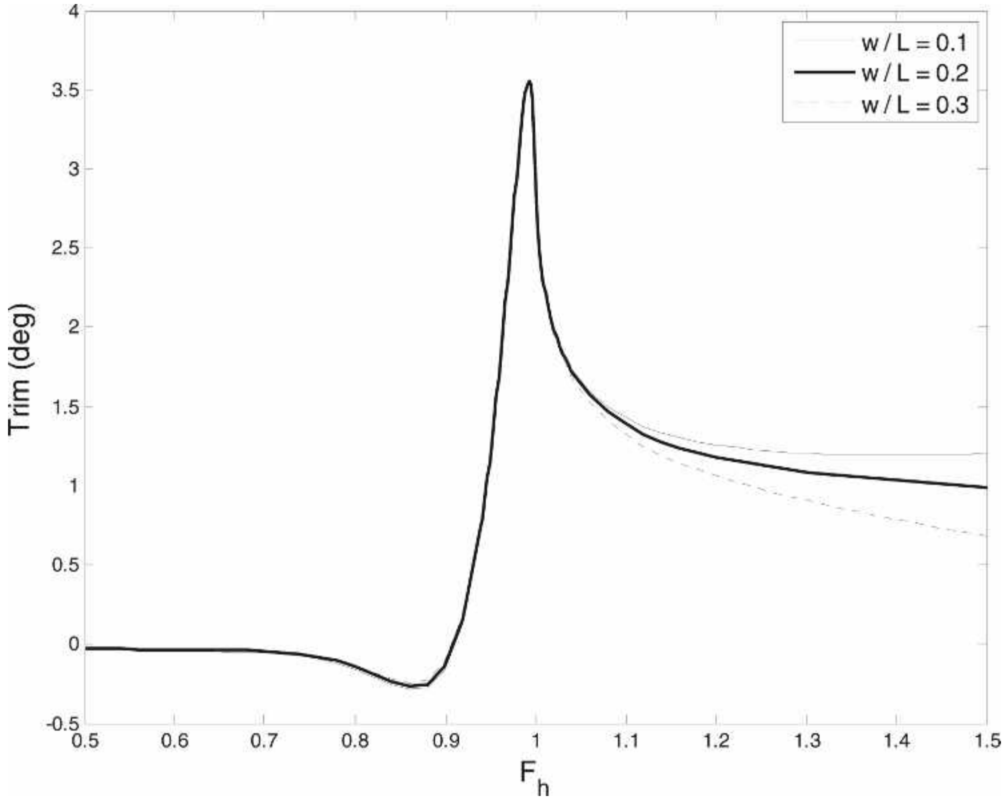

Fig. 6 Stern-down trim, in degrees, of NPL catamaran at $h/L = 0.10$, for different centerline spacings

where

∇ = ship's volume displacement
L = ship's waterline length
h = undisturbed water depth

According to linear transcritical shallow water theory, the coefficients $C_{\text{max\_midships}}$, θ_{max}, and $C_{\text{max\_stern}}$ are unaffected by stretching of the hull in any direction and are only weakly dependent on the water depth/waterline length ratio, assuming this is small. For a monohull, the sinkage coefficients were found to have values

$$C_{\text{max\_midships}} = 0.4\text{–}0.6$$
$$C_{\text{max\_stern}} = 1.5\text{–}2.0$$

over a wide range of hull shapes.

We shall use the same formulation for a catamaran and calculate the maximum sinkage coefficients for a variety of hull shapes. For a catamaran, the displaced volume ∇ is double that of a single demihull operating independently. However, as we have seen, the maximum midship and stern sinkage of a catamaran are also nearly double that of a single demihull. Therefore, we might expect that the maximum sinkage coefficients for a catamaran will be very similar to those of a monohull.

4.1. Hulls tested

The list of high-speed displacement demihulls tested numerically is shown in Table 2, along with their block coefficient, longitudinal center of buoyancy (LCB), and longitudinal center of floatation (LCF). Note that due to the linearization, calculated coefficients are independent of the demihull length/beam or beam/draft ratio. Some of the particulars are calculated from body plans provided and are approximate.

We have seen that the demihull centerline spacing makes very little difference to the maximum sinkage, so all calculations have been done using a centerline spacing of 0.2 *L*.

4.2. Computed results

Calculated results for the example hulls are shown in Table 3, for the depth to waterline length ratio $h/L = 0.10$. A sensitivity analysis shows that these results vary little over the range of interest $0.05 < h/L < 0.15$.

A comparison with the monohull results presented in Gourlay (2006) shows that across all hull types, $C_{\text{max\_midships}}$ for a catamaran is around 10% less than for a monohull of the same hull type, while $C_{\text{max\_stern}}$ is around 5% less.

For catamaran demihull shapes of any of the types shown in Table 2, equation (12) and the computed coefficients shown in Table 3 allow calculation of the maximum midship and stern sinkage that the vessel will experience while traveling through the critical speed in a given depth of water.

The results from the NPL and High-Speed Displacement series hulls can be used to give a general estimate for modern fast displacement catamarans:

$$C_{\text{max\_midships}} \approx 0.4$$
$$C_{\text{max\_stern}} \approx 1.5 \quad (13)$$

Table 2 Relevant particulars of catamaran demihulls to be tested numerically

Hull	Block Coefficient	LCB Aft (% of Waterline Length)	LCF Aft (% of Waterline Length)
Taylor standard series A3 hull, destroyer type, cruiser stern (Graff et al. 1964)	0.59	~0.0%	~1.8%
Taylor standard series B5 hull, destroyer type, transom stern (Graff et al. 1964)	0.54	~0.4%	~4.7%
NPL standard series hulls, round bilge, transom stern (Bailey 1976)	0.40	6.4%	8.4%
High-speed displacement ship series model 1, fine bow, wide transom (Blok & Beukelman 1984)	0.40	5.0%	9.2%
High-speed displacement ship series model 3, bluff bow, narrow transom (Blok & Beukelman 1984)	0.40	5.2%	6.8%
Wigley hull, simple hull with parabolic waterplanes and parabolic sections (Shearer & Cross 1965)	0.44	0.0%	0.0%

Table 3 Calculated maximum sinkage coefficients for example catamarans

Hull	$C_{max\_midships}$	θ_{max}	C_{max_stern}
Taylor standard series A3 hull (destroyer type, cruiser stern)	0.56	3.18	2.03
Taylor standard series B5 hull (destroyer type, transom stern)	0.49	2.79	1.76
NPL standard series hulls (round bilge, transom stern)	0.31	2.29	1.30
High-speed displacement ship series model 1 (fine bow, wide transom)	0.36	2.57	1.50
High-speed displacement ship series model 3 (bluff bow, narrow transom)	0.36	2.64	1.54
Wigley hull (simple hull with parabolic waterplanes and parabolic sections)	0.56	2.98	1.95

These coefficients used in equation (12) provide an estimate of the maximum midship and stern sinkage of any modern displacement catamaran with an LCB of 4% to 8% aft and LCF of 5% to 10% aft. As mentioned previously, the dynamic trim reduction effect of stern flaps or wedges should also be taken into account if these are fitted.

5. Conclusions

A theoretical method has been developed for calculating sinkage and trim of a fast displacement catamaran in shallow open water, based on linear slender-body theory. The method is valid for subcritical, transcritical, or supercritical flow.

It was shown that the largest sinkage of a catamaran occurs at just below the critical speed, when the stern sinkage may reach 3 to 4 meters for a large vehicle/passenger ferry. Away from the critical speed, sinkage is very small.

Maximum midship and stern sinkage were calculated for several standard series hull forms, and the results were used to suggest guidelines for estimating the maximum sinkage of any modern fast displacement catamaran.

No experimental verification has been possible at this stage due to an absence of full-scale sinkage data, or publicly available model test data in a sufficiently wide tank. Provided the general dimensional nature of the solution is correct, coefficients can be adjusted in future as experimental results come to hand.

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