ISSN 0140 3818
SSSU 27

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by C.J. Satchwell

Ship Science Report No. 27

September 1986

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ABSTRACT

Publication of Japanese operational experience with sail-assisted ships has shown that substantial reduction in roll motion and associated propulsive benefits accrue from the use of sail. It is suggested that there will be cases where these benefits can be used to justify both the lowering of installed engine power and the removal of stabilising tanks from a ship's specification. A method is presented for predicting the roll reduction from an unstalled, rectangular-planform marine aerofoil and the nature of marine aerofoil roll damping is explored. The requirement for roll reduction has implications for the control of a marine aerofoil, which are examined. Evidence for the associated propulsive benefits is reviewed and some possible processes which may produce these benefits are identified.

ACKNOWLEDGEMENTS

1. The work was completed with the benefit of advice from staff of the Department of Ship Science, University of Southampton. Specific thanks are due to Prof. G.J. Goodrich, for providing the author with the background to ship motions analyses, and to Dr. J.F. Wellicome for his observation that airspeed changes induced by a rolling vessel generate a significant roll damping moment on a marine aerofoil.

2. The work was completed whilst the author was supported by an SERC (Marine Technology Directorate) contract. The author expresses his gratitude to SERC for that support.

I INTRODUCTION

Wind-assisted ships of a modern design have been operating in Japanese waters since 1980 and some operational experience has now been published. An original publicised aim of the Japanese project was to use sail to augment propeller thrust and provide up to 10% fuel savings from the wind. Current levels of fuel savings from sails alone are claimed to be 20-25%, ref (8), with unforeseen propulsive advantages derived from their motion damping effect. It is further suggested that useful savings in installed engine power can be made.

In the light of this experience, it may be better to think of marine aerofoils as roll dampers, rather than propulsive devices, and the motivation for their installation might eventually be to acquire a range of benefits of which wind propulsion is only one. Little has been published on the level of roll reduction that can be achieved with a marine aerofoil and so this paper aims to take a first step towards its prediction.

Interest in predicting marine aerofoil roll damping comes from both technical and commercial aspects of ship procurement. If the degree of roll reduction can be established, then some other roll-reduction device (e.g. stabilising tanks) might be eliminated from a specification. The degree of direct and indirect sail propulsion is of interest both for evaluating fuel savings as well as for providing answers to questions involving the level of installed engine power. Preliminary calculations suggest that the cost of a marine aerofoil is roughly equivalent to the savings in installed engine power, roll stabilising tanks and cargo volume occupied by roll stabilising tanks. This could justify the installation of a marine aerofoil through capital cost considerations alone, whilst offering fuel saving and emergency propulsion as a bonus.

Japanese work, refs (1) and (10) make it clear that the net fuel savings are much greater than can be explained by the wind energy resource transmitted through direct sail propulsion. They suggest that improvements in ship motion reduce ship resistance and indirectly improve the propulsive effect of the sails. Once the improvements in motion are known, this question might be properly investigated. Consideration given to resistance in this paper will be restricted to reviewing evidence, appraising possible processes for motion-derived resistance reductions, and an initial assessment of magnitude for one of these processes.

It should also be pointed out that the investigation is preliminary, with the objective of establishing a context for other windship technology work, exploring possible areas for future work and identifying new opportunities for the installation of marine aerofoils.

An initial question involves the prediction of motion improvement, since subsequent benefits are derived from this. Accordingly, the early part of the paper is concerned with understanding and quantifying roll reduction brought about by a marine aerofoil.

II NOTATION AND DEFINITION

Dimensional notation for a wind assisted ship is shown in Figure 1. Apparent and true wind conditions are shown in Figure 2.

WIND ASSISTED SHIP NOTATION

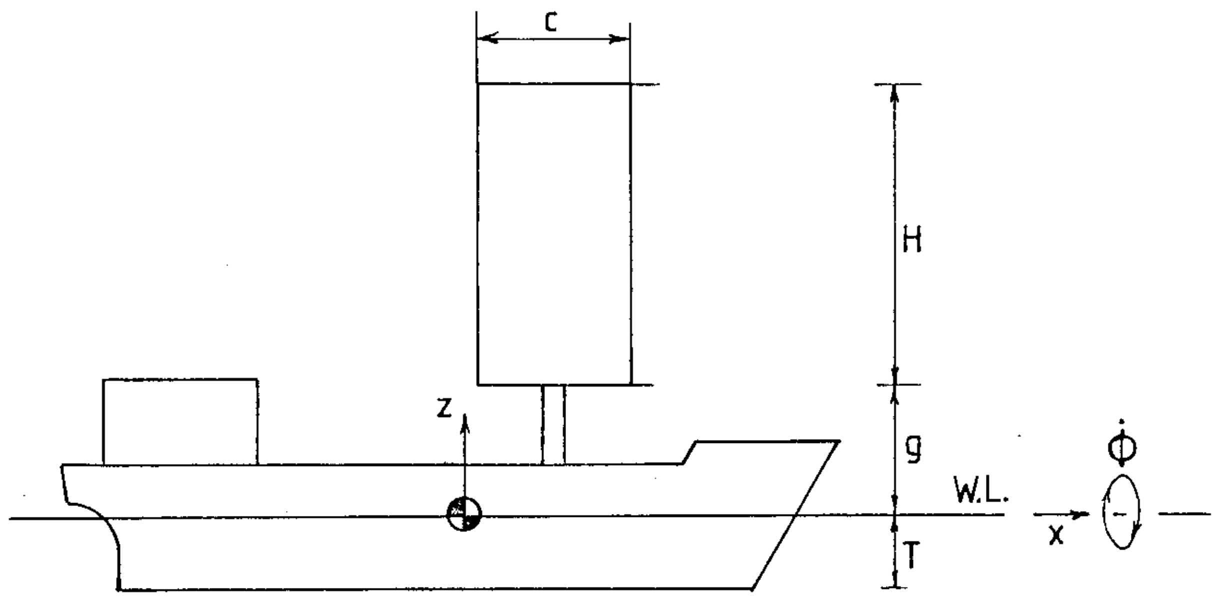


FIG 1

APPARENT AND TRUE WIND CONDITIONS

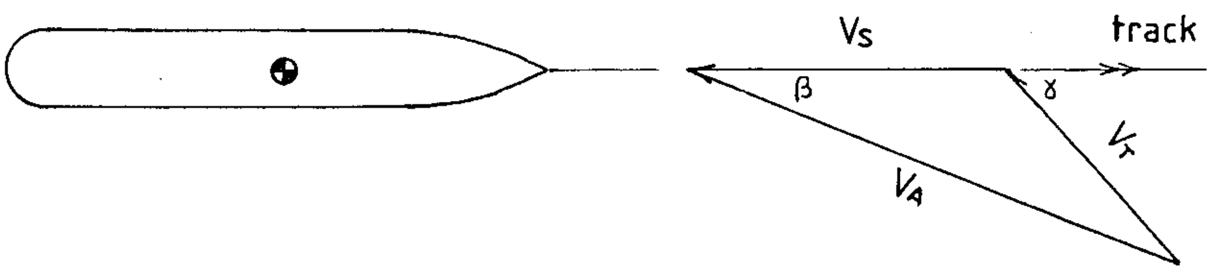


FIG 2

Notation

Speeds and Angles:

V_T	–	true wind speed (see Figure 2)
V_S	–	ship speed (see Figure 2)
V_A	–	apparent wind speed (see Figure 2)
γ	–	true wind angle (see Figure 2)
β	–	apparent wind angle (see Figure 2)
a	–	ship speed/true windspeed ratio
α	–	angle of attack
α_i	–	induced angle of attack
α_o	–	section angle of attack
$\dot{\phi}$	–	angle velocity in roll
ϕ_{MAX}	–	maximum roll amplitude without aerofoil fitted
ϕ_{MAXA}	–	maximum roll amplitude with aerofoil fitted
λ	–	leeway angle
θ	–	angular coordinate defined by $z = H\cos\theta$
V	–	free stream velocity at lifting line
$\bar{V}$	–	mean free stream velocity over lifting line
W	–	downwash due to trailing vortices at lifting line

Ship:

$N\phi_A$	-	roll damping coefficient from marine aerofoil, (roll damping moment = $N_{\phi A}.\dot{\phi}$)
$N\phi_{A\alpha}$	-	incidence damping component of $N_{\phi A}$
$N\phi_{AV}$	-	airspeed damping component of $N_{\phi A}$
H	-	rig span
g	-	gap between bottom of rig and sea
Δ	-	weight displacement
GM	-	transverse metacentric height
T_ϕ	-	natural roll period of ship
V_ϕ, K_1	-	non-dimensional roll damping coefficients
$V_{\phi A}$	-	non-dimensional roll damping coefficient from aerofoil
A	-	aspect ratio (span^2/area)
R_i	-	induced resistance
Ⓒ	-	resistance coefficient for upright ship
Ⓒ$_i$	-	induced resistance coefficient (associated with leeway)
k_1, k_2, k_{DC}	-	constants from ref (6)
T	-	maximum draught of ship
$\nu_{\phi A}$	-	volumetric displacement
c	-	rig chord

Aerodynamic:

ρ_a	–	air density
C_l	–	local lift coefficient (lift/unit span/$\frac{1}{2}\rho_a V_A^2 c$)
C_{lo}	–	value of C_l when $\alpha = 0$
C_L	–	global lift coefficient (lift/$\frac{1}{2}\rho_a V_A^2 cH$)
An	–	coefficients of Fourier series describing spanwise
Γ	–	circulation
a_∞	–	$dC_l/d\alpha$ for an infinite aspect ratio wing
f1	–	derivative related to $N_{\phi A\alpha}$ } defined by
f2	–	derivative related to $N_{\phi AV}$ } equations 4

III THE NATURE OF MARINE AEROFOIL ROLL DAMPING

A partial explanation of aerodynamic damping from marine aerofoils is given in ref (5). That explanation was based on incidence changes produced by ship motions, whereas a full explanation would also include the effects of ship-motion-induced airspeed changes. For simplicity, the explanation and formulae offered in this paper will be confined to a rectangular-planform aerofoil, although the basic approach could be applied to aerofoils of arbitrary planform.

Figures 3 to 5 show the process of a marine aerofoil rolling, the rolling causing incidence and speed changes, which in turn produce lift and roll damping.

ROLL DAMPING MECHANISM

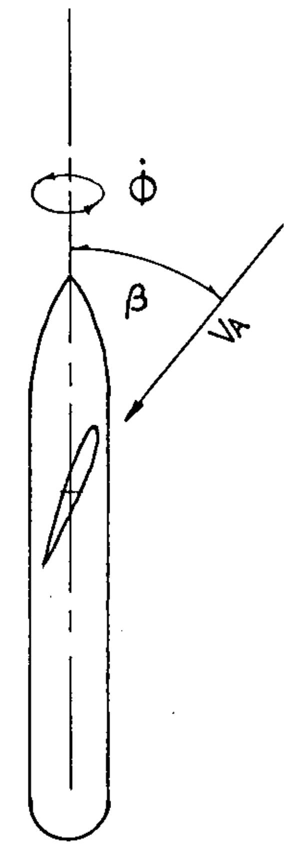


FIG 3 (plan)

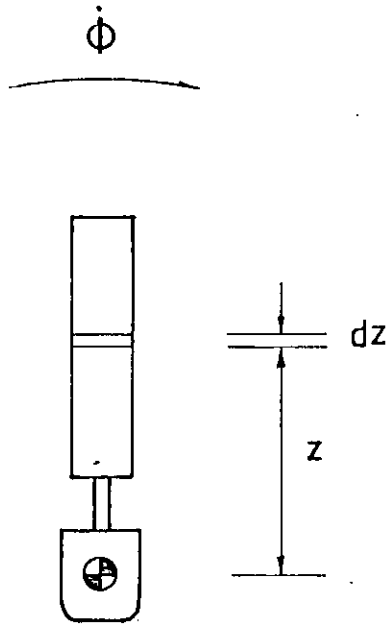


FIG 4 (end view)

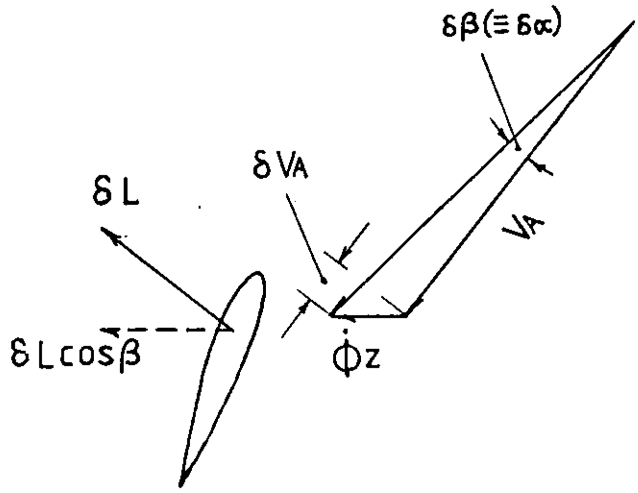


FIG 5 (detail of velocity and force changes due to rolling)

Figures 3 and 4 show an aerofoil element `$\delta z$` on a rolling ship with an apparent wind speed `$V_A$` approaching from an apparent wind angle `$\beta$`.

Figure 5 shows that an incidence change `$\delta\beta$` and airspeed change `$\delta V_A$` are induced as a consequence of rolling. The resulting lift change `$\delta L$` can be separated into components attributable to `$\delta V_A$` and `$\delta\alpha$`. This simplifies both explanations and formulae.

Consider first the effect of incidence changes ($\delta\alpha$) induced by rolling.

From Figure 7,

$$\delta\beta = \dot{\phi} z \cos\beta / V_A = \delta\alpha$$

$$\delta L\alpha = \Delta C_l . \tfrac{1}{2}\rho_a V_A^2 c\delta z$$

$$= \frac{dC_l}{d\alpha} . \dot{\phi} \frac{z\cos\beta}{V_A} . \tfrac{1}{2}\rho_a V_A^2 c\delta z$$

$$\delta N\phi\alpha = \delta L\alpha . \cos\beta . z / \dot{\phi}$$

$$= \frac{dC_l}{d\alpha} . \frac{z^2\cos^2\beta}{V_A} . \tfrac{1}{2} \rho_a V_A^2 c\delta z$$

Summing over the marine aerofoil,

$$N\phi A\alpha = \int_{\eta H}^{H} \frac{dC_l(z)}{d\alpha} . z^2 \cos^2 \beta . \tfrac{1}{2} \rho_a V_A c\delta z$$

The analysis will be simplified further with the assumptions that density (ρ_a), apparent windspeed (V_A) and chord (c) do not vary with height, so that

$$N\phi A\alpha = \tfrac{1}{2} \rho_a V_A c \int_{\eta H}^{H} \frac{dC_l}{d\alpha} (z) z^2 \cos^2 \beta\delta z \qquad (1)$$

Consider now the effect of a change in apparent windspeed (δV_A) due to rolling.

From Figure 5,

$$\delta V_A = \dot{\phi} z \sin\beta$$

$$\delta L_V = C_1(z) \cdot \tfrac{1}{2}\rho_a\, c\, \delta z\, \{(V_A + \delta V_A)^2 - V_A\}$$

$$= C_1(z) \cdot \tfrac{1}{2}\rho_a\, c\, \delta z \cdot 2V_A \delta V_A \quad \text{(neglecting } \delta^2 V_A\text{)}$$

$$= C_1(z) \cdot \tfrac{1}{2}\rho_a\, c\, \delta z \cdot 2V_A \dot{\phi}\, z \sin\beta$$

$$N\phi_{AV} = \delta L_V \cos\beta / \dot{\phi}$$

$$= C_1(z) \cdot \tfrac{1}{2}\rho_a\, c\, \delta z \cdot 2V_A\, z^2 \sin\beta \cos\beta$$

Summing over the height of the aerofoil and assuming ρ_a, c and V_A to be invarient with z,

$$N\phi_{AV} = \tfrac{1}{2}\rho_a V_A\, c \int_{\eta H}^{H} 2\, C_1(z) \cdot z^2 \sin\beta \cos\beta\, dz \qquad (2)$$

Summing both components of $N\phi_A$, given by equations (1) and (2):

$$N\phi_A = N\phi_{A\alpha} + N\phi_{AV}$$

$$= \tfrac{1}{2}\,\rho_a\,V_A\,c\,\cos\beta \int_{\eta H}^{H} \{\frac{dC_l}{d\alpha}(z)\,\cos\beta + 2C_l(z)\,\sin\beta\}\,z^2dz \qquad (3)$$

Equation (3) describes a roll damping coefficient $N_{\phi A}$, due to lift only. Equation (3) consists of one term dependent on $\frac{dC_l}{d\alpha}(z)$ and another dependent on $C_l(z)$. The incidence-derived term is multiplied by $\cos^2\beta$, which is positive for all β, implying that this component of damping ($N_{\phi A\alpha}$) will tend to follow both the sign and magnitude of the lift slope. Damping due to incidence changes will normally be positive for unstalled aerofoils, negative for stalled aerofoils and zero for aerofoils without a fixed Kutta point, such as the Flettner rotor.

Equation (3) also contains a term involving $\sin\beta\,\cos\beta\,C_l(z)$, describing damping from the airspeed changes induced by rolling. For $\beta > 90^o$ and $C_l(z) > 0$, $N_{\phi AV}$ is negative, although wind-assisted propulsion is still present. For $\beta > 90^o$ and $C_l(z) < 0$, then $N_{\phi AV}$ is positive, implying that damping from airspeed changes can be obtained but at the expense of wind propulsion. Consequently if $\beta > 90^o$, there is a conflict between propulsive and roll damping considerations for choosing the optimal value of $C_l(z)$.

IV QUANTIFYING AERODYNAMIC LOAD

Initial attempts to quantify aerodynamic loads involved the use of charts of aircraft stability derivatives, ref (4), together with appropriate corrections. This approach involved a regression analysis of published data, from which conclusions could be drawn regarding $C_1(z)$ and $\frac{dC_1}{d\alpha}(z)$. Unfortunately, these conclusions proved to be physically unrealistic, implying that aspects of the present problem lie outside the scope of data in ref (4).

The approach used in ref (4) to find aircraft stability derivatives involves the use of lifting surface theory which was originally developed from lifting line theory. In the present problem it was decided to revert to lifting line theory to quantify aerodynamic loads. Reasons were partly to help retain a physical insight into flow characteristics but also because there are a number of uncertainties about the nature of hull superstructure vortex shedding, atmospheric turbulence and sea surface effects, which limit expectations of accuracy from lifting surface analyses of the problem. Given these uncertainties, together with the preliminary nature of the investigation, it was difficult to justify the more refined technique.

Background on the lifting line technique is given in ref (7), notation for the lifting line/reflection plane problem tends to follow that given in ref (12) and a derivation of essential formulae is given in ref (13). Use of the lifting line approach ignores all starting vortex effects and all distortions of an (assumed) planar trailing vortex wake. The analysis is quasi-static, implying that unsteady flow effects are accounted for by a sequence of steady-flow calculations.

The lifting line technique may be summarised:

(1) define an angular coordinate `$\theta$` as:

$$z = \frac{H}{2}\cos\theta$$

(2) Express bound vorticity as $\Gamma(\theta) = 2H\overline{V}\sum_{n=1}^{m} An \sin n\theta$

(3) Note from ref`s (12) and (13) that the downwash due to trailing vortices is given by

$$W(\theta) = \overline{V}\sum_{n=1}^{m} nAn\left[\frac{\sin n\theta}{\sin\theta} - \frac{\{q-(q^2-1)^{\frac{1}{2}}\}^n}{(q^2-1)^{\frac{1}{2}}}\right]$$

where $$q\ (\theta,\ g,\ H) = 2(1+\frac{2g}{H}) - \cos\theta$$

This leads to an expression for the induced angle of attack

$$\alpha_i = W(\theta)/V(\theta)$$

(4) Introducing $C_l(\theta) = C_{lo} + a_\infty(\theta)\ .\ \alpha_o(\theta)$

$$\alpha(\theta) = \alpha_o(\theta) + \alpha_i(\theta)$$

and equating to conditions at `m` equally spaced angular coordinates leads to a system of `m` equations:

$$\left[\frac{n\sin n\theta}{\sin\theta} + \frac{4H}{a_\infty(\theta).c}\sin n\theta - n\,\frac{(q-(q^2-1)^{\frac{1}{2}})^n}{(q^2-1)^{\frac{1}{2}}}\right]\{An\}$$

$$= \{\ \frac{V(\theta)}{\overline{V}}\ (\alpha(\theta) + \frac{C_l(\theta)}{a_\infty(\theta)}\ )\}$$

which can be solved for An, for any specified $\alpha(\theta)$ or $V(\theta)$.

Values of $N_{\phi A \alpha}$ and $N_{\phi A V}$ may be defined in terms of functions f1 and f2 as:

$$\left.\begin{aligned} N_{\phi A\alpha} &= \cos^2\beta \,.\, \tfrac{1}{2}\, \rho_a V_A\, c\, (g + H)^3 \,.\, f_1 \\ N_{\phi AV} &= \cos\beta \sin\beta \,.\, \tfrac{1}{2}\, \rho_a V_A\, c\, (g + H)^3 . C_L . f_2 \end{aligned}\right\} \quad 4$$

Values of f1 and f2 are found by examining aerodynamic moments produced by rolling and yawing in the lifting line analysis model. Values were computed for a marine aerofoil of 20m span, with varying aspect ratio and gap/height ratios. These results are presented in Tables I and II. Values of f1 and f2 deduced from the results of ref (4) were around 25% less than the lifting line results presented in the tables. Clearly, any differences in span loading near the tip of a marine aerofoil produce major differences in heeling moments. Span loadings from ref (4) are appropriate to a different physical problem, implying that different span loadings must be expected. Against this background, the two methods of computing derivative values f1 and f2 have a level of agreement compatible with realistic expectations. Equations (4) may be combined to obtain a value for $N_{\phi A}$ as:

$$\boxed{N_{\phi A} = \tfrac{1}{2}\, \rho_a V_A\, c\, (g+H)^3 \cos\beta\, (\cos\beta \,.\, f1 + C_L \sin\beta \,.\, f2)} \qquad (5)$$

It is sometimes useful to rewrite equation (5) in terms of a true wind speed `$V_T$`, true wind angle `$\gamma$` and (shipspeed)/(true windspeed) ratio `a` as:

$$\boxed{N_{\phi A} = \tfrac{1}{2}\, \rho_a V_T\, c\, (g+H)^3 \frac{(a+\cos\gamma)}{\sqrt{a^2+1+2a\cos\gamma}} ((a+\cos\gamma) \,.\, f1 + C_L \sin\gamma \,.\, f2)} \qquad (6)$$

TABLE I: Values of f1 (for $N\phi_{A\alpha}$)

g/H \ A	2	3	4	5	6
.1	.969	1.159	1.289	1.383	1.457
.2	.974	1.166	1.297	1.391	1.464
.3	.974	1.166	1.296	1.390	1.463

TABLE II: Values of f2 (for $N\phi_{AV}$)

g/H \ A	2	3	4	5	6
.1	.6113	.6189	.6235	.6272	.6302
.2	.6266	.6306	.6337	.6362	.6383
.3	.6308	.6337	.6372	.6379	.6395

VI ASSESSMENT OF ROLL REDUCTION PRODUCED BY MARINE AEROFOILS

The usual way to assess the impact of a marine aerofoil on any component of ship motion is to establish the effect of the device on all ship stability derivatives, and then solve a system of simultaneous partial differential equations with the required wave excitation.

In this preliminary study, only the effects of marine aerofoil lift on a single ship stability derivative have been assessed, and so a roll amplitude analysis method appropriate to this level of investigation is sought.

In ref (2) a rolling ship is described by the differential equation:

$$I\ddot{\phi} + \frac{T\phi \Delta K_1 \overline{GM}}{\pi^2}\dot{\phi} + \Delta\overline{GM}\,\phi = f(1) \tag{7}$$

The term $T\phi\Delta k_1\overline{GM}/\pi^2$ describes a linear hydrodynamic damping coefficient, similar to the linear aerodynamic damping coefficient $N_{\phi A}$. More recent analyses of the same problem e.g. ref (3), have tended to include any non-linear damping in a linearised equivalent damping coefficient ($\nu\phi$), appropriate to a ship rolling through a full rather than half cycle. For the present purposes, the newer notation of $\nu\phi$ needs to be fed into the older analysis described in equation (7) via:

$$\nu\phi = 2K_1$$

Using the notation of ref (2), equation (7) is strictly correct only when non-linear damping is absent. However, it will now be understood that the concept of a linearised equivalent damping coefficient will now be extended to the notation of ref (2), so that non-linear damping may be accounted for by an appropriate increase in K_1.

In ref (2) equation (7) is solved. The solution for ϕ_{MAX} is proportional to wave slope and $1/K_1$ (or $1/\nu\phi$ using more recent notation). ϕ_{MAX} occurs when the natural roll period of the ship coincides with the period of the waves, and this is usually the case where roll reduction is most required. The proportionality between ϕ_{MAX} and $1/\nu\phi$ suggests a direct method of calculating the reduction in ϕ_{MAX} due to a marine aerofoil. A value of $\nu\phi_A$ may be found by identifying the damping term in equation (7) and equating this to $N\phi_A$ from equation (6). ϕ_{MAX} is now inversely proportional to the sum of aerodynamic and hydrodynamic linearised equivalent damping coefficients. This logic leads to:

$$N_{\phi A} = \frac{T_\phi \ \Delta \ \nu\phi \ \overline{GM}}{2\pi^2}$$

$$\nu_{\phi A} = \frac{2\pi^2 \ N_{\phi A}}{T_\phi \ \Delta \ GM}$$

Introducing equation (6) for $N_{\phi A}$ gives:

$$\boxed{\nu_{\phi A} = \frac{\pi^2}{T_\phi \ \Delta \ GM} \rho_a V_T \ c \ (g+H)^3 \frac{(a+\cos\gamma)}{\sqrt{a^2+1+2a \cos}} \{(a+\cos\gamma) \ f1 + C_L \sin\gamma . f2\}} \qquad (8)$$

Noting that:

$$\phi_{MAX} \propto 1/\nu\phi$$

$$\phi_{MAXA} \propto 1/(\nu\phi + \nu\phi A)$$

and also that:

$$\frac{\phi_{MAX} - \phi_{MAXA}}{\phi_{MAX}} = \text{fractional roll reduction due to marine aerofoil}$$

then

$$\boxed{\frac{\phi_{MAX} - \phi_{MAXA}}{\phi_{MAX}} = \frac{\nu\phi_A}{\nu\phi + \nu\phi_A}} \qquad (9)$$

To summarise, if $\nu\phi$ is known, then $V\phi_A$ may be calculated from equation (8) and the fractional reduction in resonant roll amplitude is obtained from equation (9). Away from resonant conditions, equation (9) will become progressively less accurate, although the requirement for roll damping may also be less as the roll response to wave excitation subsides.

Limitations of this analysis should be appreciated. The ship is assumed to experience sinusoidal waves, of small amplitude, coming from the beam, and then respond to these waves without stalling the marine aerofoil. General trends for the unstalled operation of a marine aerofoil should be indicated by this approach.

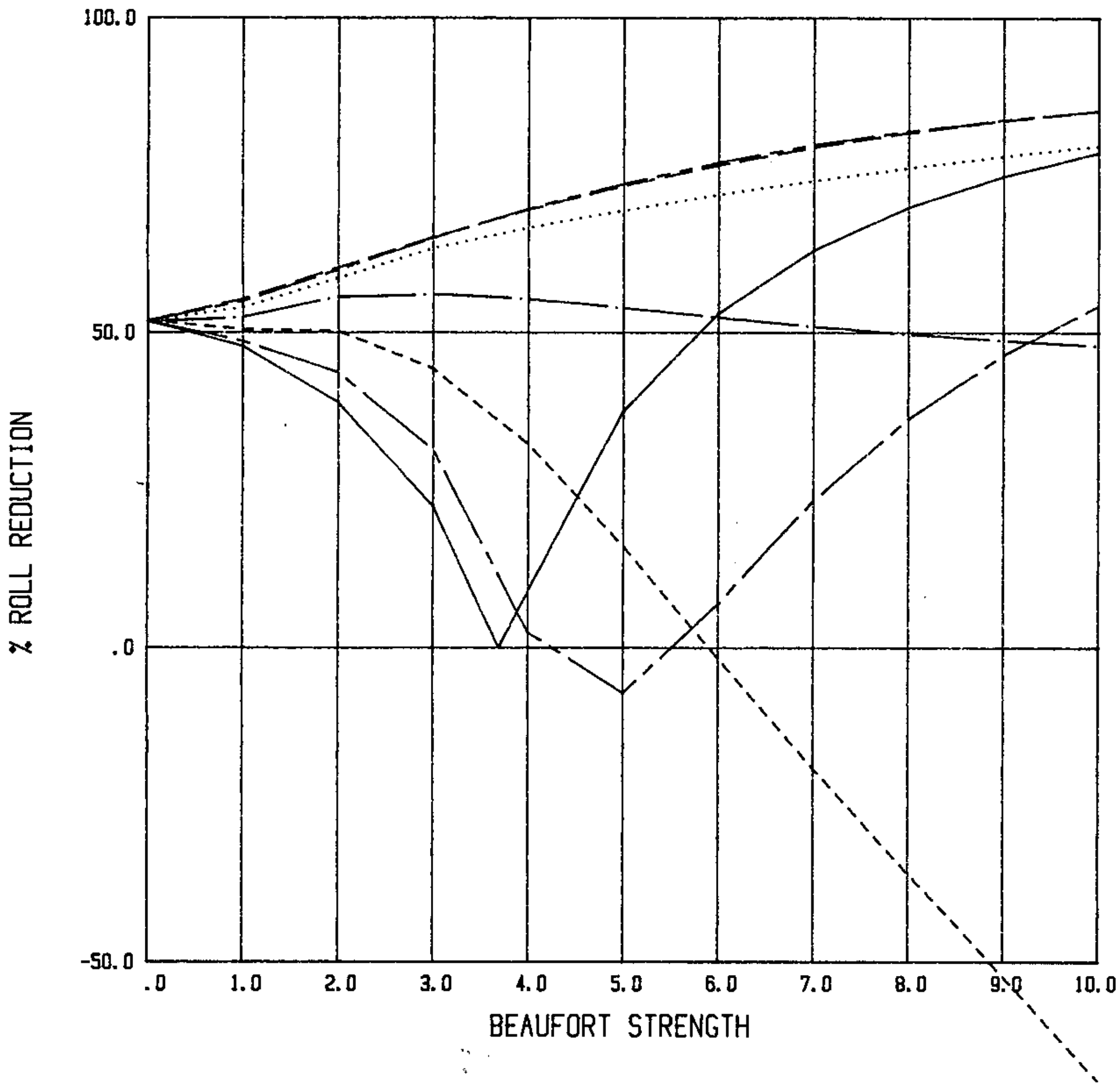
Some guesses at representative inputs for the Japanese vessel 'Aitoku Maru' have been used to test equations (13) and (14). Input data used was:

$\nu\phi$ = .05	V_S = 6 m/s	ρa = 1.225 kg/m^3
c = 10m	H = 20m	g = 5m
T_ϕ = 8.5 sec	$\overline{GM}$ = 1m	Δ = 24137309N(2400m^3)

Values of C_L were selected (i) on the basis of maximising wind propulsion and (ii) on the basis of maximising roll damping. Results are presented in Figures 6 and 7. The difference between the two figures lies in the strategy for choosing the lift coefficient, which from equation (6), can have a large influence on the roll damping. Further comment on this point will be reserved until later in the paper.

General trends indicated by Figures 6 and 7 show very good damping when $\gamma < 90^{o}$, but problems when $\gamma > 90^{o}$. There are three basic reasons for this. Firstly, when $\beta = 90^{o}$ the lift vector has no lateral component and so roll damping from lift vanishes, although there may be roll damping from aerodynamic drag, which is not included in the present formulae. Secondly, when $\gamma = 180^{o}$ and $V_S = V_T$, then $V_A = 0$, and damping vanishes. In other words, when a ship sails downwind at the same speed as the true wind, the apparent wind strength is zero and so no aerodynamic forces can be produced to provide roll damping. Thirdly, there is the question of the method of aerofoil incidence control, which governs the lift coefficient (C_L) and hence roll damping. This question merits separate consideration.

ROLL REDUCTION FROM A MARINE AEROFOIL



LEGEND

Roll amplitude reduction from a marine aerofoil is shown for a range of true wind angles, measured in degrees.
CL is optimised for direct wind propulsion, without regard to roll damping.

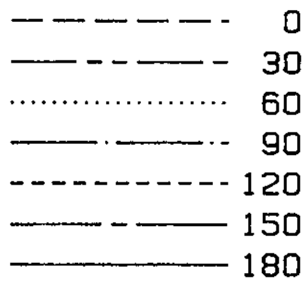


FIG 6

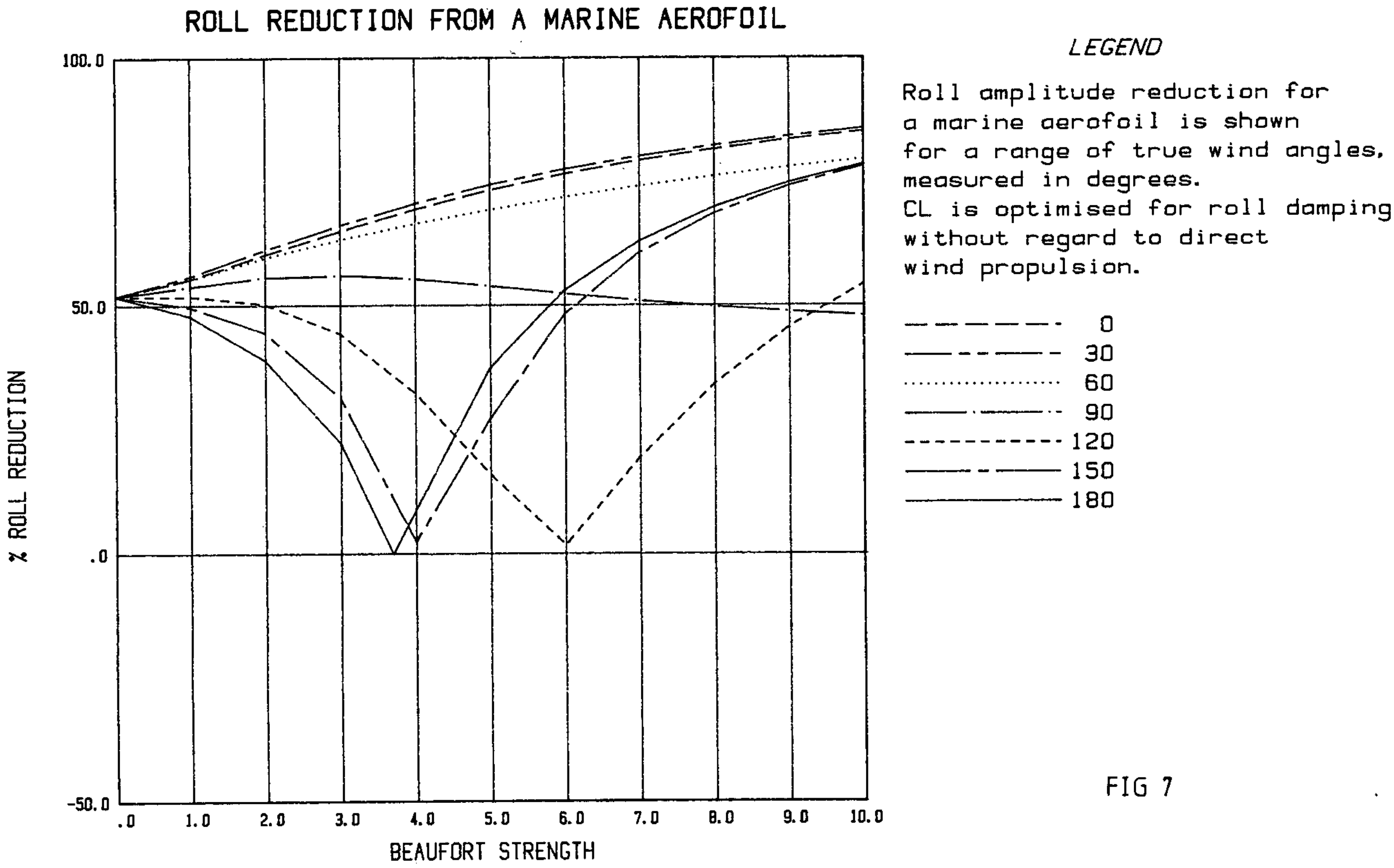

ROLL REDUCTION FROM A MARINE AEROFOIL
100.0
50.0
.0
-50.0
% ROLL REDUCTION
.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
BEAUFORT STRENGTH
LEGEND
Roll amplitude reduction for
a marine aerofoil is shown
for a range of true wind angles,
measured in degrees.
CL is optimised for roll damping
without regard to direct
wind propulsion.
0
30
60
90
120
150
180

FIG 7

VII CONTROL OF A MARINE AEROFOIL FOR ROLL REDUCTION

Control of a marine aerofoil needs to follow guidelines, which might prove difficult to define. One quite logical objective might be to try to maximise net wind propulsion, leading to the graph shown in Figure 6, where high negative roll damping occurs with strong beam winds. Another objective might be to maximise roll damping (Figure 7), but this results in wind retardation in strong beam winds. Compromise objectives might be formulated along the lines of obtaining maximum wind propulsion, but progressively reducing it in strong beam winds so as to avoid negative roll damping. Variations on this theme might involve a movement towards less direct wind propulsion, but more roll damping. This would maximise overall propulsive benefits, which include an element of reduced resistance associated with overall improvements in ship motion. Figures 6 and 7 have had their inputs selected so as to represent the realistic range of roll damping to be expected from a marine aerofoil with an incidence control system geared only to some mean apparent wind. Any conflict between direct wind propulsion and roll damping will need to be resolved on an individual basis, depending on the ship, its loading, the route and a host of other factors.

Marine aerofoils could also have their control systems modified so as to directly increase roll damping. A control system might incorporate a device to sense roll amplitude, velocity and acceleration, and then introduce incidence changes so as to enhance the natural roll damping effect of the rig. Such a system might be analagous to an aircraft roll damper, working through ailerons, or a hydrovane roll damping system for ships. This type of system works by enhancing incidence-derived roll damping. It is also theoretically possible to enhance airspeed-derived roll damping, by continuously varying the sweepback angle of the marine aerofoil, although such a system would be difficult to justify on damping grounds alone.

The practicability of a roll-damping incidence control system needs careful study to avoid problems with stalling. Steady-flow stalling characteristics are often enhanced by approaching a stall dynamically, but may also exhibit hysterisis phenomena once the stall is passed. This creates a problem of knowing exactly when a marine aerofoil will stall,and suggests that there should be an incidence margin between an operating C_L and the best estimate of C_{LMAX}. Figure 8 illustrates this idea on a graph of C_l v α. The size of the incidence margin needs to be adjusted in line with the incidence changes induced by rolling. If additional incidence changes are introduced by the control system, to enhance roll damping, then the stall incidence margin needs to be increased. The implication is that the introduction of a roll-damping incidence control system may decrease the maximum operational lift coefficient. Some estimates of incidence margins and the effect of a roll damping incidence control system need to be made.

The local lift coefficient for a rolling marine aerofoil can be written:

$$C_l(z)|_{\text{rolling}} = C_l(z)|_{\text{steady}} + \frac{dC_l}{d\alpha}(z) \, . \, \delta\alpha$$

$$= C_l(z)|_{\text{steady}} + \frac{dC_l}{d\alpha}(z). \, \frac{\dot{\phi} z}{V_A} \, |\cos\beta| \qquad (10)$$

Once again, the lifting line model can be used to examine $C_l(z)$ for a variety of roll velocities and (g+H) values, to determine the increase in the maximum values of $C_l(z)$ over the span of the marine aerofoil, i.e. $\max|C_l(z)|$ (rolling) − $\max|C_l(z)|$(non rolling) = ΔC_l. If it is assumed that a stall is to be avoided, then there must be an incidence margin of approximately $\Delta C_l/(dC_l/d\alpha)$, to provide the necessary stall protection. An examination of a 20 m span, 5m gap marine aerofoil was carried out to investigate the magnitude of incidence margins required. Results are presented in Table III, for different values of $(H+g)\cos\beta/V_A$ and aspect ratio.

The effect of a roll-damping incidence control system may be thought of an an effective increase in $\dot{\phi}$. This means any implications for the incidence margin may be judged from the effective gain in $\dot{\phi}$ and the results of Table III.

For the case of a vessel with a roll period of 8.5 sec, 20m rig, 5m gap and 10 m/s apparent wind, rolling 5^o, $\dot{\phi}(H+g)|\cos\beta|/V_A$ amounts to .16 $\cos\beta$, at worst. An incidence margin of around 5^o could prevent stalling, although in practice it may be better to risk some separation and use a smaller incidence margin, as maximum roll velocities represent only a small proportionof a roll period. When $\cos^2\beta$ becomes small, a roll damping incidence control system could usefully restore roll damping as the incidence margin can be reduced in proportion to $|\cos\beta|$.

TABLE III: INCIDENCE MARGIN NEEDED TO AVOID STALLING (units: degrees)

$\frac{\dot{\phi}(H+g)\lvert\cos\beta\rvert}{V_A}$ \ A	2	4	6
.05	2.08	2.09	2.10
.1	4.30	4.31	4.36
.2	8.78	8.87	9.00

C_l-α GRAPH AT SPANWISE STATION WITH MAX $C_l(z)$

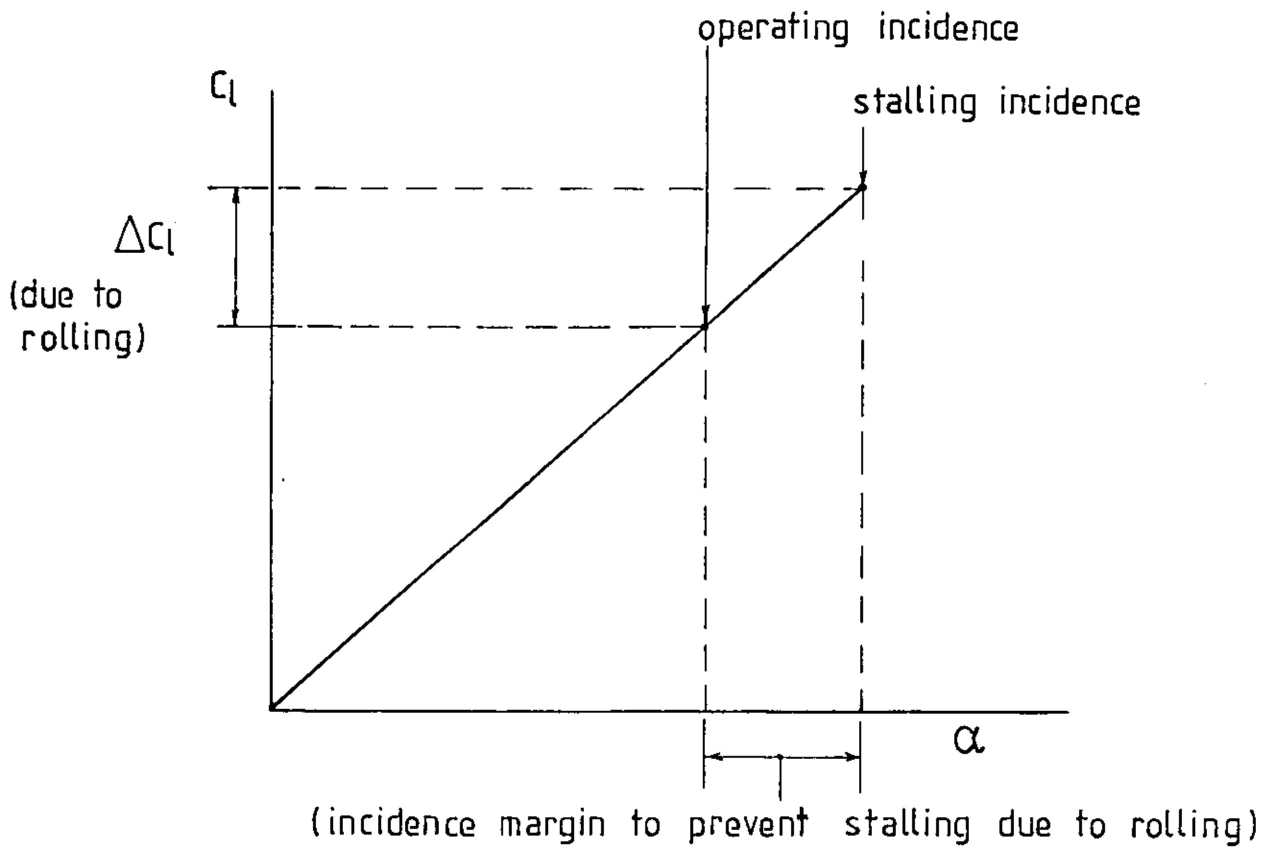


FIG 8

VIII RESISTANCE IMPLICATIONS OF MARINE AEROFOIL DAMPING

No comprehensive quantitative theory can be offered to explain resistance reductions associated with marine aerofoil motion damping. The degree of yaw, sway and pitch reduction has not yet been established, nor have the processes for achieving those reductions. Only when all motion reductions are identified can an accurate estimate of resistance reduction be made. In the interim, it may be possible to associate a component of resistance reduction with a particular type of motion reduction.

The first step with this question is to review the evidence which suggests that motion and resistance reductions occur. Most of this comes from translated Japanese reports on voyage analyses of the sail-assisted vessels `Shin Atoku Maru` and `Usuki Pioneer`. Translations come with a number of grammatical errors, but the meanings are usually clear. Ref (1) contains the following quotes and information:

"The Shin Atoku Maru proved hardly (sic) susceptible to either yawing, rolling or pitching whether into or off the wind."

An interesting `race` was held between `Shin Aitoku Maru` and a more recent fuel efficient ship `H. Maru`, `Shin Aitoku Maru` won, using far less fuel. Comments on this event in ref (1) included the statement:

"Simple conversion of the wind forces working on the sails of the Shin Aitoku Maru into horsepower would be insufficient for explaining this great difference. A more convincing reason is the oscillation-reducing effect of the sail rigging and, as stated in Paragraph 6.3, the consequent smaller loss of power owing to waves, i.e. the smaller sea margin."

In ref (1) there is an account of a performance comparison of the vessel `Aitoku Maru` before and after sail rigging. This vessel has the same lines as `Shin Aitoku Maru` which must have aided interpretation of the data. A plot of performance data both before and after rigging shows useful performance gains. However the surprising result involves sailing to windward with sails furled. This attracted the comment "unexpectedly, there was a speed recovery by 5 percent or so even when the sails were furled." Further comments are made later to emphasise the validity of the unexpected speed gain of five percent (power gain of 16 percent) when going to windward with furled sails. A similar comment for unfurled sails was, "Meanwhile, with the sail unfurled when the wind was blowing ahead within a 20^{o} deviation to either side, the speed gain (sic) as much as 5 to 9 percent."

The foregoing comments indicate a reduction in all types of motion after sail retrofit, as well as a 16-30% power gain on windward courses where only a power loss would be predicted from conventional wind propulsion theory. In ref (1) there is a comment about course keeping which suggests that some of the power gain comes from this source; "The Shin Aitoku Maru also proved excellent in course keeping performance and, unlike conventional ships, permitted rudder meeting (sic) within only 5 degrees even in a rough weather. Resistance due to the rudder is reduced, resulting in energy conservation by an estimated 2 or 3 percent". Ref (1) also refers to the lower propeller loadings helping to retain propeller smoothness.

In ref (11), additional fuel savings are identified which arise from a lower propeller thrust coefficient under sail. Clearly, any lessening of resistance will lower the propeller thrust coefficient, which will usually increase propeller efficienty and create additional fuel savings.

The level of motion reduction is indicated by a paragraph in ref (1) "During a sea trial at a wave height of 3 metres, a wind direction of 45 degrees right and a wind velocity of 15 meters, the hull rolled 10 degrees to the left and 17 degrees to the right in 7.9 second cycles, but when the sails were furled, the rolling angle increased to 15 degrees to the left and 22 degrees to the right in 7.3 second cycles. Thus her rolling angles were reported to be over 30 percent less, with the rolling period nearing 8 seconds,when the sails were unfurled."

Another indication of the levels of motion reduction comes from ref (8); "In the case of the `Usuki Pioneer`, the use of the sail system has resulted in reductions of 20-30% in roll, and 10-18% in yawing. Reductions in ship motion have resulted in improvements in sea margin, and the improvement in course-keeping ability has led to further reductions in fuel consumption." There is then an interesting comment that no final conclusions have been reached about exact figures for reducing installed power followed by; "In the case of `Usuki Pioneer` installed engine power was reduced from an originally intended figure of approximately 8000 ps in the light of results from other vessels". From ref (9) Usuki Pioneer can be seen to have engines of 2 x 3300 BHP, indicating that a reduction of 17.5% in installed engine power was felt justified by the presence of her two-masted low aspect ratio rig.

These measurements confirm that significant motion reductions occur and indicate that there are unexplained power savings when at least one sail assisted vessel goes directly to windward. The JAMDA hypothesis about motion-derived fuel savings seems very plausible, especially since any resistance reduction is likely to bring about an improvement in propeller efficiency.

In the light of this review, the next step must be to try to identify the various processes for saving fuel and then to plan to observe these processes.

It has been established by both theory and observation that sails reduce rolling. When a vessel rolls, its underwater profile becomes asymmetric, and it behaves like a low aspect ratio cambered aerofoil. As water flows over the heeled hull, the effect is to generate a sideforce and yawing moment, resulting in sway and yaw.

Sway and yaw combine to produce leeway, which results in induced resistance (Ri).

There may also be some resistance directly due to rolling, associated with vortex shedding and possible separation from the bilge keels.

Aerodynamic pitch damping will also be present on some points of sailing, although this looks small in comparison with hydrodynamic pitch damping.

Gyroscopic effects should be reduced by reductions in rolling. A gyrosopic yawing moment comes from roll-pitch coupling and a gyroscopic pitching moment from roll-yaw coupling. The magnitude of gyroscopic moments is normally considered to be small.

Of the various motion-related fuel saving processes reviewed, sway/yaw reduction can be identified as a process which offers certain prospects of fuel savings. The degree of yaw reduction has been indicated as 10-18% for Usuki Pioneer. For Shin Aitoku Maru, there is a deduction that a 16% power gain comes from unexplained sources when going directly to windward, but no figure in ref (1) for yaw reduction. An indication of yaw reduction on a windward sailing point comes from the video record of `H Maru` and `Shin Aitoku Maru` sailing together ref (10). `H Maru` is shown to yaw, whereas `Shin Aitoku Maru` is said not to yaw, but shown with a very small amount of yaw. For the sake of this example, the yaw on `H Maru` will be assessed at 5^{o}.

On the video sound track, there is an inference that the sails remove the yawing oscillation. This inference assumes the vessels to be equal in all other respects. As this may not be the case the inference should be regarded as tentative.

If quasi-steady assumptions are employed, then formulae from ref (6) can be used to examine the resistance associated with a sinusoidal 5^{o}. A time-averaged induced resistance coefficient $\textcircled{c}_i$ can be defined as:

$$\overline{\textcircled{c}}_i = \frac{1}{T_\psi} \int_o^{T_\psi} \frac{250 \ Ri(t) \ dt}{\pi \ \rho_s \ V_s^2 \ \nabla^{2/3}} \qquad (11)$$

Where T_ψ is the period of yawing.

From ref (6)

$$R_i = \rho_s \ V_s^2 \ K_{DC} \ \lambda^2 \ (k_1 T^2 + k_2 LT|\lambda|) \qquad (12)$$

If λ varies sinusoidally with time, and has a maximum value of λ_{MAX}, evaluation of time-averaged integrals gives:

$$\overline{\textcircled{c}}_i = \frac{250 \ k_{DC} \ \lambda^2{}_{MAX}}{\pi \ \nabla^{2/3}} \ \left(\frac{k_1}{2} T^2 + \frac{4}{3\pi} k_2 \ LT \ |\lambda_{MAX}|\right) \qquad (13)$$

Taking estimated values of λ_{MAX} = .087 rad, T = 5.2m, L = 66m, k_1 = 2, k_2 = .25, k_{DC} = 1.1 and ∇ = 2473, then from equation (13):

$$\overline{\textcircled{c}}_i = .109$$

For smaller angles of leeway,

$$\overline{\textcircled{c}}_i = 14.1 \ \lambda^2{}_{MAX}$$

The total resistance of the vessel at sea is difficult to assess, but would probably correspond to a $\textcircled{c}$ value of around 1.1, suggesting that the 5^{o} sinusoidal yawing might contribute around 10% of total resistance. Removal of this yawing by the sails should remove this resistance. This would go part way to explaining the unaccounted power gain experienced by 'Shin Aitoku Maru'. In the caseof 'Usuki Pioneer' the estimated yaw reduction of around 14% would lead to a reduction in $\overline{\textcircled{c}}_i$ of $\overline{\textcircled{c}}_i .(1-.86^2)$ or $.26\overline{\textcircled{c}}_i$.

The potential for sail-induced yaw reduction is a topic that deserves investigation, ideally in the wider context of sail/roll/yaw/sway interaction. Clearly, if a wind-assist device can be designed and sited so as to reduce yawing, then significant additional fuel savings will accrue. A long term objective might be to make resistance estimates for various components of ship motion reduction, with a view to evaluating motion-derived sail propulsive benefits. Ideally, these estimates would also account for resistance effects due to interactions between different components of ship motion.

It is appropriate to point out that experiments to determine the impact of marine aerofoils on ship motions, and related resistance changes, look worth pursuing in the light of Japanese experience. This type of experiment might be done by measuring ship motions and wind conditions before a rig is fitted, followed by similar measurements after a rig is fitted. Experiments involving measurements on a vessel, with sails alternately furled and unfurled, may also provide an indication of sail benefits. In these experiments there may be some unaccounted residual effect of a furled sail. If enough data is obtained, results should acquire sufficient statistical significance and problems with measuring waves can be avoided.

To summarise, there is evidence that sails reduce rolling yawing and swaying, and that useful reductions in resistance come from reduced yaw/sway. There may be a small resistance reduction associated with reduced roll. There is favourable comment about the effect of sails on pitching, but no published measurements have been found to show that sails have any substantive effect on this motion. However, it should be noted that even a small reduction in pitching can lead to a useful reduction in resistance, but that a very accurate experiment may be needed to investigate the resistance implications of possible pitch reductions due to sail.

IX CONCLUSIONS

The original technical aims were to try to quantify the motion improvement to be gained from a rig and then to appraise any implications for ship resistance. A review of the main points introduced in this paper will assist in drawing conclusions.

The nature of marine aerofoil roll damping has been examined and shown to have components dependent on the incidence and airspeed changes induced by rolling. Incidence damping is beneficial for unstalled aerofoils, whereas airspeed damping may be adverse and even dangerous in reaching conditions. It has been shown that any danger can be avoided by operating the aerofoil at a reduced C_L, but at the expense of wind propulsion.

Aerodynamic roll damping has been quantified using lifting line theory and checked against alternative calculations derived from data in ref (4). Results of calculations for rectangular aerofoils are summarised in equation (5) and Tables I and II.

Resonant roll amplitude has been identified as being inversely proportional to the hydrodynamic damping coefficient $\nu\phi$, and equation (8) describes the aerodynamic damping coefficient $\nu\phi_A$. This simple law of inverse proportion has been exploited to predict the reduction in resonant roll amplitude, due to a marine aerofoil, and is described by equation (9). Examples of roll reduction from a marine aerofoil are shown in Figures 6 and 7. These show very high levels of roll damping on upwind courses, declining to zero with beam winds, and increasing again when winds are aft of the beam and the rig operated so as to avoid negative damping.

A conflict between control for propulsion and control for damping has been identified, and the idea of a roll-damping incidence control system introduced. This could restore some of the lost damping when wind was close to the beam, but would not help when wind was on the beam. A requirement for an incidence margin for stall prediction has been identified, and quantified for one example, with results in Table III.

Evidence for sail-derived motion improvements and resistance reductions has been reviewed. Sail-induced yaw reduction has been identified as a process leading to significant resistance reduction. There may also be some resistance reduction due directly to reduced rolling. The effect of a marine aerofoil on pitching is believed to be slight. Experiments are recommended, both to observe the resistance-reducing processes identified and to investigate possible new processes.

The question of using a marine aerofoil as a roll damping device has now been investigated in sufficient depth to form initial conclusions. When marine aerofoils are operated unstalled, they become good roll dampers on upwind courses, but may sometimes be poor roll dampers on reaching and downwind courses. On upwind courses, roll damping increases with increasing wind strength, whereas on downwind/reaching courses, roll damping exhibits a more complicated variation with wind strength. Any decision to employ a marine aerofoil in place of another roll damping device can be expected to depend on anticipated wind and wave characteristics. Where a vessel can anticipate winds predominantly forward of the beam, a marine aerofoil deserves serious consideration as a roll damper. Where a proposed operation involves frequent strong winds on, or slightly aft of the beam, and the vessel's roll response is excited by waves from the stern quarter, then some other roll damping device looks more appropriate. Course changes, speed changes and modified methods of aerofoil control are all ways of enhancing marine aerofoil roll damping.

The justification for reducing installed engine power due to the presence of a marine aerofoil is a complex topic. Sometimes, installed engine power may be needed to sustain a given calm water speed, whereas in other cases, there may be a significant increase in installed engine power to account for resistance increase due to waves. Justification for installed power reduction must depend on the rationale for its initial magnitude. From ref (1), it can be seen that `Shin Aitoku Maru` has a minimum speed capability when going directly to windward, and that this is likely to be a critical heading for selecting installed engine power. It is also stated that on this heading, sails enhance speed by 5-9%, which corresponds to a 16-30% power gain. There is therefore a case for reducing installed engine power by 16-30%, if the rationale is to provide a minimum speed capability in heavy weather. One other relevant point is that voluntary speed reductions, for reasons of avoiding very bad ship motions, should be less likely with a marine-aerofoil-equipped ship. Thus, the presence of a marine aerofoil can result in an enhanced speed capability, in conditions where it is very desirable.

The comment in ref (8) regarding the absence of firm conclusions about installed power reductions is very relevant, in view of the breadth of Japanese experience with sail-assisted vessels. Also relevant, is the example that on the basis of this experience, they appear to have justified a 17.5% cut in the planned installed engine power of `Usuki Pioneer`. Until sail/motion/resistance interactions are understood, there can be no way of accurately estimating the speed capability of a sail-equipped ship, and so any reductions in installed engine power are likely to err on the conservative side.

One of the original objectives was to try to find the importance of motion-derived benefits in order to help establish a context for other windship research in the area of direct wind propulsion as well as exploring areas for future work. Methods for estimating fuel savings, such as refs (6) and (11) ignore motion-derived benefits. The propulsive impact of a rig on a ship can now be seen to be made up of a number of components including:

* Resistance reduction, which comes from improvements in ship motion brought about by the presence of the rig.

* Improved course keeping, and less rudder resistance.

* Flapping wing propulsion, which comes from the wave energy absorbed by a marine aerofoil during roll damping being converted into a momentum increase in the airflow direction.

* Gust propulsion, due to lateral gusts at the marine aerofoil, converted into a momentum increase in the airflow direction.

* Usually, improvements in overall engine/propeller efficiency due to a reduction in propeller thrust coefficient.

Flapping wing and gust propulsion have been included to complete the parts of the overall picture that are qualitatively understood at the present time. These may be propulsive or resistive, depending on the apparent wind direction.

Changes in overall engine propeller efficiency are discussed in ref (11).

Japanese experience, combined with current calculations, suggest that motion-derived sail propulsive benefits can be as important as direct wind propulsive benefits, and that greater efforts should be made to understand them, so that the effectiveness of marine aerofoils can be predicted and improved. This is now acknowledged as an important area for future research.

Opportunities to install marine aerofoils occur when their capabilities offer a cost-effective answer to requirements. Capabilities include fuel savings, an opportunity to reduce installed engine power, emergency propulsion and effective motion reduction which does not compromise cargo space; particularly when the predominant wind is forward of the beam. It is thought that many vessels could utilise these benefits, with Ro-Ro`s looking particularly suitable.

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