ISSN 0140 3818
SSSU 16

UNIVERSITY OF SOUTHAMPTON

DEPARTMENT OF SHIP SCIENCE

FACULTY OF ENGINEERING AND APPLIED SCIENCE

THE EVALUATION OF WIND POWER FOR COMMERCIAL VESSELS

BY C.J. SATCHWELL, PhD

Ship Science Report No 16

THE EVALUATION

OF

WIND POWER

FOR

COMMERCIAL VESSELS

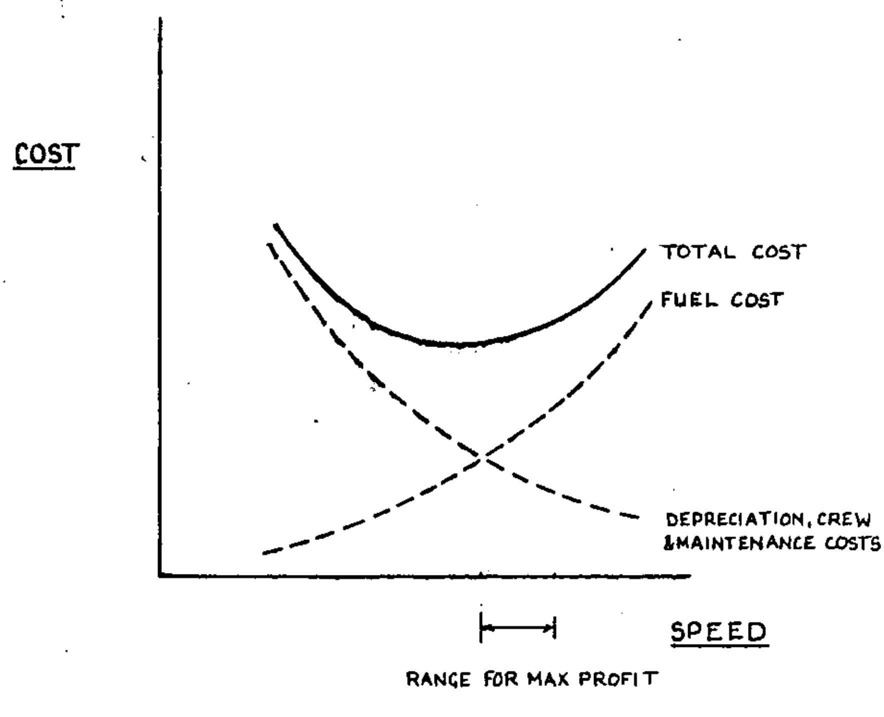
by

C. J. Satchwell, PhD.

THE EVALUATION OF WIND POWER FOR COMMERCIAL VESSELS by C.J. Satchwell

Wind power can make a useful contribution to operators' fuel economy drives, but the design details can be very complex with numerous opportunities for bad decisions. This account is intended to make a wider audience aware of some current thoughts, developments and positive results produced at the Department of Ship Science, Southampton University. The work described is within the context of a fundamental law of transport economics, illustrated in Fig. 1. This shows that operators can either burn more fuel, with the effect of improving productivity of ship and crew and attracting more revenue, or burn less fuel with the reverse effects, but lower fuel costs.

Fig 1 COST - SPEED RELATIONSHIP



Choice of speed is clearly highly individual, depending on the ship, route, operational requirements etc. The impact of wind power is to change the fuel/speed relationship for the better, at some extra cost in terms of depreciation, operation and maintenance. Recent research has produced a method of quantifying the fuel/speed improvement which can enable operators to make better judgements about fitting wind-assist devices.

Firstly a brief survey of three possible categories of wind-assist device will help to provide necessary background for the direction in which these developments have progressed.

1. Elevated Sails or Kites

Principles of elevated sails are shown in Fig. 2.

Fig 2 PRINCIPLES OF KITE PROPULSION

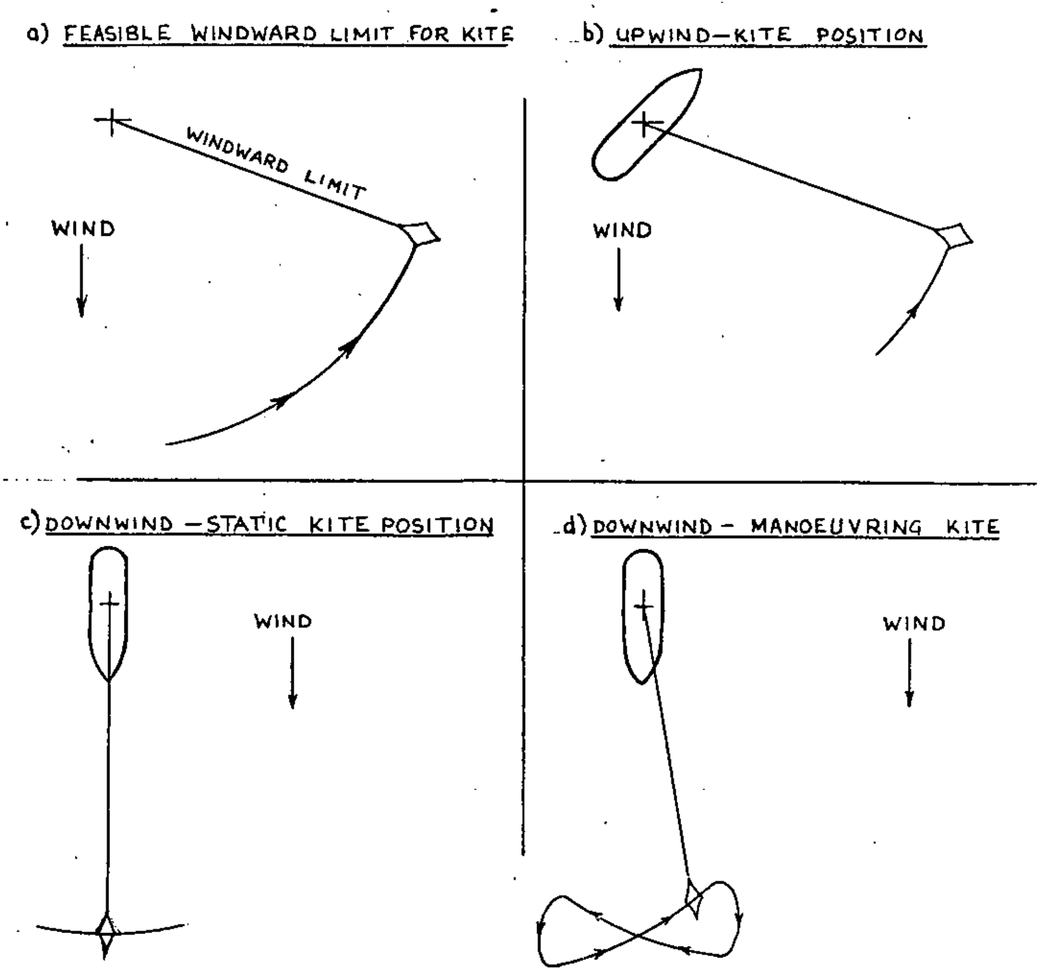


Fig. 2a shows the feasible flying arc for a stationary pilot flying a controllable kite. In 2b a ship is superimposed onto the picture and the kite line can be seen to be forward of the beam, pulling the ship to windward. Fig. 2c shows the ship going downwind. Downwind performance is enhanced by the figure of eight manoeuvre shown in fig. 2d. This increases the apparent windspeed over the kite and enables it to harvest wind energy from a greater swept area.

Points that can be made in favour of the kite include:

1. It can work high up,where winds are stronger.
2. Wind direction changes with height, and this effect can be usefully exploited to improve pointing ability.
3. Downwind, kite manoeuvring increases the useful thrust well beyond levels that can be achieved with other devices.

The basic argument against is that kite design is in its infancy, with much more R & D effort needed on take off, altitude control, landing and design for optimum overall performance. Southampton has conducted a pilot study in this field and the long term prospects look promising.

2. Windmill Ships

In theory, windmill ships can be sailed in three possible ways; as a windmill coupled to a water propeller, as an autogyro with no propeller coupling or as a water mill driving an air propeller. The first two modes have been demonstrated, but the third is believed to be unproven.

Numerous operational, financial and structural arguments have been given against windmill ships, but their uniquely-useful quality is an ability to propel a vessel directly into a head wind. This is done in the windmill/propeller mode shown in fig. 3a.

If the windmill is relied on as the sole means of propulsion, then with typical ship and wind speeds, disc areas are impractically large. Additionally, windmill drag adds to propeller disc loading, leading either to lower efficiency or a requirement for a larger diameter.

Actuator disc theory can be used to compute the power from a windmill in terms of an effective power coefficient (C_{EP}), ship speed/true windspeed ratio (a) and drag coefficient of the windmill (C_D). Such results are optimistic, but may be used to define performance limits for windmill ships. Specifically,

$$\text{Effective Power} = C_{EP} \cdot \tfrac{1}{2}\rho_a A C_D \cdot V_T^3$$

Into a Head Wind, $C_{EP} = C_D \left\{ \frac{\eta_D \eta_T}{2} (1+a)^3 \left[1 + \sqrt{1-C_D} \right] - a(1+a)^2 \right\}$

where A = windmill area; η_D = quasi propulsive efficiency

ρ_a = air density; η_T = Transmission efficiency

V_T = true windspeed

C_D = Disc drag/$\tfrac{1}{2}\rho_a V_T^2 A$

The absolute boundary of positive effective power is plotted on fig. 3b for η_D=.67 and η_T=.94. These efficiencies are probably higher than would be achieved in practice.

An examination of Fig. 3b shows that as 'a' increases, so the windmill needs to be operated at a lower drag coefficient. This amounts to saying that its relative performance in lighter winds will be much worse than in heavy and that maximum possible effective power will probably scale as V_T^4 or V_T^5, rather than V_T^3. Power could be improved by reducing ship speed, but that would run contrary to the basic aim of improving ship economics.

Impressions obtained from this and other studies are that the only proven justification for fitting a windmill is to have an ability to go dead to windward. What is usually overlooked is that windward effective power depends heavily on 'a' and for the majority of present wind/ship speeds, will be either absent or minimal. Motor-sailing ability looks depressing. Blackford recently completed a windmill/sail comparison and concluded that windmills could be recommended for fishing vessels when 'a' was less than .5. He did not recommend them for ships.

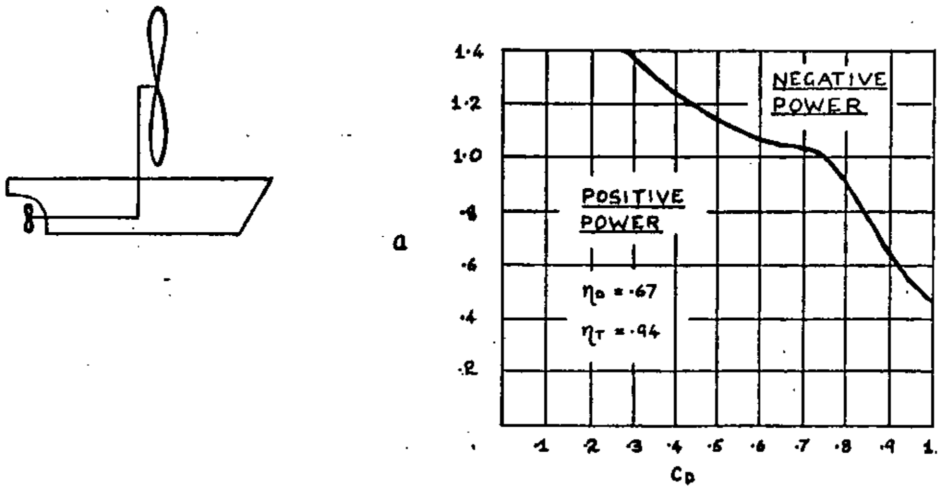
On other points of sailing the windmill can be de-coupled from the propeller and run in autogyro mode. In this way, it can be made to emulate the performance of an inefficient wing of similar dimensions to the disc area.

Impressions so far have related to previously-proposed methods of windmill operation and the future of this device for ships may be connected with current developments in energy storage. On downwind routes or at anchor, windmill energy could be stored for later use on passage. For the present, only specialist applications are envisaged.

Fig 3 WINDMILL SHIP PERFORMANCE LIMITS

a. SCHEMATIC DIAGRAM OF WINDMILL/PROPELLER COUPLING

b. 'OPTIMISTIC' PERFORMANCE LIMITS FROM ACTUATOR DISC THEORY



EXPLANATORY NOTE:

FOR A SHIP GOING INTO A HEADWIND, AN OPTIMISTIC ASSESSMENT OF THE ZERO-POWER BOUNDARY IS SHOWN IN FIG 3b. VARIABLE 'a' DENOTES SHIP SPEED/TRUE WINDSPEED RATIO AND 'C_D' IS A DRAG COEFFICIENT FOR THE WINDMILL, BASED ON DISC AREA.

3. Marine Aerofoils

The term 'marine aerofoil' has been coined as a generic phase covering sails, Flettner rotors, wingsails etc. These devices are more of a known quantity and a fuller background of theory and practice exists to predict their performance. Recent work at Southampton has concentrated on researching such devices for the purposes of ship propulsion, bearing in mind constraints such as cargo handling, limited deck space and the need for low-maintenance materials. These devices can be designed to work through most of the ship speed/true wind speed ratios encountered in practice, but unlike the windmill, do not go directly to windward and unlike the kite, are more limited down wind. They are however, operationally-feasible and lend themselves well to the harvesting of wind energy in a motor-sailing mode, on an opportunist basis. Limits to their usefulness come only from the lift/drag ratios of the rig and keel, which could be made as high as 50:1 in an extreme case. The principal interest lies in a sub-category which is typified by the original Flettner rotorship 'Bukau', and a linear theory has been developed to describe the fuel/speed performance of this type of device during passage. This was presented at a symposium in Florida during May '83 and was the result of a joint effort by the present author and Dr. James Mays of OceanRoutes Inc.

Concepts behind Linearised Theory of Sailing and Motor Sailing for high aspect ratio rigs.

Introduction

A number of linearising assumptions are made in the theory, which are justified in the case of a ship having a high aspect ratio rig and keel. In all other cases, modifications for non-linear effects need to be made.

The theory is in two parts. One concerns the force description of a sailing vessel and concludes that the performance of a given rig/hull/keel combination can be described in terms of just two variables. This is then related to speed and fuel saving. This part of the theory also forms the basis of an interactive computer program written to optimise rig/hull/keel initial designs as well as rig use.

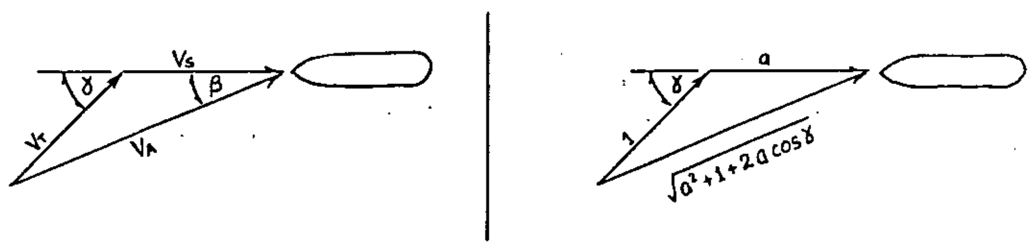
The second part concerns the combination of rig performance with weather data. Weather data has been used to form probability density functions for wind speed, related to direction, location, time of year etc. The basic premise is to combine rig/hull/keel/engine/propeller data with weather statistical data and come out with either a probable fuel saving (at known ship speed) or probable voyage time, under pure sail. Such figures represent statistical probabilities, like those used by insurance companies to fix premiums. Over a long period, performance should converge to these figures, enabling them to provide a basis for investment decisions involving wind assist devices.

Linear Theory Part I

A sailing vessel appears at first sight to involve a large number of different variables, from which no clear answer can be expected. Initially the problem is to reduce the number of variables to manageable proportions, which is achieved by the use of known relationships and new non-dimensional variables. This is illustrated in Fig. 4 for simple velocity triangles involving true and apparent conditions.

Fig 4 VELOCITY TRIANGLES

DIMENSIONAL | NON-DIMENSIONAL



V_S — SHIP SPEED

V_T — TRUE WIND SPEED

V_A — APPARENT WIND SPEED

γ — TRUE WIND ANGLE

β — APPARENT WIND ANGLE

$a - V_S/V_T$

$V_A - V_T\sqrt{a^2+1+2a.\cos\gamma}$

$\sin\beta = \sin\gamma/\sqrt{a^2+1+2a.\cos\gamma}$

$\cos\beta - (a+\cos\gamma)/\sqrt{a^2+1+2a\cos\gamma}$

In the non-dimensional form, use is again made of the non-dimensional speed variable 'a' which will be shown later to be of fundamental importance in understanding water/air interface problems. The combination of 'a' with trigonometry allows three speed vectors to be expressed in terms of 'V_T','a' and 'γ'. Similarly, the apparent wind angle (β) is expressed in terms of 'a' and 'γ'.

The next stage is to consider the lifting problem of the ship and keel. Gerritsma showed this could be thought of as an equivalent 'wing' problem, with the details tied in with slender body theory. Fig. 5 illustrates the concept and type of relationships that result.

Fig 5 EQUIVALENT LIFTING PROBLEM FOR KEEL

SHIP/KEEL — EQUIVALENT 'WING'

NOTES

1. INDUCED RESISTANCE (R_i) IS PRODUCED FROM KEEL LIFT.
2. PROFILE RESISTANCE (R_{oeK}) IS ASSOCIATED WITH KEEL AREA.
3. THE REFLECTION PLANE IS POSITIONED USING SLENDER BODY THEORY.

VARIABLES

AR – ASPECT RATIO
L – LIFT
R – RESISTANCE
S – AREA
ρ – DENSITY
C_L – LIFT COEFFICIENT
C_D – DRAG COEFFICIENT
k – INDUCED DRAG FACTOR

RELATIONSHIPS

$$C_{LK} = L_K / \tfrac{1}{2}\rho_S V_S^2 S_{eK}$$

$$R_i = \tfrac{1}{2}\rho_S V_S^2 S_{eK} \frac{k_K C_{LK}^2}{\pi AR_{eK}}$$

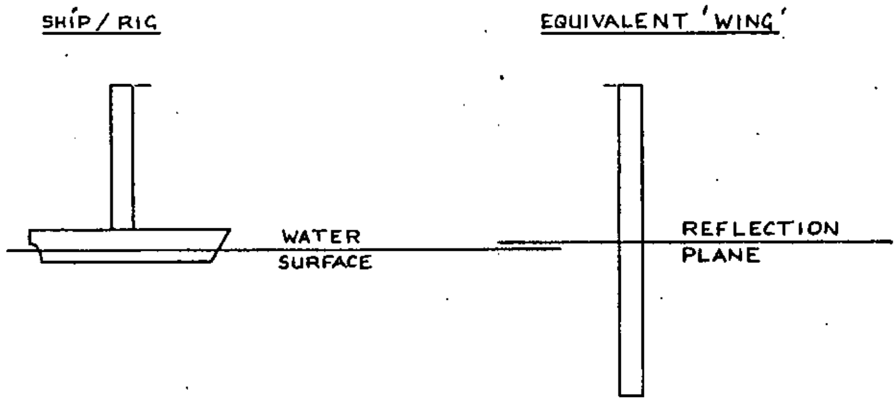
$$R_{oeK} = C_{DoeK} \cdot \tfrac{1}{2}\rho_S V_S^2 S_{eK}$$

SUFFIXES

e – EQUIVALENT
s – SEA
k – KEEL
o – PROFILE
i – INDUCED

Similarly, the high aspect ratio rig is reduced to an equivalent lifting problem. In practice, this is less well justified than for the keel and non-linear corrections involving $AR_{er}(a,\gamma)$ may be needed if the 'equivalent' problem depends strongly on apparent wind angle. For the high aspect ratio device assumed, the equivalent lifting problem for the rig is shown in Fig. 6.

Fig 6 EQUIVALENT LIFTING PROBLEM FOR 'RIG'



NOTES

1. FOR A RIG THAT IS TALL RELATIVE TO FREEBOARD AND FLUSH WITH DECK, SLENDER BODY THEORY INDICATES THAT WATER SURFACE AND REFLECTION PLANE ARE ALMOST COINCIDENT.
2. IN OTHER CASES, $AR_{er} = AR_{er}(a,\gamma)$, $K_{er} = K_{er}(a,\gamma)$
3. SEE FIG 5 FOR ADDITIONAL DEFINITIONS

RELATIONSHIPS

$$C_{Lr} = L_r / \tfrac{1}{2}\rho_a V_A^2 S_{er}$$

$$C_{Dr} = D_r / \tfrac{1}{2}\rho_a V_A^2 S_{er} = C_{Doer} + k_{er} C_{Lr}^2 / \pi AR_{er}$$

SUFFIXES

A – APPARENT
a – AIR
r – RIG

Next the ship upright resistance is expressed as

$$R_T = \frac{Ⓒ \, \pi \rho_S V_S^2 \nabla^{2/3}}{250}$$

where Ⓒ and ∇ have their usual meanings of ship resistance coefficient and volumetric displacement.

Finally it is required to find the fuel used by an engine in delivering the same effective power (EP) as a rig/hull/keel. An engine with a specific fuel consumption of SFC, coupled to a drive of transmission efficiency η_T, linked to a propeller of quasi propulsive efficiency η_D, produces power of $EP/\eta_T\eta_D$.

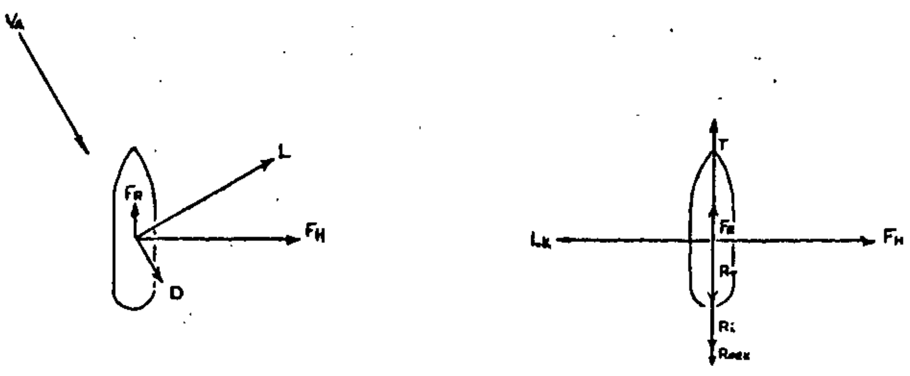
Fuel used equals SFC x TIME $\dfrac{X\ EP}{\eta_T\eta_D}$

This background to the individual components of the force balance of a motor-sailing vessel enables the complete problem to be drastically simplified. The force balance is shown in fig. 7, together with observations on the role of the rig/keel combination.

Fig 7 FORCE BALANCE OF A MOTOR-SAILING VESSEL

a) RESOLVE LIFT & DRAG INTO DRIVE & SIDE FORCES

b) COMPLETE FORCE BALANCE



OBSERVATIONS

1. NET DRIVING FORCE FROM RIG/HULL/KEEL IS $F_R - R_i - R_{oek}$
2. NET POWER FROM RIG/HULL/KEEL IS $V_S(F_R - R_i - R_{oek})$
3. NET EFFECT OF RIG/HULL/KEEL IS INDEPENDENT OF © BUT DEPENDS WEAKLY ON FREEBOARD AND DRAUGHT
4. EFFECTIVE DRIVE COEFFICIENT (C_{ER}) DEFINED BY:

$$C_{ER} = (F_R - R_i - R_{oek}) / \tfrac{1}{2}\rho_a V_T^2 S_{er}$$

5. EFFECTIVE POWER COEFFICIENT (C_{EP}) DEFINED BY:

$$C_{EP} = V_S(F_R - R_i - R_{oek}) / \tfrac{1}{2}\rho_a V_T^3 S_{er} = a.C_{ER}$$

Now the net effect of the rig involves the quantities F_R, R_i, R_{oek} and V_s. For a motor-sailing vessel, these quantities are independent of R_T and depend essentially on rig, keel, draught, freeboard, speed ratio (a) and true wind angle (γ).

Two new coefficients are defined, an effective drive coefficient (C_{ER}) and effective power coefficient (C_{EP}).

$$C_{ER} = (F_R - R_i - R_{oek}) / \tfrac{1}{2}\rho_a V_T^2 S_{er}$$

$$C_{EP} = (F_R - R_i - R_{oek}) V_s / \tfrac{1}{2}\rho_a V_T^3 S_{er}$$

Naval architects may use these coefficients during powering calculations to obtain the net drive or net power contributed by the rig/hull/keel combination.

For initial design purposes, changes in rig or keel can be investigated from:

$$C_{ER} = \sqrt{a^2+1+2a\cos\gamma}\,.\,(C_{Lr}\sin\gamma - C_{Dr}[a+\cos\gamma]) - C_{Doek}.\frac{\rho_s}{\rho_a}\frac{S_{ek}.a^2}{S_{er}} - \frac{K_k.(a^2+1+2a\cos\gamma)(C_{Lr}[a+\cos\gamma] + C_{Dr}\sin\gamma)^2.\rho_a.S_{er}}{\pi AR_{ek}.\rho_s.S_{ek}.a^2}$$

$$C_{EP} = a.C_{ER}$$

Fuel savings accruing from the use of a rig/keel are assessed from the power that would otherwise need to be provided by the engine, i.e.

$$\text{Fuel Saving} = \frac{\text{SFC.TIME.}C_{EP}.\tfrac{1}{2}\rho_a V_T^3 S_{er}}{\eta_T \eta_D}$$

where SFC, η_D etc are assumed not to change as a result of motor sailing. That particular assumption requires an efficient system of managing engine power and propeller pitch, and needs to be reviewed and possibly corrected for in almost every case. Good motor-sailing involves having a low SFC over a wide power range, which might be achieved with a multiple-engine arrangement. Other techniques can be used to keep the SFC low, such as running the engine at an efficient power level and accepting a change of ship speed. Optimum design and operating compromises are likely to vary widely and the formula given should be regarded as the maximum potential fuel saving from motor-sailing.

The main results to come from the theory are summarised as:

1. Under pure sail, speed performance can be defined in terms of 'a' and 'γ' within the range of constant ⓒ .

2. For a given rig/hull/keel combination under motor sail, the useful contributions to drive and power from the rig can be described in terms of non-dimensional coefficients which depend only on the two variables 'a' and 'γ'.

3. The theory provides a rational basis for the design and operation of both pure and motor-sailing vessels, with high aspect ratio rigs and keels.

4. Maximum potential fuel savings can be assessed directly from the useful net power contributed by the rig/hull/keel combination in specified wind conditions.

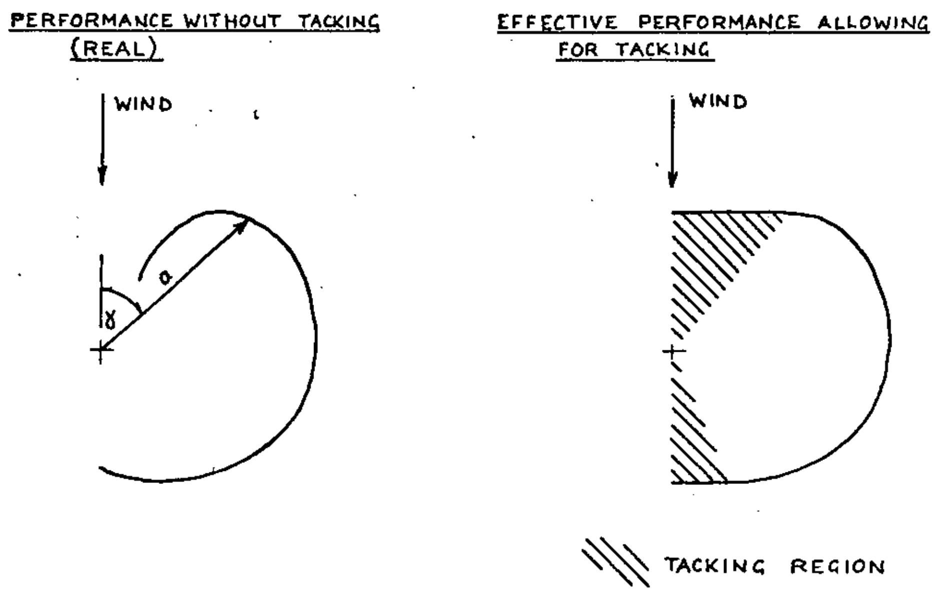
5. Corrections for heeling effects can be shown to be equivalent to a change in 'a' and 'γ'.

Linear Theory Part II

The second part of the theory is concerned with combining performance information with weather statistical information, to arrive at probable voyage times or fuel savings.

Performance polars need to be made realistic in the sense that they reflect the ability to tack and change rig lift and drag for optimal use. In the case of a pure sailing vessel, both the basic and effective performance polars are shown in Fig. 8, where the ability to tack is reflected by a positive value of 'a' going directly into wind.

Fig 8 REAL AND EFFECTIVE PERFORMANCE POLARS



EXPLANATORY NOTE:
FOR VOYAGE TIME AND FUEL SAVING CALCULATIONS, THE REAL PERFORMANCE POLAR IS REPLACED BY AN 'EFFECTIVE' POLAR WHICH REFLECTS THE CHOSEN TACKING ANGLES.

A similar change can be made to the $C_{EP}\sim\gamma$ polars and the tacking angle chosen to maximise any objective function. In the cases, examined, the tacking angle was chosen to maximise fuel saving, but minimum cost or some other criteria could also have been used. Such 'effective' polars of $C_{EP}(a,\gamma)$ and $C_{ER}(a,\gamma)$ will be understood to apply to all of the following work.

Weather information needs to be introduced, and this is done by constructing probability density functions(pdf) of wind speed and direction from records spanning many years. This is defined by:

$$\int_0^\infty \int_0^{2\pi} pdf(V_T,\theta)d\theta dV_T=1$$

and it is understood that:

$$pdf = pdf(V_T,\theta,\text{location, time of year etc})$$

$$\theta = \text{wind direction}$$

$$\theta_1 = \text{track}$$

$$\gamma = \min\{|\theta-\theta_1|,2\pi-|\theta-\theta_1|\}$$

For a pure sailing vessel, the expected speed (V_{ps}) is given by

$$V_{ps}= \int_0^\infty \int_0^{2\pi} V_T.a(\gamma)pdf(\gamma,V_T)d\gamma dV_T$$

This needs to be evaluated at a number of places over the intended track and divided into a related segment of distance to obtain a time increment. Summing such time increments gives an expected voyage time.

For a motor sailing vessel, operating at a known speed, along a track of length D, the expected fuel saving (F_p) is given by:

$$F_p = \int_0^D \int_0^\infty \int_0^{2\pi} \frac{pdf(\gamma, V_T).C_{EP}(a,\gamma).\frac{1}{2}\rho_a V_T^{\,3}.S_{er}.SFC.d\gamma.dV_T.dD}{V_s \eta_D \eta_T}$$

Once again the route is segmented and the inner double integral evaluated at a number of locations along the track. Summation of segment fuel savings gives the final fuel saving F_p.

This technique does not allow for improvements due to weather routeing or other tactical manoeuvres. At present, the question of deciding what proportion of the potential fuel saving is removed by marine engineering difficulties must be left for assessment on an individual basis. Within these constraints, figures have been computed for an SD14 cargo ship with a powerful rig and keel on a hypothetical voyage Tampa-Southampton-Tampa. The speed assumed was 14 knots and fuel savings computed appropriate to the month in which the voyage was made. Details are shown in the Table.

SD14 CARGO VESSEL FITTED WITH POWERFUL TALL RIG AND KEEL, GOING TAMPA-SOUTHAMPTON-TAMPA AT 14 KTS

Month	Fuel Saved Tonnes	Av Wind Speed kts
Jan	366.7	18.6
Feb	365.9	18.6
Mar	343.4	17.4
Apr	307.6	15.6
May	248.5	13.4
June	215.4	11.9
July	192.6	10.9
Aug	203.1	11.5
Sept	258.1	13.6
Oct	310.0	15.7
Nov	340.6	17.2
Dec	359.0	18.1

These figures should be regarded as potential fuel savings which are likely to be attained after wind powered ships have been in service for some time, the initial design problems resolved and the rigs used to full advantage. Note that the ship speed used was a constant 14 knots and there are no adverse implications for voyage times as a result of using the rig.

For the case examined, with oil at £120 per tonne, average fuel savings at around 300 tonnes/voyage and ten voyages per year, the annual savings amount to £360,000. That represents the maximum available for debt servicing, depreciation, operation and maintenance costs of the rig/keel.

Final points to be made are:

1. The historical evolutionary approach to motor-sail design and fuel saving assessment is inappropriate for large vessels. The present work offers a realistic alternative as well as the possibility of evaluating 'revolutionary' devices.

2. The theory can be used to set cost-design objectives for the development of new forms of wind-assist device.

3. For windpowered ships, the usefulness of the speed ratio variable 'a' has not been properly appreciated in the past. Simplifications arising from its use have resulted in the present linear theory as well as a positive definition of performance boundaries for windmill devices.

Acknowledgements

The author would like to acknowledge financial support from the Wolfson Foundation, academic support from members of the Department of Ship Science, Southampton University and the valuable assistance of Dr. James Mays of OceanRoutes (Inc) with ocean climatology.