PROPOSAL OF A SAIL SYSTEM FOR THE PROPULSION OF A 25.000 TDW BULK-CARRIER

by

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ABSTRACT

Applications of sail propulsion for a 25.000 tdw Bulk-carrier are examined.

A program of calculations is developed to ascertain the performances of a system of sails at different wind forces and different angles of attack.

Performances are studied assuming as sail profiles either a curved plate or NACA symmetrical profiles. Applications of fabric sails are examined.

The possibility to eliminate the leeway is also investigated, by use of trimming keels.

Finally a typical voyage has been assumed and performances of many sail plans are calculated and compared.
1. INTRODUCTION

Among the possible applications of sails to ship propulsion, we have thought it convenient to investigate the use of sails on a bulk-carrier of the following dimensions:

- Length (Lpp) 168 m
- Length (Lwl) 176 m
- Breadth 22.90 m
- Draft 10.20 m
- Displacement 32.100 t
- Deadweight 25.300 t
- Block coefficient 0.78

A ship as above is usually fitted with a 10,000 ÷ 11,000 HP engine and her speed (at trials) would be about 17.5 knots.

The aim of our investigation is to ascertain what valuable fuel economy can be realistically expected by equipping the ship with a wind propulsion system.

To this purpose, following the current tendency of research, we have given the vessel a cruise speed of 14 knots and we intend to study what contribution could be obtained by a sail system under such conditions. In other words, we have chosen the solution of a "sail-assisted" ship and we are interested to see, in all possible wind conditions, the thrust required by the propeller to maintain the speed of 14 knots.

A reduction of propeller thrust will correspond to any increase of sails driving force, but the 14 knots speed will be kept.

In order to have a better understanding of the sail efficiency, some other conditions will also be taken into account, such as speeds lower than 14 kn or increase of speed due to wind when propeller thrust is kept constant.

2. FORCES DIAGRAM

A ship at sea with sails and engine is a hydrodynamic/aerodynamic system as shown in Fig. 1. For the equilibrium it is necessary that both the resultants of forces along X and Y are zero.

\[
\begin{align*}
T \sin \gamma &= A_y (\omega, a) - L_h (\gamma) - L_f (\delta) \\
T \cos \gamma &= R_o + R_h (\gamma) + R_f (\delta) - A_x (\omega, a)
\end{align*}
\]

As a first approach we shall forget the effect of moments, and in particular the yawing moments. In practice the aerodynamic wind force acting on the sail and the hydrodynamic force acting on the hull due to the leeway could give rise to a yawing moment to be compensated by rudder. For reasons that will be explained further on, we shall neglect the rudder action and therefore the Rr force.

If the vessel is fitted with trimming fins it would be possible to compensate the whole leeway and in that case not only the above assumption would be true, but also Rhx and Rf will be zero.

We shall also neglect the action of waves, supposing the vessel proceeding in smooth sea. Furthermore due to the small sail area compared to the ship dimensions, heeling action will not be taken into account.

Of course for large sail area and strong winds the condition would be imposed that list of vessel
would not exceed a certain value (for ex. 10 deg) and therefore we should calculate in which conditions reefing would be required.

3. EQUATIONS OF EQUILIBRIUM

We can write equation (1) in the following form

\[ Ay \langle w_a, a \rangle - Lh \langle \gamma \rangle - Lf \langle \beta \rangle = \left[ Ro + Rhx \langle \gamma \rangle + Rf \langle \beta \rangle - Ax \langle w_a, a \rangle \right] \tan \gamma \] (2)

and its solution is found using a computer program, flow diagram of which is shown in Fig. 2. We can consider the vessel with fin or without.

Case A - without fin

Equation (2) will be simplified as

\[ Ay \langle w_a, a \rangle - Lh \langle \gamma \rangle = \left[ Ro + Rhx \langle \gamma \rangle - Ax \langle w_a, a \rangle \right] \tan \gamma \] (3)

For any couple of values \((w_a; \omega)\) that we introduce in the computer, considering already known:

- \(e\) (air and water density)
- \(S_a\) (sail area)
- \(V_h\) (hull velocity)
- \(V_w\) (wind velocity)
- \(H_a\) (hull projected area)
- \(R_o\) (resistance of hull at given \(V_h\))

![Fig. 1 - A ship proceeding under sail is subject to aerodynamic forces (right) and hydrodynamic forces (left).](image)
Fig. 2 - Computer program flow diagram
we get, by use of a velocity triangle, the vector of apparent wind and therefore the components \( A_x; A_y \).

Consequently equation (3) will have \( \gamma \) only as an unknown variable, through the functions

\[
Lh(\gamma) ; \quad Rhx(\gamma) ; \quad \text{tg}(\gamma)
\]

The solution will give the angle \( \gamma \) of leeway.

Case B - with fin

In this case two further data will be put into the computer

\[
Fa \quad \text{(fin area)}
\]

\[
\text{Polar of fin}
\]

Furthermore, besides the couple \((\omega_w;\omega)\) already mentioned, the value of \( \beta \) must be given.

The calculation will proceed as previously said, since here also the only unknown variable is \( \gamma \), having the computer calculated both \( Lf(\beta) \) and \( Rf(\beta) \).

As an alternative we can omit indicating \( \beta \) and instruct the computer to scan different \( \beta \) values, selecting the one able to fully compensate the leeway, i.e. the \( \beta \) value that makes \( \gamma = 0 \).

In any case (with fin or without fin) once \( \gamma \) is known, we obtain \( T \) value from eq. (1), that means we know the thrust to be supplied by the propeller to keep the 14 kn speed, with a true wind velocity \( V_w \) in the given conditions \((\omega_w;\omega)\).

We can instruct the computer to find, for every \( \omega_w \) of true wind, the best sail trimming \( \omega \) to get the highest driving force. In this way the best results are achieved for the couple \( V_h \) and \( V_w \) i.e. the highest thrust reduction under those conditions.

Repeating the calculation for other values of \( V_w \) a complete chart can be obtained showing all ship performances and particularly the \( T \) thrust, at 14 kn speed and under all wind conditions.

4. CASE OF CONSTANT THRUST

As a complement of the former case, we have also investigated the sail performance when the thrust \( T \) is kept constant and we take advantage of sail driving force increasing the ship speed.

In practice what is kept constant is the engine output and therefore the thrust will be influenced by wake effect which in its turn is function of ship speed. Nonetheless for simplicity we shall carry out our calculations assuming \( T = \text{const} \).

The aim of this second investigation is to ascertain what saving can be had by sails using, not in terms of fuel saving but in terms of time saving, because keeping constant speed and reducing thrust is not always a profitable policy.

This is evident at low engine outputs, if revolutions must be decreased below normal rate.

The program still start from equations (1) and inputs are still \((\omega_w;\omega)\) but initial given data are slightly different and namely :

\[
\begin{align*}
\varrho & \quad (\text{air and water density}) ; \quad \text{Polars of hull and sail} \\
V_w & \quad (\text{wind velocity}) ; \quad \text{Ro} \quad (\text{resistance of hull, function of } V_h) \\
Ha; Sa & \quad (\text{hull and sail area}) ; \quad \text{To} \quad (\text{propeller thrust, given value})
\end{align*}
\]
The calculations begin by assuming a tentative hull velocity $V_h$ and a corresponding $R_o$. Then, through velocity triangles $A_x$ and $A_y$ are deduced. As in the case of $T = \text{const}$, also here the only variable to be calculated is $\gamma$.

Known this latter, $T$ can be calculated using eq. (1) and its value is compared with $T_0$: their difference, with sign, indicates in what sense $V_h$ must be altered for the next iteration.

Eventually, for the given thrust $T_0$, we can calculate $V_h$ for any wind condition.

5. POLAR CURVES OF HULL

The behaviour of a hull proceeding under leeway, as shown in Fig. 1, is similar to that of a low-ratio wing section.

Unfortunately not many reports have been found concerning this subject and furthermore they often give results quite different from each other and at any rate hardly comparable.

Wagner (1) and Smith & Chisbitt (2) have carried out tests on a Mariner class hull; Welnicki (3) and Martin (4) on hulls of different types. In our uncertainty we have deemed more convincing the results of Welnicki who gives lift and drag coefficients fairly similar to those given by Wagner, even referring to a different type of hull.

Of course, in a more accurate approach it would be necessary to measure in a towing tank the coefficients of the real hull.

Another uncertainty is the position of the center of hydrodynamic forces, that is the point of application of forces $L_h$ and $R_{hx}$. For this purpose we have referred to the tests of Welnicki who gives positions of hydrodynamic center fairly comparable with data known from wing sections and thin plate behaviour.

It can be seen that it is possible to arrange the sails so as to have the $A_x$ component of aerodynamic force and the $L_h$ component of hydrodynamic force in equilibrium without giving rise to a yawing moment.

In this condition the ship will proceed along the $X$ direction without the need of rudder corrections. In the present study this approximation has been assumed and rudder forces neglected.

Fig. 3a shows $C_x$ and $C_y$ curves versus $\gamma$ angles, and Fig. 3b shows $R_o$ curve versus $V_h$ velocity.

![Hull Polar Curves](image1)

![Hull Towing Resistance](image2)
6. SAIL PLANS

Since so many proposals have been put forward in recent years, we have deemed it useful to extend our investigation to some typical sail plans.

First we have selected the following profiles:

A - Curved thin plate, with f/c = 1/6.66 supported by a circular section mast
B - NACA profile 0018
C - NACA profiles 0012 and 0015
D - NACA profile 0018 with 30% flap

In addition also a square rig has been considered, assuming the results reported by Bernaerts and Kurmis (5)

E - Square fabric sail

Clearly, solutions A and E have no aerodynamic pretence, but they recommend themselves for their simplicity and economy. It is not by chance that sail fitted ships actually in service have adopted solutions of this kind. On the other hand, for a first experience we would not propose sophisticated solutions.

Another important choice is that concerning the aspect ratio.

Having previously decided to investigate mainly the sail-assisted ship, cruising at the constant speed of 14 knots, it is expected that in light or medium winds, the ship will sail close to the wind most of her time since the angle between apparent wind and true course will be prevailingly small.

In these conditions it is known that an aerodynamic profile is more efficient when its aspect ratio is higher. Conversely a high aspect ratio requires higher masts with all relevant aero-elasticity problems. At the end this will require a higher cost.

It is therefore advisable to investigate low values of A.R. as well, considering that this solution has been chosen for the existing ships.

For the same reasons an investigation has also been carried out for constant speed lower than 14 kn.

In our study we have taken into account three typical A.R.

1; 2.5; 5

and have considered the following couplings between sail plans and aspect ratios.

A 5
B 1; 2.5; 5
C 2.5; 5
D 2.5; 5
E 1.25 as proposed in ref. (5)
Polar curves of sails have only been deduced analytically. In a next stage of our investigation we intend to carry out systematic tests in the wind tunnel with models similar to the one shown in Fig. 4.

Comparisons with available experimental data have been made, but confined to a range of angles of attack of aeronautical interest i.e. from zero to the CLmax angle. From here to the 90 deg angle the investigation has been performed analytically, according to (6) and (7).

Three profiles have been studied, NACA symmetrical 0012, 0015, 0018. The latter has been selected due to its higher thickness ratio which better complies with the need of containing the mast inside. Also its stall of the "trailing edge" type has influence our choice.

Profiles 0012 and 0015, compared to 0018 have one advantage only, having CDo lower by 13% and 11% but such a benefit disappears at rising angles of attack. Conversely they have lower CL and CLmax and 0012, furthermore, has a poor stall type.

As far as shape is concerned, we have considered it rectangular, unswept and not tapered. Area has been fixed at 500 sqm and three geometrical aspect ratios have been considered:

<table>
<thead>
<tr>
<th>Aspect Ratio</th>
<th>Chord</th>
<th>Reynolds Nr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>22.36 m</td>
<td>2.05x10^7</td>
</tr>
<tr>
<td>2.5</td>
<td>14.15 m</td>
<td>1.3 x10^7</td>
</tr>
<tr>
<td>5.0</td>
<td>10.00 m</td>
<td>0.92x10^7</td>
</tr>
</tbody>
</table>

with an assumed 30 knots relative wind speed.

We have neglected the effect of deck proximity, since we would recommend a clearance of 2x3 meters to allow free crew transit on the deck. Of course, if this limitation could be waived, the effective aspect ratio would rise and performances improve.

Due to the high Reynolds number and to the surface conditions, flow has been taken as completely turbulent. Since the sail is sufficiently high above sea level, the wind velocity has been assumed as constant along the height of the sail.

For the flapped wings we have selected a 30% plain type flap, spanning the whole length of the wing, with sealed gap and 30 deg. as max angle of deflection. Envelope polars are shown in Fig. 5, non-linearity of increase of CL at rising flap deflection has been considered, owing to the viscous separation effect.

In the case of curve plate, polars have been assumed from (8) also considering the additional drag caused by a 2m diameter mast, in the range up to CLmax. In the case of square rig, polars were assumed from (5). All polars are traced in Fig. 5.
Fig. 5 - Polar curves of different rigs.
Marks are set at 10; 20; 30; 50; 70 deg of angle of attack
8. TRIMMING FINS

Compared to sailing ships of a century ago, modern ones have two great advantages

- a) higher rig efficiency
- b) higher hull efficiency

As far as a) is concerned, undoubtedly modern knowledge of aerodynamics allows for the study of wing sections that is no way can be compared to the square rig of the past century.

As far as b) is concerned, notwithstanding modern hulls are much better designed in respect to resistance to propulsion, it is not sure that the same has occurred in respect of resistance to leeway.

Still, with actual knowledge we are able to fit the hull with fins that, automatically trimmed, could supply a windward force to compensate leeway completely.

Apart from fitting and maintenance costs, we have considered of some interest an investigation about a theoretical advantage that could be obtained by such a device. Two vertical fins are fitted below the hull bottom (Fig. 6) and balanced in such a way as to give rise to windward forces without yawing moment.

![Fig. 6](image)

The angle of attack $\gamma$ must be found in correspondence to which leeward forces are fully compensated.

To evaluate real advantages in respect of propulsion (thrust reduction) the two resistances must be compared:

1) Resistance of hull, without fins and therefore under leeway. Such resistance has been previously indicated as $R_{hx}(\gamma)$.
2) Resistance of hull with fins and therefore under straight course. Such resistance is given by component $R_f(\gamma)$.

Calculations have been made using a profile NACA 0018 either for the sails or for the fins with A.R. respectively 5 and 6. Besides, the following conditions have been established:

| Sail area | 3000 sqm |
| Ship speed | 14 kn |
| Wind speed | 10, 20, 30 kn |
| Fin area | 15, 25 sqm |

Results are reported in Fig. 7 where thrust reductions are traced versus true wind angle.

We see first that a small fin area (15 sqm) needs greater angles to withstand leeway and this produces high resistance. Differences between bare hull and hull with fin are greater at higher wind speed.
Fig. 7 - Comparison between hull without fins and with 15 or 25 sqm fins. Performances are expressed in thrust reduction versus true wind angle at three different wind speeds.
A further calculation has been made with improved fin area (25 sqm) and winds of 20 and 30 kn. In these conditions the presence of fins involves a remarkable deduction of thrust, particularly sailing in the wind from 30° to 80° of true wind.

Contribution of fins is then higher when sailing close to high velocity winds. Attention must be paid to the fact that in our examples we have used large sail area with high A.R., much greater than what could reasonably be accepted on an experimental ship.

Vice versa, with low A.R. sails, when wind propulsion is likely to be used mainly when sailing off the wind, such a device would not be profitable, also considering its high cost and its structural complications.

9. SAIL STRUCTURE

The sail structure has been designed bearing in mind the aeronautic wing construction. A light alloy box is fitted strong enough to withstand the acting forces on the sail; leading edge, trailing edge and flap if any are made of fiberglass sandwiches with non-metallic honey comb core.

The wing box is composed of an outer skin and front and rear spars. In addition, to withstand the bending moments, there are skin stringers, supported by frames fixed to the front and rear spars.

The sail is connected to the ship by means of a mast and a complete revolution is allowed due to suitable bearings. A hydraulic jack (or similar device) will set the profile at the requested angle of attack for any condition of wind.

In case of excess of wind speed (or when we prefer to have the sails feathering) the sail will be released and left free to rotate. To this purpose the pivot axis should be located forward the sail center of pressure.

In a preliminary study we have assumed a profile NACA 0018 with A.R. = 2.5 under a design wind of 50 knots and have considered a scantling for a 500 sqm area with fully deflected flap.

The calculated weights are approximately

<table>
<thead>
<tr>
<th>Sail (and rotating parts)</th>
<th>5500 Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast (and fixed parts)</td>
<td>7500 Kg</td>
</tr>
</tbody>
</table>

Since wing sails have been shown to be subject to flutter problems (9) either for fixed wing (operating mode) or for free wing rotation around its pivoting axis (feathering mode), a preliminary aeroelastic analysis has been performed (10).

The proposed sail structure, due to its high torsional stiffness and relatively small weight, has a critical value for the classical flexural-torsional flutter speed over 200 knots.

To overcome the flutter problems for free wing rotation (feathering mode) the hinge point between sail and mast should be located at 15% of the chord, from the leading edge. This solution, together with the relative low wing weight, ensures a high flutter speed in feathering mode too.

Further studies are being carried out, either on classical flexural-torsional flutter, or on feathering mode flutter, relying on experimental results obtained on profiles and bridge sections (11).

Other problems not to be forgotten are concerned with the gust response of sails associated with ship motion (rolling and pitching).
10. CALCULATIONS OF THRUST REDUCTION

Since the number of variables taken into account was very high, it has not been advisable to show the results of all their possible combinations.

We have only reported some of the results deemed more interesting. The conditions are listed below and all have been scanned at three wind velocities: 10, 20, 30 kn.

<table>
<thead>
<tr>
<th>Profile</th>
<th>A.R.</th>
<th>Sail area sq m</th>
<th>Ship speed kn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curved plate</td>
<td>5</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td>NACA 0018</td>
<td>1</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>1000</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td>Do.with flap</td>
<td>2.5</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>3000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td>Square rig</td>
<td>1.25</td>
<td>1000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>1000</td>
<td>12</td>
</tr>
</tbody>
</table>

The results, shown in Figs. 8 to 11, can be briefly commented.

- For low values of A.R. no great difference appears between good and poor aerodynamic design.
- The improvement of performance due to good aerodynamic design can be appreciated mainly when sailing close hugging.
- When sailing off the wind, the choice of profile has scarce influence; what could be easily expected being the performance influenced by drag coefficients only.
- Decreasing the ship speed makes poor aerodynamic solutions more attractive. This is due mainly to the fact that lower ship speed produces greater angles of apparent wind.
- With A.R. = 5 the curved plate appears to be even better than an aerodynamic profile (except when close hugging) provided the latter is not fitted with flap.
Fig. 8 - Thrust reduction versus true wind angle at three different wind speeds. High aspect ratio curved plate is more effective than aerodynamic wings except when close hauling.
THRUST REDUCTION

Fig. 9 - The flap substantially improves performances. Low aspect ratio wings are more attractive at lower Vh (ship speed).
Fig. 10 - Square rigs are competitive when reaching or sailing off the wind. This is more evident at lower ship speed.
Fig. 11 - Great thrust reduction can only be expected with high aspect ratio flapped wings and with large sail area.
11. CALCULATIONS OF SPEED INCREASE

From the results shown in the above paragraph we see that in the following conditions:

- Flapped NACA 0018 A.R. = 2.5 Sa = 3000 sqm
- Flapped NACA 0018 A.R. = 2.5 Sa = 1000 sqm
- Flapped NACA 0018 A.R. = 5 Sa = 1000 sqm

the reduction of thrust is over 50% and in some cases over 100%.

When this occurs, we have preferred to use the constant thrust program and results are reported in Fig. 12.

We have imposed the condition that below 70% of thrust, the ship will proceed at a constant 14 knots speed. Exceeding this value, the propeller thrust will not be further decreased and the sail drive will be used to improve ship speed.

Therefore in Fig. 12 the thrust reduction diagram shows a flat stretch at 70% in correspondence of which the ship speed diagram will not be 14 kn but a higher value, according to the sail drive.

12. EXAMPLE OF A TYPICAL VOYAGE

In order to make a better comparison of all types of sail plans and ship speeds, we have imagined to have our vessel sailing on the voyage Melbourne-Bishop's Rock following in the wake of the old "Great Britain".

This remake, suggested by Willoughby (12) has been done resuming the weather conditions as reported in ref. (5). Furthermore we have analized the return voyage supposing that the same wind would be met in the same place but with 180° rotation, (what is not strictly true).

<table>
<thead>
<tr>
<th>Voyage days</th>
<th>True wind angle</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>at 14 kn</td>
<td>at 12 kn</td>
<td>Northbound</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>150°</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>160°</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>170°</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>55°</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>160°</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>180°</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>60°</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>110°</td>
</tr>
</tbody>
</table>

In the histograms of Fig. 13 we have reported the example of one round trip, illustrating the thrust reduction obtained day by day. The complete list of results is reported in Fig. 14 where 21 conditions are examined. In some of them (3; 4; 5) when thrust reduction exceeds 100%, we have calculated the average reduction taking into account no more than 100%, which means that no speed increase has been considered.

In the last column we have indicated the voyage days under sail, omitting those days in which thrust reduction was under 1%.
In these examples propeller thrust is kept constant at 70% whenever sail driving force exceeds 30% of thrust. Concurrently ship speed rises over 14 kn.
Fig. 13 - Histograms showing thrust reduction day by day during the Melbourne-Channel-Melbourne 102 days round trip. Average reduction is 27.04 Northbound and 24.99 Southbound. Ship speed is kept constant at 12 kn.
Furthermore, when curved plate or square rig are concerned, we have imagined that with contrary winds they would be folded or lowered. In practice, in conditions 14; 16; 17; 18; 21 for thrust reduction less than zero we have imagined no sails aloft and resistance produced by mast drag only.

Some comments could be made about Fig. 14:

- With 3000 sqm sails the advantage would be higher than that shown, because speed increase has not been considered. For instance, during 8 or 10 days wind conditions are such as to give a sail drive higher than the propeller thrust and sometimes (condition 5) even two times higher. In these cases a better picture can be obtained from Fig. 12.

- Comparison between flapped and unflapped profiles makes it evident that the former are definitely superior. Considering conditions 9; 12; 18 for instance, we see that using NACA profile without flap is not worth while, as it gives the same performances of the square rig.

- The use of fins is not a determining factor, but in any case it is more beneficial at lower ship speed or with better aerodynamic profiles.

- It is confirmed that with low ship speed non-aerodynamic profiles (curved plate or square rig) could be taken into consideration and in this case their simplicity and low cost must not be disregarded.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sailing area sqm</th>
<th>Ship speed kn</th>
<th>Thrust reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Melbourne Channel</td>
</tr>
<tr>
<td>1</td>
<td>3000</td>
<td>14 12</td>
<td>5 5 5 1.25</td>
</tr>
<tr>
<td>2</td>
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<td></td>
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<tr>
<td>3</td>
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<td>4</td>
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<td>5</td>
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<td>6</td>
<td>1000</td>
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<td>7</td>
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<td>X X</td>
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<td>X X</td>
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<td>X X</td>
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<td>18</td>
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<td>X X</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>500</td>
<td>X X</td>
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<tr>
<td>20</td>
<td></td>
<td>X X</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>X X</td>
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</tbody>
</table>

Round trip length: At 14 kn = 88 days At 12 kn = 102 days

Fig. 14 - Comparison of results achievable in the Melbourne-Channel-Melbourne round trip in different conditions.
SYMBOLS

X  = direction of true course
Y  = normal to X
Ax, Ay = components of A; aerodynamic force on sail
L, D = lift and drag of sail
CL, CD = lift and drag coefficients of sail
T = thrust (propeller)
Lf, Rf = lift and resistance (drag) of fin
Ro = resistance of hull when proceeding straight (towing tank data)
Rhx = increase of hull resistance due to leeway
Lh = lift of hull due to leeway
Rr = hydrodynamic force on rudder
γ = leeway angle
β = angle of attack of fin
α = angle of attack of sail
ωa = angle of apparent wind
ωw = angle of true wind
Sa = sail area
Ha = hull projected area (Lwl . draft)
Fa = fin area
Vh = hull velocity
Vw = true wind velocity
ρ = density
Chy, Chx = lift and drag coefficients of hull ; \( C_{hy} = Lh/Vh^2 \); \( C_{hx} = Rhx/Vh^2 \)

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