SAIL ASSIST DEVELOPMENTS 1979-1985

by

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ABSTRACT

Wind Ship commenced intensive research on wind propulsion for ships in early 1979. The Company's 1981 comprehensive research report to the U.S. Maritime Administration entitled "Wind Propulsion for Ships of the American Merchant Marine" identified the rigs with best potential for early commercial development and developed a conceptual design for a 20,000 DWT motor ship with auxiliary wing sails. Wind Ship has now developed and tested at sea a 3,000 ft² soft sail cat rig and also designed a 3,000 ft² Wing Sail based on the principle of feathering (without flutter) as a means of reefing or furling. The wing sail's flutter inception, gust response and operating gear have been tested on a 300 ft² model using a fully instrumented test stand. Wind Ship has also extensively tested a 90 ft² Magnus Effect rotor at sea. The results of these testing programs and the conclusions reached are discussed, along with Wind Ship's performance, economic and aeroelastic models.

The merits of other high lift rigs such as the Walker Wing Sail and Cousteau TURBOSAIL are discussed. The need for accurately predicting performance at sea and economics of various rig alternatives is discussed. Wind Ship's approach to such analyses is described. A summary of results from the analyses of a variety of commercial vessels and oceanographic vessels including SWATH type ships is presented. Overall economic, market, environmental and political factors are discussed.
"Sail-assist" is a term coined by Wind Ship to describe the portion of the wind propulsion spectrum (Figure 1) in which most of the ship's propulsive power is generated by the engine driving a screw propeller, and sail power is used as an auxiliary, to save fuel and/or increase speed.

The technological and economic aspects of operating in various regions of the sail-assist spectrum were exhaustively investigated by Wind Ship commencing in 1979. The culmination of this work is represented by a 1981 report prepared for the U.S. Maritime Administration (MARAD). A synopsis of that work is included as Appendix A hereto.

The main findings of the report based on $20/bbl. Arabian crude were:

- A properly engineered automated sailing rig requires no additional manning and is an economically advantageous propulsion system when used in conjunction with conventional screw propulsion.

- Of the hardware alternatives examined in the study, wing sail rigs offer the greatest potential for simplicity, reliability and cost effective performance. An unstayed cat rig was rated as having the next greatest potential for early commercialization, taking high marks for simplicity and reliability. The Flettner, or Magnus Effect rotor was also cited as having great potential subject to further research and development.

- Sail-assist ships, with only fractionally smaller power plants than conventional vessels, will not experience the operational difficulties in maneuverability and reliability associated with pure sailing vessels.

- Sail-assist offers fuel savings of 20% to 30% (less for retrofits).

- A properly designed sail-assist ship can be built for approximately the same cost as an equivalent conventional motor ship.

- Existing motor ships can be retrofitted with sail because sail-assist is effective on conventional hull forms (since the thrust of the propeller was found to offset the induced drag created by the auxiliary rig).

- Pure sailing ships are uneconomical even if the price of fuel were to quadruple from $20/bbl. to $80/bbl.

While the study addressed ships of 1000 to 40,000 DWT the findings are also considered valid for both larger and smaller ships than those dealt with in the report. The body of this paper will confirm that the MARAD report findings have not been invalidated in the 4 years subsequent to their publication.

The conclusions of the MARAD report encouraged Wind Ship to continue research and development in the field of sail-assist. In collaboration with Ceres Hellenic Shipping Enterprises, Ltd., Wind Ship designed two 3000 square foot rigs to provide direct comparative results between the unstayed cat rig and the wing sail. The cat rig was installed aboard the M/V MINI LACE, a 3100 dwt general cargo ship in August 1981. Owner's records over 18 months showed a cut in the daily fuel rate of 24% and an increase in average speed of 5% - without throttling back. On one particularly favorable sailing route - New Orleans to Jamaica - the fuel savings came to 36% with an 18% speed increase. The 3000 ft² wing sail was not built but development of the wing sail also proceeded with the construction and testing of a 1/3 linear scale model of the 3000 square foot design and a subsequent redesign of the original 3000 sq. ft. rig - both of which are described in this paper.
INTRODUCTION

An instrumented 90 ft\(^2\) rotor was extensively tested at sea in 1983 and design development is continuing.

The primary areas of application for Sail Power Units (SPUs) at present are new buildings and existing vessels with service speeds of up to 18 knots and up to 100,000 dwt in size. Production designs of these three types of rigs have been developed in the sizes required commercially and are available. The rotor appears to have the greatest potential over the broadest ship size spectrum: 18 tons to 100,000 DWT. Liquid bulk carriers are the simplest ships to apply sail-assist to, and container ships the most difficult, but compatibility with shipboard or shoreside cargo handling gear is achievable on almost any ship. Some specific applications are addressed in Chapter IX of this paper.

The objectives of this paper are:

- To contribute Wind Ship’s sail-assist research findings to the marine community
- To evaluate the present ‘state of the art’, and hopefully,
- to educate shipowners and naval architects in general as to the potential for and limitations of sail assist.

The paper is organized in the following sections:

I Introduction
II Flettner’s Prior Research
III Wind Ship Basic Research
IV 3000 ft\(^2\) Cat Rigs
   : Design, construction & resting in commercial service
   : Correlation of modeled performance with actual performance at sea
V Wing Sail Research, Development & Design
VI Magnus Rotor Research Test & Evaluation
VII Ship & Rig Design Considerations
VIII Performance Comparison of Alternative Rigs at Large Scale
IX Performance and Economic Modeling of Rigs for Selected Ship Applications
X Overall Economic Market & Political Factors.
XI Recapitulation
II FLETTNER'S PRIOR RESEARCH

The first comprehensive research known to the authors on modern lift generating devices for auxiliary ship propulsion was done by Anton Flettner commencing in 1922.[2] Flettner, an aeronautical engineer, had previously invented the concept of a trim tab rudder both for aircraft and oceangoing ships. The trim tab auxiliary rudder, when deflected in the ship's wake, produced the power to turn the main rudder. His work on rigid airfoils was carried out at the Aerodynamic Experiment Station in Goettingen. Figure 2 shows the outboard profile of a three tower Flettner Schooner as he conceived it. In section the airfoils were symmetrical, had a thickness-to-chord ratio of 17% and the flap was 33% of the chord length (Figure 3).

![Fig. 2 Three-Tower Flettner schooner](image)

![Fig. 3 Flettner wing sail section](image)

The flaps had small trim tabs in the trailing edge. For structural reasons Flettner changed the overall configuration of his wing sails to a "triplane" configuration and placed the auxiliary rudder or control tab on a tail behind the centerline plane (Figure 4).

![Fig. 4 Flettner triplane configuration](image)

The indicated maximum lift coefficient \( (C_{L_{\text{Max}}}) \) for the wing sail from his wind tunnel tests was only 1.4, which was better than the maximum lift coefficient for soft sails of that era but, as we shall see, not as good as we can now project with confidence. A project to put such wing sails on an ocean going ship had been authorized when Flettner became convinced that the use of a Magnus-effect rotor offered greater promise after his wing tunnel test had measured a \( C_{L_{\text{Max}}} \) for the rotor of 10.0. At that point he abandoned further work on the wing sail concept.
It is important that the reader understand the basic premise for and the method and procedures used in the research reported to the United States Maritime Administration (MARAD) in 1981 [1]. Therefore a synopsis of that research effort has been included as Appendix A. The basic research report is also still available.

First, it was our thesis that performance of sailing ships, sail-assist and or motor sailing ships could be accurately modeled and predicted from available data, and that by modeling route weather statistics and economic parameters we could accurately predict the performance of any given ship on a given route with or without sail power. We also believed that by varying the ship and rig design parameters we could optimize a sailing vessel design or a sail-assist vessel design for a given route on the basis of lowest required freight rate (RFR) criterion. In other words the economic viability sail-assist ships for specific trade could and should be determined before commitment to their construction. A block diagram of our model as developed in 1978 and used in the MARAD aided research is shown in Figure 5.

![Figure 5 Integrated ship performance and economic parametric model](image-url)

Fig. 5 Integrated ship performance and economic parametric model

Early in the course of the research it became apparent that the concepts of motor sailing or sail-assisted operation would be economically more attractive than pure sailing ships in all sizes studied. Therefore, not only was much more fundamental research into the theory of economic motor-sailing and sail-assist ships undertaken, but also in order to make the optimization of the design of sail-assist ships practical, it was necessary to align the economics program directly to the passage programs in the computer - a step not originally considered necessary.

For the MARAD research, eight wind propulsion systems which represent the range of proposed modern rig alternatives were evaluated in terms of technical and economic potential for merchant ship propulsion. The eight rig alternatives are depicted in Figure 6.

![Figure 6 Rig Alternatives](image-url)

Fig. 6 Rig Alternatives
WIND SAIL BASIC RESEARCH
GENERAL PROGRAM

A sailing rig is a wind propulsion system that may be considered in terms of the same economic parameters used in evaluating conventional propulsion machinery:

- propulsive performance
- initial cost
- operating cost
- weight
- size (volume or area occupied by the system)
- reliability
- safety.

In addition to these factors, the impact of the wind propulsion system on other aspects of ship operation must be considered. For sailing rigs, the primary impact is on cargo handling with secondary impact on visibility.

A basic concept design was developed for each rig type and propulsion performance predicted. Design criteria were specified for the selected rigs - mast height, sail area, and maximum full sail wind speed were the main criteria. Other criteria covered operational considerations and storm survival. Analysis of structural loads yielded equipment specifications and the dependence of rig weight and cost on the major design criteria. The weight and cost estimating formulas were employed in a parametric study to determine the overall relative merit of the rig alternatives.

Based on these design studies, the rig alternatives were rated in terms of relative potential for shipboard application in the near term.

Stayed masts were found to weigh nearly as much as unstayed masts, and their inferior aerodynamic performance, and interference with cargo handling operations caused the stayed fore-and-aft rig to rate below the unstayed rigs. Square sails, despite their ability to fill up the envelope available for sail, were found to have relatively higher cost for their aerodynamic performance due to the complexity of the rig.

The unstayed cat rig and the wing sail were found to have the greatest potential for immediate application to marine propulsion. Both rigs are simple and reliable, have excellent propulsive performance, and are compatible with vessel operations. The findings of the MARAD report encouraged Wind Ship to continue the development of these two rigs and led to the design, construction, and installation of a 3000 square foot cat rig that entered commercial service in September 1981 aboard the M/V MINI LACE (Figure 7) and the 1/3 linear scale model of the 3000 square foot Wing Sail (Figure 8) built and tested in 1982 and the 90 ft² Magnus Rotor built and extensively tested at sea in 1983 (Figure 9). This applied research and development is described in sections IV, V and VI of this paper.

Fig. 7 MINI LACE on sea trials at Buzzards Bay, MA. August 1981
The propulsive effect of a lifting surface rig is due to the forward component of the total aerodynamic force acting on the rig. This is shown diagramatically in Figure 10. The magnitude of the propulsive effect over a range of sailing and/or motor-sailing conditions can be quantified by "measures of merit" based on the values of $C_L$ and $C_D$ at several key points in the section data polar diagram.

- **Running:** With the apparent wind directly or nearly directly astern, aerodynamic drag provides forward thrust. However, the drag of any surface oriented perpendicular to the wind is nearly the same as the drag of a flat plate in the same orientation, so the $C_D$ is not significant in comparison of rig types.

- **-reaching:** Section lift not only produces propulsive force with the apparent wind between ahead and on the quarter, but also induces 3-D drag which provides propulsive force when the wind is on the quarter or nearly astern. Thus, the maximum lift coefficient ($C_L$) is a measure of attainable propulsive thrust for most wind conditions.
Close Reaching: With the apparent wind forward of abeam, aerodynamic drag reduces forward thrust. Thus, the section drag which corresponds to maximum section lift \((C_D \text{ at } C_L \text{ max})\) is a drag penalty for carrying maximum lift when close reaching. However, ship performance modeling for motor-sailing ships has shown that it is desirable to maintain maximum lift and accept the corresponding drag in most close reaching conditions.

Head Winds: Motor-sailing and sail-assisted ships will at times proceed to windward with the rig inoperative. The effect of the rig in this condition is air resistance due to \(C_D 0\) the aerodynamic drag at zero lift.

The maximum lift coefficient \((C_L \text{ max})\) is the most significant single parameter which represents rig propulsive performance over most of its operating range. This measure of performance is quantified by the ratio:

\[
\frac{C_D}{C_L \text{ max}}
\]

which represents the portion of propulsive effect which is lost to section drag when the ship is close reaching, and by the ratio:

\[
\frac{C_D}{C_L \text{ max}}
\]

which represents the portion of propulsive performance which is lost to rig air resistance when the ship steams to windward.

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Fig. 10 Aerodynamic forces and components

The MARAD research and our subsequent cost engineering and actual cost experience have shown that, with the exception of the Flettner rotor, the costs of different rigs of about the same projected area tend to equalize. Therefore, aerodynamic performance is of paramount importance in selecting a rig. We therefore repeat in Table 1 below how various lifting surface rigs analyzed in the MARAD study rated by each of the measures of aerodynamic performance and thus why the Wing Sail was selected as superior for early commercial development. The drag coefficients includes windage of mast, stays and gear aloft for typical rigs of each type.
WINDSHIP BASIC RESEARCH
GENERAL PROGRAM

Table 1 Measures of aerodynamic performance for rig alternatives
(2D Section Data)

<table>
<thead>
<tr>
<th>RIG</th>
<th>$C_L$ max</th>
<th>$C_{Lmax}$</th>
<th>$C_{Do}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stayed Fore-and Aft</td>
<td>1.5</td>
<td>.091</td>
<td>.092</td>
</tr>
<tr>
<td>Unstayed Cat</td>
<td>1.5</td>
<td>.084</td>
<td>.063</td>
</tr>
<tr>
<td>Square</td>
<td>1.5</td>
<td>.122</td>
<td>.107</td>
</tr>
<tr>
<td>Princeton Sail Wing</td>
<td>1.6</td>
<td>.035</td>
<td>.075</td>
</tr>
<tr>
<td>Wing Sail (no flap)</td>
<td>1.0</td>
<td>.037</td>
<td>.022</td>
</tr>
<tr>
<td>(plain flap)</td>
<td>2.0</td>
<td>.051</td>
<td>.011</td>
</tr>
<tr>
<td>Flettner Rotor</td>
<td>10.0</td>
<td>--</td>
<td>.113</td>
</tr>
</tbody>
</table>

1 Based on data as reported by Flettner. A value of 13 has since been confirmed (Fig. 53).

The section data Polar Plots for several of the rig alternatives studied are depicted in Figure 11 below:

Fig. 11 Section Polar Plots for rig alternatives

Of the infinite variety of symmetrical and asymmetrical wing configurations which are available for consideration we ultimately narrowed our consideration to a symmetrical airfoil with a plain flap. This was considered feasible for use in a marine environment, considerable aerodynamic data was available for it and it was the most economical to build of those configurations which had the potential to develop a $C_L$ max of 2.0 or greater. This configuration is compared with other symmetrical wing sections in Figure 12 below. There are many more varieties of wings that have been considered for aircraft applications including wings with leading edge flaps. Ultimately some may go to sea if they pass the test of cost effectiveness.
Operational & safety considerations are also important with respect to the selection of the best rig for a given application and indeed this is what made the unstayed cat rig so attractive for commercial use, despite its lower $C_{\text{limax}}$. These considerations are treated in depth in the MARAD study so are not reviewed here except to list some of them -

- Required Development
- Compatibility with Cargo Handling
- Ease of Control
- Complexity
- Service Requirements
- Icing
- Fail Safe

and to point out the special considerations which were envisioned with respect to further development of sail power units envisioned as a result of our basic research.

Because the wing must "furl" by automatic feathering, and because it must operate at full load design wind speed without aeroelastic flutter, the wing design requires proper location of the pivot point and longitudinal center of gravity in relation to the aerodynamic center (center of lift due to angle of attack, theoretically located 25% of the chord length aft of the leading edge).

Analysis of wing sail feathering and aeroelastic behavior indicated further specific study beyond the scope of the MARAD research. As a preliminary design guideline for that study, the center of gravity and pivot point were maintained forward of the aerodynamic center. The subsequent development of this rig - as herein reported - required extensive aeroelastic analysis and experimental verification of feathering behavior. Fortunately, aeroelastic analysis procedures developed in the aeronautics industry could be adapted and applied to our wing sail full load and feathering design.

The 20,000 DWT conceptual ship design incorporating wing sails which was optimized for a North Atlantic route had five sails totaling 29,280 ft.\(^2\) of area producing an average rig horsepower of 1629 compared with the installed conventional power of 5069 which in turn was 1000 HP less than it would have been for the pure motor ship. The ship's characteristics and economics are more fully dealt with in Appendix A.
The performance component of Wind Ship's analytical model was the keystone of Wind Ship's basic research program; enabling the evaluation of the performance more than 1000 different sail-assist rig/ship configurations and the optimization of the best best for various services.

In order to predict ship performance for either fixed power and fixed speed subject to sail trim optimization and rig design wind limitation, a computer algorithm is used (The Performance Program). It is derived from the M.I.T. Velocity Prediction Program (3) which was developed for the prediction of yacht performance. An iterative solution technique is used to find the ship speed and attitude which bring hydrodynamic and aerodynamic forces and moments into equilibrium. If this equilibrium can be improved by sail trim, or the rig design wind speed is exceeded, a new equilibrium is sought. A flow chart illustrating this process (for the fixed power problem) is shown in Figure 13.

Fig. 13 Performance program flow chart for the fixed power problem.

The aerodynamic and hydrodynamic effects of importance for a first-order estimate of ship performance are taken into account; they include the following effects on the above water portion of the ship:

- sail section lift/drag performance
- sail induced drag dependence on sail plan and apparent wind angle
- sail blanketing effects
- benefits to be obtained by trimming sails to optimize performance
- Reefing imposed by rig structural limits
Performance Component (cont'd)

- sail heeling moment dependence on sail plan
- hull topside and superstructure windage and healing moments

and the following effects on the underwater portion of the ship:

- hull frictional and residuary resistance
- hull leeway and induced drag dependence on side force
- propulsive efficiency
- hull righting moment dependence on heel angle.

Two simplified engine use strategies are available:

1. fixed power - engine operating continuously at 90% of maximum continuous rating
2. floor speed - engine power varied dynamically to attempt to keep ship speed at a given minimum speed

A simplified voyage performance model takes account of the dependence of ship performance on wind conditions.

A performance program flow chart for the fixed power program is shown in Figure 12.

The performance component is a key portion of Wind Ship's model for parametrically analysis and optimizing new sail assist designs (a capability regretfully not yet fully employed). It is also the basic building block in our Retrofit Analysis Model. The latter was first used to predict the performance economic aspects of retrofitting sail-assist to m/v MINI LACE. These were subsequently validated based on actual MINI LACE performance data as described in Section V of this paper. The model has to date been used to analyze over 75 specific ship configurations as discussed in Section IX.

As various refinements and extensions are made to it, it is becoming and will become increasingly valuable. Chapter III of the MARAD report [2] outlines some of these areas of further refinement as we saw things in 1981. Wind Ship has subsequently accomplished some of them, such as the handling of reefing. Others remain to be tackled. We also identified in Chapter III several areas of fundamental research in the sail-assist field some of which are being addressed by papers being given at this symposium.

Retrofit Analysis Model

This computer-based model (Figure 14) is used to assess the economics of installing a sailing rig on a given ship. The given ship can be an existing ship for which retrofit is being considered, or a new ship for which the owner wants to know the incremental economics of adding a sail rig.

Using a voyage scenario and parametric ship description supplied by the owner, the model is used to determine the net annual return for a given sailing rig retrofit. The calculations take into account the effects of engine use strategy, cargo deadweight reduction due to rig weight, rig maintenance and repair, and fuel savings. A more detailed description of major components of the model follows.

![Diagram of Retrofit Analysis Model](image)

**Route Wind Analysis**

Wind statistics for the given voyage scenario are derived from a magnetic tape data base of weather statistics which covers all oceans of the world. The data tapes were supplied by the U.S. National Climatic Center, and compile the data from years of shipboard and weather station
Retrofit Analysis Model (cont'd)

observations. The data is broken down to statistics for every 50 by 50 square of latitude and longitude, and by month. Average wind speed, wind speed distribution, and wind direction distribution relative to the ship's heading are derived according to the wind statistics in each square which the ship will transit, the length of the course through each square, and the average heading in each square. This statistical description of the wind is then passed to the Performance Analysis portion of the model. The route wind analysis component is further described in Appendix B.

Performance Analysis

The Performance Analysis Program predicts average ship speed and fuel consumption for a motor ship, motor-sailing ship, or pure sailing ship operating in the wind statistics derived by the wind analysis. Additional outputs include heel angles, leeway angles, and optimized sail trim for a full range of wind conditions. Included in the optimized sail trim are the effects of reefing (or feathering for wing sails) in high winds exceeding the rig design wind speed. Engine use strategy is also accounted for, and is specified either as a constant engine power output or as a target ship speed. A target ship speed strategy is usually used, with target speed varied to give the ship speed for most rapid rig payoff.

Retrofit Model

The Retrofit Model takes as input the characteristics of the existing ship, and a description of the desired sailing rig. This description of the ship with rig is passed to the performance model along with a specified engine use strategy. The performance model passes back ship speed and fuel consumption, which are combined with the logistics of the voyage scenario to determine annual transport capacity and annual "variable" costs (fuel cost + port fees + rig maintenance and repair). The computation of annual transport capacity takes into account the loss in CDWT capacity associated with rig weight. By specifying a range of engine use strategies, the relationship between annual transport capacity and annual cost is determined over a full range of speeds between slow steaming and maximum speed. This set of calculations is performed once for the ship without a rig, and the results form the benchmark for evaluation of rig alternatives being considered for the ship. Subsequently, this analysis is repeated for each retrofit rig option.

The fuel saving performance of the retrofit ship is easily determined by comparison of fuel consumption rates with those of the benchmark ship. A comparison of the annual costs to those for the benchmark operated at the same annual transport capacity gives the net annual return generated by the sailing rig.

In addition, using the existing ship operating at its normal service speed as the benchmark, detailed results are presented for the retrofit ship operating at:

1. equal annual transport capacity with reduced annual cost;
2. equal annual cost, with increased annual transport capacity.

The annual cost savings, or the increased cargo capacity, is the "net annual return" associated with the particular rig being studied. Using these results along with the estimated cost of construction and installation, the overall economics of any proposed sailing rig can then be determined.

Retrofit analyses have been made on over 75 ships of various types and possible rigs. Some selected examples are analysed and discussed in Section IX.
MINI LACE Ship Characteristics

In January 1981 Wind Ship supported by Ceres Hellenic Shipping Enterprises Ltd of Piraeus, Greece commenced design of a sail assist rig for the 3000 DWT general purpose cargo ship m/v MINI LACE, a vessel operating in a tramping mode out of New Orleans, LA. The ship's principal characteristics as a motor ship are as follows:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length B.P.</td>
<td>206.0 ft</td>
</tr>
<tr>
<td>Beam</td>
<td>50.2 ft</td>
</tr>
<tr>
<td>Depth</td>
<td>22.2 ft</td>
</tr>
<tr>
<td>Draft</td>
<td>12.7 ft</td>
</tr>
<tr>
<td>Midship Coeff</td>
<td>.995</td>
</tr>
<tr>
<td>Block Coefficient</td>
<td>.810</td>
</tr>
<tr>
<td>Displacement (av)</td>
<td>2905 LT</td>
</tr>
<tr>
<td>Light Ship</td>
<td>855</td>
</tr>
<tr>
<td>Deadweight</td>
<td>2050</td>
</tr>
<tr>
<td>Service Speed</td>
<td>8 K</td>
</tr>
<tr>
<td>Installed Power (MCR)</td>
<td>1000 h.p.</td>
</tr>
<tr>
<td>Specific Fuel Consumption</td>
<td>0.5 g/hp.hr</td>
</tr>
<tr>
<td>Lateral Hull Area</td>
<td>3114 ft²</td>
</tr>
<tr>
<td>Transverse Hull Area</td>
<td>1547 ft²</td>
</tr>
<tr>
<td>Metacentric Height</td>
<td>9 ft</td>
</tr>
</tbody>
</table>

Shipowner's Requirements & Design Criteria

The basic requirements for the MINI LACE sailing rig or Sail Power Unit (SPU) as stipulated by Mr. George Livanos on behalf of the owners were as follows:

- Economic viability (substantial fuel savings)
- Simplicity
- Rugged reliability in continuous service at sea
- Remotely operable from the bridge
- No additional crew required
- Design and installation subject to approval of the American Bureau of Shipping (ABS)
- No interference with cargo handling

In response to these requirements and since the rig would be a prototype, the rig was conservatively designed to be fully operational (with full sail) in winds up to 35 knots, and to survive winds of 50 knots when furled.

Principal Rig Dimensions

Mast height of the rig was specifically limited by the height of the Sunshine Bridge 160 miles above the mouth of the Mississippi River. The boom length was constrained by clearance to a cargo crane at midships. These effectively determined the maximum sail area that could be fitted. The dimensions of the rig as installed are:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail: Area</td>
<td>2940 sq. ft</td>
</tr>
<tr>
<td>Luff length</td>
<td>105 ft</td>
</tr>
<tr>
<td>Foot length</td>
<td>57 ft</td>
</tr>
<tr>
<td>Mast height above</td>
<td>134 ft</td>
</tr>
<tr>
<td>ballast waterline</td>
<td></td>
</tr>
<tr>
<td>Boom length</td>
<td>60 ft</td>
</tr>
</tbody>
</table>

Mechanical Features

The system provides hydraulically powered control of the amount of exposed sail, the angle of the sail in relation to the vessel, and clewouthaul and downhaul tension. These functions are all controlled electrically from the bridge, so that no manual handling of the rigging is required.

The SPU is comprised of three major structural components. The first one is the rotating frame which acts as the structural backbone of the rig. Both the boom and the mast are attached to this structure. The second structure is the unstayed mast which stands 116 feet above the deck and is mounted via a slewing ring type bearing to the top of the rotating frame. The third structure is the boom which is cantilevered from the rotating frame. The boom and the frame rotate as a unit on a second slewing ring type bearing mounted between the bottom of the rotating frame and the rig foundations.

Hydraulic sheet winches, mounted on the boom, control sheet lines to swing the boom out to the desired angular position. The mast and boom rotate independently. A hydraulic motor rotates the mast in relation to the boom so that the sail may be reefed without changing the position of the boom.
The 3000 square foot loose-footed triangular sail sets on slides from a track on the mast. Tension on the clew of the sail is provided by an outhaul and a downhaul, which operate independently of each other. The outhaul line, under continuous tension in conjunction with the rotation of the mast, acts to take in or let out sail. The downhaul mechanism is mounted on the boom and connected to the clew, and travels in and out along the boom with movement of the clew, maintaining a continuous downhaul tension during such movement. Adjustment of tension on the outhaul and downhaul is provided by hydraulic winches and cylinders.

Construction, Installation, Test & Trials

The rig design was released for manufacture in March 1981, the prefabricated and assembled components of the rig were installed at New Bedford in August. The rig was thoroughly dock tested, and after successful sea trials the ship entered commercial service on September 7, 1981. A view of MINI LACE under sail is shown in Figure 7. (A general arrangement of the rig is shown in Figure 15.)

Engineering Excellence

The MINI LACE sail-assist project was recognized by the National Society of Professional Engineers as one of the ten outstanding engineering achievements in the United States in 1981.

Performance

As a prerequisite to commencing the actual design of the MINI LACE rig an engineering study was undertaken using Wind Ship's computer-aided Retrofit Analysis Model to predict annual fuel savings for the MINI LACE. The power generated by the rig is a function of the wind conditions in which the ship operates, and estimates of "rig horsepower" were made. Rig horsepower is the net reduction in required engine output achieved with the sailing rig in a specified wind condition while maintaining a constant service speed. If, instead of throttling back, the "standard" engine revolutions are maintained, the rig horsepower increases the total propulsive thrust and increases the ship speed accordingly. Figure 4 is a plot of the MINI LACE's rig horsepower vs. true wind for a full range of wind speeds. By averaging the fuel savings over the wind conditions expected on the given trade routes, fuel savings predictions of 20% annually were made.

Service Record

After the rig had been in service for 18 months, the owner reported that his basic requirements had been fully met and performance expectations have been exceeded. Based on his ship records and bunkering records it was reported that the average daily fuel rate had been cut by 24% and the average speed has been boosted 5%, largely without throttling back. On one favorable sailing route - New Orleans to Jamaica - the fuel savings came to 36% with an 18% speed increase.

In addition to these performance records, there were other unexpected benefits. Use of the sail in heavy, confused Gulf Stream seas enabled the m/v MINI LACE to maintain a 7 knot (in excess of her recorded actual average speed of 5.7 knots) speed when sisterships were slowed to 3 knots. When the engines were experimentally throttled back to compensate for sail generated thrust, fuel savings of over 30% were recorded, and certain ballast runs gave reductions of 60% to 80%.
3000 ft² CAT RIG
DESIGN, CONSTRUCTION & TESTING IN COMMERICAL SERVICE

Mississippi River transit time from the sea buoy to New Orleans has been cut in half. Also, the use of the sail enhances ship operation in heavy river currents and is generally called for by the pilots. In one case, the MINI LACE sailing rig brought the ship into port on schedule after an engine failure had occurred at sea.

Detail Ship’s Records

It is to be noted that the shipmaster(s) maintained detail logs of fuel consumption, ship speed, wind speed, sea state, rudder angle, leeway angle, list and other data while underway. Wind Ship engineers also were aboard the ship for extended periods during the first 14 months of the ship operation with the rig maintaining similar logs and checking the ship’s data. All of this data was later compiled and enabled correlations of actual performance with Wind Ship predictions based on performance modeling. The results are reported later in this section.

Economics of MINI LACE Rig

The prototype rig cost, exclusive of engineering, was $250,000. Based on the owner’s records for fuel consumption, the average annual savings is $48,000 for the then current fuel price of $327 per metric ton. The increased revenue from speed increase and the consequent extra voyages was $9,200 per year for a time charter rate of $2,000 per day. The total yearly benefit was $57,200. When the investment period is based simply on rig cost the first year’s fuel savings, the rig cost is returned in 4.4 years. However, if the same criterion is applied to a year of operation on favorable sailing routes, the total economic benefit goes up to $148,000 and the payback period goes down to 1.7 years. An economic summary is presented in Table II. No figure for maintenance is included as the nominal maintenance required was performed at sea, except for the sail. The annual sail maintenance was included in the price of the sail based on a five-year service life.

Table 2 MINI LACE sail-assist performance record

<table>
<thead>
<tr>
<th>Route Scenario</th>
<th>Ship(s)</th>
<th>Actual Average Fuel Rate (gal/day)</th>
<th>Actual Average Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MINI LACE (w/rig)</td>
<td>2.13</td>
<td>5.70</td>
</tr>
<tr>
<td></td>
<td>MINI LACE &amp; MINI LADY (w/rig)</td>
<td>2.70</td>
<td>5.45</td>
</tr>
<tr>
<td>TRAMPLING Differences</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Av. Fuel Savings</td>
<td>.66 gal (245)</td>
<td>.25 x (4.45)</td>
</tr>
<tr>
<td></td>
<td>Av. Speed Increase</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MINI LACE (w/rig)</td>
<td>1.70</td>
<td>6.42</td>
</tr>
<tr>
<td></td>
<td>MINI LACE &amp; MINI LADY (w/rig)</td>
<td>1.35 gal (521)</td>
<td>.97 x (17.35)</td>
</tr>
<tr>
<td></td>
<td>ROUTE (S) FOR SAILING Differences</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Av. Fuel Savings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Av. Speed Increase</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11. ECONOMIC CONCLUSIONS BASED ON OWNER’S 14 MONTH DATA

(Based on Fuel $327/Metric Ton)

<table>
<thead>
<tr>
<th>Tramping Mode</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annualized fuel savings</td>
<td>$48,000</td>
<td></td>
</tr>
<tr>
<td>Increased revenue/extra voyages</td>
<td>$9,200</td>
<td></td>
</tr>
<tr>
<td>Total yearly benefit</td>
<td>$57,200</td>
<td></td>
</tr>
</tbody>
</table>

Full Time Operation on Most Favorable Sailing Routes

| Annualized fuel savings | $70,000 |                    |
| Increased revenue/extra voyages | $16,000 |                    |
| Total yearly benefit | $86,000 |                    |

MINI Lace Prototype Rig Cost ($): $250,000

Range of Payback Depending on Route Scenario

(Simple payback w/o cost of money) 1.7 - 4.36 years
Design Refinements - Cat Rig MK II

The Cat Rig was further refined based on the MINI LACE experience. The resulting MK II rig is functionally the same as the CAT RIG MK I SPU. The principal changes are to unitize and rationalize the design for production and to make preassembled and pretested sail power units more easily installed or retrofitted on a large variety of ships in the shortest possible ship availabilities. (48 hours is an attainable goal for a rig installation availability). The MK II rig also offers the option of substituting a unique combination of hydraulic cylinders to move the boom positively through a 170° rotation as opposed to the MK I system of boom control by means of wire rope sheets. A general arrangement for a Cat Rig MK II is shown in Figure 17. As in the case of the MK I rig, a hand-operated emergency furling system is provided in the event of power failure. Both the Cat Rig MK I and the Cat Rig MK II are proprietary hardware; U.S. patents have been granted and foreign patents applied for.
CORRELATION OF MODELED SAIL-ASSIST PERFORMANCE AND ACTUAL PERFORMANCE AT SEA

Summary

In the light of 14-month (September 1981-October 1982) performance records reported for the MINI LACE and her sisterships, Wind Ship was able to correlate the results with modeled performance predictions made prior to installation of the cat rig sail power unit on the MINI LACE. The predicted savings based on the new data increased from .76 T/day at 8.0 knots to .83 T/day at 5.7 knots. This increase is mostly due to the difference in the displacements and propulsive efficiencies used in the two cases.

The owner's bunkering record correlates very well with Wind Ship's modeled predictions when the latter is adjusted to logged conditions. This was an important verification of the analytical models accuracy. Whereas the owner's records [4] show a 26% reduction in main engine fuel use with a 0.2 knot increase in speed, the Wind Ship model predicts 24% reduction for a speed increase of 0.2 knots (see Table 3).

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Mini-Class modeled and actual performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preinstallation</td>
<td>Modeled Performance</td>
</tr>
<tr>
<td>Performance Prediction</td>
<td>Based on Actual Loads and Wind Conditions</td>
</tr>
<tr>
<td>Length BP (ft)</td>
<td>206</td>
</tr>
<tr>
<td>Beam (ft)</td>
<td>50.2</td>
</tr>
<tr>
<td>Depth (ft)</td>
<td>21.6</td>
</tr>
<tr>
<td>Draft (ft)</td>
<td>16.1</td>
</tr>
<tr>
<td>B/T</td>
<td>3.1</td>
</tr>
<tr>
<td>Displacement (LT)</td>
<td>3885</td>
</tr>
<tr>
<td>Propulsive Coefficient</td>
<td>.35</td>
</tr>
<tr>
<td>Speed (kt)</td>
<td>8.0</td>
</tr>
<tr>
<td>Resistance</td>
<td></td>
</tr>
<tr>
<td>Average Wind Speed (kt)</td>
<td>13.7</td>
</tr>
<tr>
<td>Wind Direction</td>
<td></td>
</tr>
<tr>
<td>Daily Fuel Use, Main Engine Only (T/day)</td>
<td></td>
</tr>
<tr>
<td>Motor Ship</td>
<td>3.42 @ 8.0 kt</td>
</tr>
<tr>
<td>Sail-Assist</td>
<td>2.66 @ 8.0 kt</td>
</tr>
<tr>
<td>Savings</td>
<td>23% (Houston-Panama)</td>
</tr>
<tr>
<td>18% (Houston-Paramaribo)</td>
<td>31% @ 5.7 kt</td>
</tr>
</tbody>
</table>

Ship and Voyage Parameters

The ship characteristics and voyage parameters were mainly the same for the preinstallation performance prediction and for the new performance prediction. The major differences were the displacement, resistance, propulsive efficiency, and the wind distribution.

Displacement

The original predictions were based on a full load displacement of 3885 LT. The voyage records were reviewed and the fraction of the time the ship sailed in ballast was combined with the fraction of the time the ship sailed loaded to give an average displacement of 2905 LT.

Resistance

Since the displacement used for the predictions changed from 3885 LT to 2905 LT, the resistance estimate was necessarily revised. Figure 18 compares the resistance estimate for the preinstallation performance prediction and for the current performance prediction. The preinstallation prediction used towing tank data on full form ships reported by Hydronautics, Inc. [5] while the current prediction uses the regression on a much wider range of ship forms performed by Guldhammer and Harvald [6]. The two curves are remarkably similar in shape. The estimate for the 2905 LT displacement case is about 300 lb lower throughout the range of interest, but gets steeper at higher speeds as a result of the higher beam/draft ratio.
Propulsive Efficiency

The propulsive efficiency for the preinstallation case was obtained by assuming a 25% service margin and using the propulsive efficiency that results from the relationship between resistance and input power. The performance model predicted a fuel consumption of 3.42 tons/day at an average ship speed of 8.0 knots for propulsive efficiency of 35%. However, the owner's records show a motor ship main engine fuel consumption of 2.45 tons/day. To obtain agreement with this report, we adjusted the propulsive efficiency to match the motor ship fuel use. This was justified on the grounds that the ship actually has a lower propulsive efficiency over its operating profile due to wave interactions than the calm water powering requirement would indicate. The propulsive efficiency indicated by this technique is 18%.

Wind Distribution

The data sheets from the MINI LACE were reviewed to determine the actual winds that were experienced. It was found that the average wind speed encountered was the same as was predicted from analysis of the pilot charts for the region: 13.7 knots. However, the distribution of these winds was unfavorable (Figure 19), being heavily weighted toward head winds. Use of the MINI LACE on a route with more favorable winds, similar to the Houston-Panama route, could result in considerably more savings, as predicted by the performance model.

Fig. 18 Mini-Class ships resistance curves  
Fig. 19 Wind distribution
Potential of alternate rigs

The owner's reported fuel consumption is plotted in Figure 20 along with the Wind Ship performance model predictions. Note that the predicted sail-assist ship fuel consumption is slightly higher than the reported sail-assist ship fuel consumption.

A possible design modification to the 3000 square foot cat rig is to reduce the full sail wind speed to 25 knots. Above this speed, sail would be shortened to limit the structural loads (and reduce rig cost.) Comparing two cat rigs designed to 25 knots and 35 knots, the difference in performance is not very large; referring to Table III and comparing the ship performance at 5.7 knots, the savings decrease from 31% to 28%.

Of the two, the wing sail remains the superior performer, with the 40 knot design wind speed version showing a predicted fuel savings of 43% at an average ship speed of 5.7 knots. This assumes that the wing sail develops the maximum lift coefficient of 2.0 that our 1/3 linear scale model tests indicate. A 450 ft² rotor with a design wind speed of 25 knots would yield 25% fuel savings. Daily fuel savings from the above sail power units at an average ship speed of 5.7 knots are compared in Table 4.

**Table 4** Comparison of predicted savings with various sail power units at average ship speed of 5.7 kts

<table>
<thead>
<tr>
<th>Sail Power Unit</th>
<th>Nominal Sail Area (ft²)</th>
<th>Design Wind Speed (kt)</th>
<th>Daily Main Engine Fuel Rate (MT/day)</th>
<th>Daily Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (Motor Ship)</td>
<td>--</td>
<td>--</td>
<td>2.72</td>
<td>--</td>
</tr>
<tr>
<td>Cat Rig</td>
<td>3000</td>
<td>35</td>
<td>1.89</td>
<td>.83</td>
</tr>
<tr>
<td>Cat Rig</td>
<td>3000</td>
<td>25</td>
<td>1.96</td>
<td>.76</td>
</tr>
<tr>
<td>Wing Sail</td>
<td>3000</td>
<td>40</td>
<td>1.55</td>
<td>1.17</td>
</tr>
<tr>
<td>Rotor</td>
<td>450</td>
<td>25</td>
<td>2.03</td>
<td>.69</td>
</tr>
</tbody>
</table>
First Design Iteration

The MK I wing sail design of 3000 ft\(^2\) was commenced in January 1981 as part of a jointly funded effort by Wind Ship and Ceres Hellenic Shipping Enterprises Ltd. of Piraeus, Greece. The objective was to develop and test on identical MINI ship hulls of 3100 DWT an unstayed cat rig prototype and a wing sail prototype using the conceptual designs worked up for the MARAD study as benchmarks. It was expected that this would allow an in-service test and evaluation of both types of rigs. It was recognized however that the wing sail, because of the feathering concept, would require an iterative design process whereby the aeroelastic qualities of each design as it was developed would be analytically modeled.

The Wing Sail design criteria and parameters were changed from those of the rig for the 20,000 CDWT benchmark ship design as indicated in the following tabulation of rig design criteria, parameters and features.

### Table 5 Wing sail design criteria & parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>10,000 CDWT Concept</th>
<th>MK I Wing Sail 1st Iteration</th>
<th>Reason for Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected Area</td>
<td>6,000 sq. ft.</td>
<td>3,000 sq. ft.</td>
<td>Smaller ship for bridge height clearance</td>
</tr>
<tr>
<td>Design Wind Speed</td>
<td>45 K</td>
<td>47.5 K</td>
<td>---</td>
</tr>
<tr>
<td>Survival Wind Speed Goal</td>
<td>60 K</td>
<td>60 K</td>
<td>200 K considered unreasonably restrictive by Ceres</td>
</tr>
<tr>
<td>Further Inception Wind Speed</td>
<td>100 K</td>
<td>100 K</td>
<td>---</td>
</tr>
<tr>
<td>Boating/Feathering</td>
<td>200</td>
<td>200</td>
<td>---</td>
</tr>
<tr>
<td>Section Type</td>
<td>NACA 66015</td>
<td>NACA 66015</td>
<td>---</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>2.65</td>
<td>2.65</td>
<td>---</td>
</tr>
<tr>
<td>Flaps as % of Total Chord</td>
<td>25</td>
<td>25</td>
<td>---</td>
</tr>
<tr>
<td>Petal Area % of Total Chord at Leading Edge</td>
<td>20</td>
<td>15</td>
<td>To enhance feathering</td>
</tr>
<tr>
<td>Ship Roll Amplitude</td>
<td>---</td>
<td>90°</td>
<td>---</td>
</tr>
<tr>
<td>Ship Roll Period</td>
<td>---</td>
<td>3 Sec.</td>
<td>---</td>
</tr>
<tr>
<td>Ship Roll Axes Below Wing Base</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Assume Lift and Drag Coefficients</td>
<td>---</td>
<td>2.0 0.56</td>
<td>---</td>
</tr>
<tr>
<td>Features</td>
<td>---</td>
<td>2.0 0.56</td>
<td>---</td>
</tr>
<tr>
<td>Mast</td>
<td>Tubular steel, tapered from Deck bearing to Mast step</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Mast Bearings</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Mast Step/Foundation</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Mast/Wing Rotation &amp; Feathering</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Network System</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Wing Structure</td>
<td>Steel frame welded to mast</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Wing Covering</td>
<td>Epoxi coated plywood</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Flaps</td>
<td>Steel transplywood skin</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Flap Drives</td>
<td>Electric driven actuators</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Instrumentation &amp; Control</td>
<td>Angular rotation of wing &amp; flap</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

The structural design was then developed using the aerodynamic loads determined from the design wind speed and the assumed lift and drag coefficients and the inertia and gravity forces corresponding to the roll characteristics of the ship. It is of interest to note that the roll characteristics of the MINI ship resulted in the inertia and gravity forces equaling approximately 50% of the total rig design loads.

Concurrently with the development of design details and weights, aeroelastic models were developed as discussed in Section IV. The interaction of the aeroelastic modeling and wing sail design development is shown diagramatically in Figure 21. This enabled gust response and flutter prediction to be made for the design. The results were unacceptable. The indicated survival wind speed in a feathering mode was 85 knots and the indicated flutter inception wind speeds were but 45-60 knots in a "wing-locked" mode and only 25-40 knots in a "wing-feathering" mode.
First Design Iteration (cont'd)

As a result of this aeroelastic modeling changes were then made in design criteria and parameters as a basis for the second MK I iteration as shown in Table 6, below.

<table>
<thead>
<tr>
<th>Item</th>
<th>1st Iteration</th>
<th>2nd Iteration</th>
<th>Reason for Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast</td>
<td>Single steel rotating mast</td>
<td>Steel rotating mast fitted over fixed stub mast</td>
<td>Increase stiffness of mast in bending and reduce rotating weight</td>
</tr>
<tr>
<td>Mast</td>
<td>--</td>
<td>Stub mast rigidly attached to ship's structure and extended 1/3 of wing span above wing base</td>
<td>Increase stiffness of mast in bending and reduce rotating weight</td>
</tr>
<tr>
<td>Mast Bearing</td>
<td>Roller bearing at base of wing</td>
<td>Roller bearing at top of stub mast</td>
<td>Increase support of rotating mast</td>
</tr>
<tr>
<td></td>
<td>Radial thrust roller bearing at mast step</td>
<td>Guide bearing at base of wing</td>
<td>Reduce loads on bearings</td>
</tr>
<tr>
<td></td>
<td>Mast step incorporated with drive machinery enclosure at deck level</td>
<td>(See stub mast above)</td>
<td>Allow for expansion and contraction of mast</td>
</tr>
<tr>
<td>Wing Rotating &amp; Feathering Release System</td>
<td>Electric driven roller chain drive with air-activated clutch</td>
<td>Hydraulically actuated &quot;grab &amp; go&quot; system of brake bands on common drive</td>
<td>Reduce rotational inertia of feathering wing</td>
</tr>
<tr>
<td>Wing Structure</td>
<td>Steel frame welded to mast</td>
<td>Wood frame bolted to mast</td>
<td>Reduce rotating weight</td>
</tr>
<tr>
<td>Wing Skin</td>
<td>Plywood</td>
<td>Plywood</td>
<td></td>
</tr>
<tr>
<td>Flap Drive System</td>
<td>Electric driven actuators</td>
<td>Hydraulics cylinders</td>
<td>Reduce cost</td>
</tr>
<tr>
<td>Design Wind Speed</td>
<td>40 K</td>
<td>40 K</td>
<td>Reduce structural loads and weight</td>
</tr>
<tr>
<td>Section</td>
<td>NACA 0015</td>
<td>NACA 0015</td>
<td>Allowed wider mast section to be used at relocated pivot point</td>
</tr>
<tr>
<td>Span</td>
<td>104 ft</td>
<td>92.25</td>
<td>Reduce structural loads and weight</td>
</tr>
<tr>
<td>Chord</td>
<td>20.3</td>
<td>32.3</td>
<td>Maintain area</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>3.45</td>
<td>3.61</td>
<td></td>
</tr>
<tr>
<td>Flaps</td>
<td>298 ± 40°</td>
<td>298 ± 40°</td>
<td>Reduce control moment of flaps</td>
</tr>
<tr>
<td>Pivot Axis</td>
<td>175</td>
<td>105</td>
<td>Enhance feathering behavior</td>
</tr>
</tbody>
</table>

Second Design Iteration

The second design iteration reduced the rotating weight per rig from 79,700 lbs to 31,700 lbs and the total weight per rig including hull reinforcement from 108,000 to 71,700 lbs. This was a step in the right direction since rig cost is very much a function of rig weight. In the aeroelastic department the rig acquired eminent respectability. The modeled survival wind speed checked in at exactly the goal of 100 knots and the modeled flutter inception wind speed in both an operating mode and a feathering mode was greater than 200 knots. This design was completed in January 1982.
Because of adverse economic conditions in the shipping industry, Ceres decided not to proceed with a full-scale 3000 sq. ft. prototype rig as they had done with the cat rig in 1981. As a result, Wind Ship decided to build a 1/3 linear scale Wing Sail which was completed in September 1982 and tested throughout the fall. Figure 22 shows a general arrangement of the test rig. A photograph of the prototype wing sail passively feathering in 25 knots of breeze, gusting to 40 knots, is shown in Figure 8.
WING SAIL RESEARCH, DEVELOPMENT & DESIGN PROGRAM
ONE-THIRD LINEAR SCALE MODEL WING SAIL

Wing Design Characteristics

The test rig was made of significant (one third linear scale) size to avoid scaling uncertainties and errors when forecasting aerodynamic performance for full scale wing sails. The scale model wing sail was virtually an exact replica of the 3000 square foot MI-I design; the framing system, bearings, and rotating drive system were all the same. The wing sail was mounted on an instrumented test trailer, and a method of retracting the wing was developed so the rig could be towed to test sites including the Wind Tunnel at Langley Field, VA. The design characteristics are outlined in Table 7.

Table 7 Design characteristics of scale model wing sail

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
<td>NACA 0018</td>
</tr>
<tr>
<td>Span</td>
<td>29.25 ft.</td>
</tr>
<tr>
<td>Chord 10.25 ft.</td>
<td>299.8 ft²</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>2.85</td>
</tr>
<tr>
<td>Flaps</td>
<td>Three 0.2 chord plain flaps ± 45°</td>
</tr>
<tr>
<td>Pivot axis</td>
<td>0.1 chord aft of leading edge</td>
</tr>
<tr>
<td>Total including support structure</td>
<td>5350 lbs.</td>
</tr>
<tr>
<td>Rotating weight</td>
<td>2100 lbs.</td>
</tr>
<tr>
<td>Hydraulic Power Unit</td>
<td>500 psi, 3 gpm</td>
</tr>
<tr>
<td>Maximum allowable apparent wind speeds</td>
<td></td>
</tr>
<tr>
<td>Operating Mode: Flaps deflected</td>
<td>40 knots</td>
</tr>
<tr>
<td>Flaps aligned</td>
<td>52 knots (approximate)</td>
</tr>
<tr>
<td>Feathering Mode: Survival wind speed</td>
<td>90 knots</td>
</tr>
<tr>
<td>(gust response)</td>
<td></td>
</tr>
<tr>
<td>Flutter inception</td>
<td>182 knots (feathering)</td>
</tr>
<tr>
<td>Average wing rotation speed</td>
<td>1.0 degrees/second</td>
</tr>
<tr>
<td>Operational wing rotation speed</td>
<td>2.1 degrees/second</td>
</tr>
</tbody>
</table>

Test Objectives

- Demonstrate the feasibility of passive feathering.
- Verify performance-lift, drag and sail thrust for a full range of wind conditions and angles of attack.
- Confirm efficacy of drive system in operation.
- Provide operations experience and data as needed to develop practical parameters for development of an automatic control system.
- Confirm absence of flutter in operational and feathering modes.
- Check actual gust response vs. predictions.

Construction

The prefabricated trailer, support structure, brake drum, floating frame and stub mast were assembled at the site and the radial thrust bearing installed ready for the rotating mast and wing to be fitted to the stub mast. The tubular rotating mast served as part of the assembly jig for the sitka spruce main body frames, main body skin panels, nose assembly and flaps. All of the latter had been previously fabricated and epoxy joined in suitable sub-assembly jig to close tolerances. All wooden surfaces were epoxy sealed. The leading edge of the wing nose section was finished to a chordwise waviness tolerance of .020" to insure that premature leading edge stall would not occur during testing.

Drive System Development

The criteria for the drive system were 360° continuous rotation in either direction, low additional rotational inertia when feathering, reliable fail-safe operation, and low cost. The new drive mechanism was hydraulically actuated and remotely controlled, and could hold the wing at any angle or release it to rotate freely in the wind. Wing rotation was controlled by two sets of band brakes operating on a common drum. The lower set of bands were anchored to the support structure. The upper set was positioned by hydraulic cylinders aligned tangentially to the brake drum. Brake operation was sequenced for alternate engagement. With the upper brake engaged and the lower released, the drive cylinders moved the wing in the desired direction to the limit of their stroke. The lower brake then engaged and held the wing in position while the cylinders, with upper brake released, returned to their starting position.

Retraction System

A manually operated retraction system was provided. A full scale retraction system would employ hydraulic cylinders acting in tandem with enough extension to lower the rig sufficiently so that the top of the wing would clear most bridges in major ports.
WING SAIL RESEARCH, DEVELOPMENT & DESIGN PROGRAM
ONE-THIRD LINEAR SCALE MODEL WING SAIL

Equipment

The instrumented test stand included a trailer with the equipment necessary to raise and lower the wing sail and outrigger legs to resist overturning moments in any direction for the wing operating in 40 knots wind speed with flaps fully deflected. The rig was flexibly mounted to the trailer so that a load cell could measure the thrust generated by the wing along the centerline of the trailer. The hydraulic power unit was mounted on the trailer. Directional control valves for the wing rotation and flap angle drive systems were also mounted on the trailer and controlled from a manual push button control station. Wind speed and direction were measured by a wind instrument which gave a generator output seen across a sine/cosine potentiometer.

AEROELASTIC MODELING

Introduction

The potential problems in achieving dynamic stability and proper feathering were recognized at the time the idea of a feathering wing was being hypothecated for the (previously described) conceptual design of the sail-assisted 20,000 DWT cargo vessel. Concurrent with the commencement of the MK I wing design the development of a theoretical aeroelastic model (Figure 23) was commenced and was used in the design development cycle for both iterations of the MK I wing sail, the One-Third Linear Scale Model Wing Sail and the subsequent MK II 3000 ft² production prototype wing sail design.

The gust response component of the aeroelastic model deals with the forces generated and the time required for the wing sail to respond to an instantaneous change in the wind direction when feathering freely, not operating. Two separate formulations were needed to account for this unsteady gust response: (1) when the wing responds in a lifting mode and (2) when the wind angle change is so large that the wing stalls.

The gust feathering model was based on a formulation presented by Bisplinghoff [7] and modified by York [8]. Bisplinghoff's work was primarily for airplane wings and control surfaces, and used the "elastic axis" of the wing as a rotation point. York reformulated the problem by referencing motions to the wing pivot axis. For the purposes of the gust response model, the wing is assumed to be rigid enough to neglect the influence of the deflection of the structure on the air loads. Further assumptions are that the airfoil thickness is negligibly small compared to the chord, the chord is negligibly small compared to the span, and that superposition of the linear results of harmonic motion will hold.
WING SAIL RESEARCH, DEVELOPMENT & DESIGN PROGRAM
AEROELASTIC MODELING

The problem was originally attacked by Theodorsen. He solved Laplace's equation, subject to a linearized time dependent boundary condition on the airfoil, using a source-sink distribution. He used vortices distributed along the chord and downstream along the wake to satisfy the Kutta condition. Subsequent to solving the general problem of airfoil unsteady motion, Theodorsen solved the harmonic oscillation problem and formulated a function that represents the reduction in amplitude and shift in phase due to a transverse motion of the foil.

Wagner solved the problem of response to an instantaneous angle of attack change by writing the excitation in terms of Fourier coefficients. Then, for small angle changes, the time-domain solution can be compiled as a sum of solutions in the frequency domain.

The major wing sail design parameters that affect the feathering response are the pivot point location and the weight of the wing sail. The effect of these parameters on the survival wind speed is shown in Figure 24. Survival wind speed is stipulated here as the wind speed that induces a force during the response to a 180° step gust that equals the steady-state aerodynamic force at the structural design wind speed.

Flutter Analysis

The flutter component of the aeroelastic model deals with the stability of the wing sail when operating or feathering. This problem is one of fluid-structural interaction: when a small amplitude vibration is set up in the structure by way of an external force, do the air loads induced by the vibrating foil tend to dampen or amplify the structural vibrations? When the airloads tend to amplify the vibrations, a condition known as flutter is experienced, which can lead to catastrophic failure within a few cycles.

Although there are several types of flutter that the wing sail may be subject to, such as panel flutter, the most dangerous type results from a coupling between the bending and torsional motions of the wing sail. There are five parameters which control flutter inceptions.

1. Pivot axis location
2. Ratio of natural frequencies in bending and torsion
3. Distance from the pivot axis to the center of gravity
4. Radius of gyration
5. Ratio of wing density to air density

The wing will exhibit vibrations as induced by ship motions or inflow unsteadiness. The wing is modeled structurally as a non-uniform cantilever beam whose natural frequencies and normal mode shapes can be calculated. At zero wind speed it is assumed that the vibratory motion of the wing is a superposition of these normal modes. At a given wind speed, the rate of decay or divergence is determined by the airloads produced by the motions. The airloads at each section can be computed from the lift and moment responses to harmonic motions at the respective vibratory frequencies. The bending vibrations of the wing induce forces due to lateral motions; torsional vibrations also cause an angle of attack oscillation. At low speeds, the air damps all vibrations. As the wind speed increases, one mode no longer decays and diverges at the minimum flutter speed for the wing. History has shown that the lowest vibratory modes lead to flutter inceptions [7].

Fig. 24 Effect of pivot point location and wing weight on survival wind speed
Flutter Analysis (cont'd)

Wind Ship's flutter analysis program calculates the uncoupled normal modes of the wing sail for the first and second modes of vibration in bending and torsion. At each wind speed, the wing is "driven" at a series of frequencies to find the maximum response at that wind speed when either bending or torsion is driven. Flutter speed is taken to be the minimum wind speed at which the bending and torsional frequencies coincide and reach a combined resonance. The results for flutter calculations on the scale model wing sail are given in Section V.

Results of Modeling on Wing Designs

The concerns that led to the development of the aeroelastic models proved to be justified, at least within the limits of what the analytical models could show. The first analysis of the steel-framed wing sail yielded a flutter speed of approximately 50 knots. That problem was solved by redesigning the stubmast to be substantially stiffer. The problem of meeting a 100 knot survival wind speed proved to be less tractable, however, and eventually necessitated the shift to wood framing to cut the weight, and a forward movement of the pivot point (from 15% of chord to 10% of chord) to improve response time.

Modeled Aeroelastic Properties of 300 ft² Wing Sail

Preliminary aeroelastic results were compiled to give a first estimate of the expected results. These results were based on a weight estimate drawn from the plans. The discretization of the wing is shown in Figure 25. The rotating mast in segments 2, 5, and 6 is 10 inch 10 gage tubing, and the mast in segments 3 and 4 is 10 inch Schedule 40 pipe. The distributed properties over each segment include the rotating mast and mast wing woodwork. The concentrated properties of each node include the flanges, main frames, flap drives, and flap supports.

The beam dynamics were calculated using basic beam theory and the Rayleigh-Ritz method to connect the continuous and the concentrated properties. The aeroelastic calculations accept the beam dynamics as input and use linear, quasi-steady aerodynamic strip theory for the air loading.

Fig. 25 Discretization of 300 ft² wing sail for aeroelastic modeling

A vertical beam dynamics program was used to calculate the natural frequencies and mode shapes of the stubmast and the wing in its operating and feathering modes.

The shape of the first mode of stubmast lateral vibration is that of a typical beam. This will be the only mode excited by the low frequencies considered in the aeroelastic calculations. The centroid of the generalized mass of this mode is 2.9 feet from the upper bearing, so by moment equilibrium the equivalent mass of the stubmast seen by the wing through the bearing is 3.57 slugs. The stubmast bears no torsional load from the wing through the upper bearing.

The mode shapes of the operating wing sail are shown in Figure 26. The torsional modes are flat in the region of the upper bearing because of the high torsional stiffness of the Schedule 40 pipe that is to either side of the bearing.
The bending characteristics of the Wing Sail while feathering are the same as during operation, but the feathering torsional modes are shown in Figure 27. A nominal drive system rotary stiffness was used since a zero stiffness creates computational problems. We have found that the results are insensitive to this parameter. The modes correspond to what we should expect for a free-free beam vibrating in torsion. The rigid body mode (0th) is necessary for the flutter calculations.

Wind Ship's FLUTTR program was used to perform the aeroelastic calculations. The maximum response for each wind speed and the frequency of the response for the bending and torsion branches of the system are plotted in Figures 28 and 29. The "response" is defined as the ratio of the deflection to the deflection obtained by applying a static force of the same magnitude.

The operating characteristics are shown in Figure 27. Coupling the lowest bending and torsional modes does not yield flutter up to 200 knots. When the second bending mode and the first torsional mode are coupled, flutter inception speed is just above 200 knots.

The only coupling of interest in the feathering mode is the first bending mode with the rigid-body torsional mode. The bending response goes unstable above 182 knots. The bending and torsional frequencies lock in and the aerodynamic response to each tends to amplify the vibratory response.
Modeled Aeroelastic Properties of 300 ft$^2$ Wing Sail (cont'd)

The response of the wing in feathering mode was calculated using the FEATHR program. Figure 29 shows the results. The left half is the response to sinusoidal gusting, similar to the conditions that would exist when rolling. To get some idea of the force that these loadings can cause the wing to transmit to the structure, refer to Figure 30. The upper plot gives the roll period necessary to excite the force resonance at various wind speeds. The lower half of Figure 30 shows the force amplitude for 5° and 10° roll angles, assuming that the ship is rolling at the period to excite the maximum force. The design loading is exceeded for a 10° roll angle at 65 knots if the roll period drops below 4 seconds. This is very fast, but could occur in the ballast condition in an unconventional hull such as the MINI class.

The right half of Figure 29 shows the time domain response to a step gust. The maximum force level occurs when the leading edge of the gust has moved 1.5 times the chord downstream from the leading edge. The survival wind speed as a function of gust angle is presented in Figure 31. The maximum wind speed for survival in a 10° step gust, for instance, is 90 knots.
Modeled Aeroelastic Properties of 300 ft² Wing Sail (cont'd)

Fig. 31 Maximum force excited by rolling, motoring head to wind

Fig. 32 Predicted 300 ft² wing sail survival wind speed vs. gust angle

**Scaling Laws**

In the following, we review the laws for scaling the 300 ft² wing sail to full size, the effects of scale on those results, the range of results expected from the wing sail data, and the results actually attained in the reduced scope test program.

**Steady Net Forces**

A load cell was installed to measure the net force in the axial direction along the trailer. Lift and drag can be resolved by taking 2 force measurements, leaving the wing sail oriented in the same respect to the wind and rotating the trailer under it. Since the model is geometrically identical to the full scale prototype, the flow patterns are the same and thus the forces scale simply as:

\[ \text{FORCE} \propto \rho \times V^2 \times S \]

where:
- \( \rho \) = fluid density
- \( V \) = free-stream flow
- \( S \) = wing area
Scaling Laws (cont'd)

Fig. 33 Wing section inflow schematic

The fluid density is also the same for the test model and the full scale unit, so for the same wind speed the force measured on the model will be 1/10 the force experienced in the full scale case.

**Pressure Distributions**

At any point on the wing, the pressure scales as:

\[
\text{PRESSURE} \propto \frac{1}{V^2}
\]

Thus, for the same wind speeds, and wind shear, the pressure on the model wing will be the same as at the corresponding point on the full scale wing.

**Unsteady Response**

The time-dependent response of the unlocked wing sail is dependent on another parameter: the reduced frequency. The test for wing feathering will be to release the slewing clutch at some angle of attack and monitor the force and position as a function of time (See Figure 29).

The frequency of oscillation, is: \( W = 2f \), and the reduced frequency is:

\[
K = \frac{Wc}{2V}, \text{ where } c = \text{chord length.}
\]

Thus to get the same time-dependent response for the model and the full scale unit, the wind speed must be approximately one-third the full scale wind speed. Conversely, for the same wind speed, the frequency of response of the prototype will be one-third the model frequency. Scaling forces at different reduced frequencies is not as simple and requires accounting for phase lag.[9]

Flutter is a dynamic instability occurring while the wing is loaded, where the bending deflection of the airfoil interacts with the airfoil loading to produce time-varying forces. Since the mass distribution is the same for model and full scale, the span ratio is 1/3 and the wind speeds are the same, the time scale factor is determined from:

\[
\frac{T_m}{T_w} = \frac{U_m L_m}{U_w L_w} = \frac{1}{3}
\]

Thus we should expecting model natural frequencies 3 times higher than we predict for the full scale wing.

**Scale Effects**

In order to directly compare the forces for the model and full scale wing sails at various wind speeds, the lift, drag, and thrust should be expressed in terms of non-dimensional coefficients. The question is whether all factors are properly accounted for. The most important factor neglected in defining the coefficients is viscosity. The effect of viscosity manifests itself in two ways:

- Development of the boundary layer
- Shedding of periodic vortices from the trailing edge
Scale Effects (cont'd)

The first problem has significance for the measurement of steady forces and pressure distributions; the second for the unsteady (feathering) response. In addition, the difference in wind shear from model to full scale will have some influence on the spanwise pressure distribution.

Static Measurements

The Reynolds number is the dimensionless parameter used to evaluate the effects of viscosity:

\[ \text{Re} = \frac{Vc}{\nu} \]

Where \( \nu \) is the kinematic viscosity of the fluid. The Reynolds numbers at 20 knots wind speed are:

<table>
<thead>
<tr>
<th>Model</th>
<th>Full Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 million</td>
<td>6.0 million</td>
</tr>
</tbody>
</table>

First glance tells us that we should not have any major scaling difficulties, since the common wisdom has it that an order of magnitude change in Reynolds number is needed to be significant. NACA wind tunnel tests [10] give a wealth of data on scale effect, and findings from other tests provide guidance as well. Table V gives a summary of some other related tests and their Reynolds numbers.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reynolds Number Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>[11] Imperial College Wing Sails</td>
<td>25000-250000</td>
</tr>
<tr>
<td>[12] Hamburg Square Sails</td>
<td>240000</td>
</tr>
<tr>
<td>[13] NKK Square Sails</td>
<td>3.8 x 10^5 (Model)</td>
</tr>
<tr>
<td>[14] Patient Lady C-Class Wing Sails</td>
<td>about 1.0 x 10^6</td>
</tr>
<tr>
<td>[15] NLAIME Unsteady Airfoils</td>
<td>118000</td>
</tr>
<tr>
<td>Wind Ship Wing Sail</td>
<td>2.16 x 10^6 (300 sq.ft.)</td>
</tr>
<tr>
<td></td>
<td>5.98 x 10^6 (3000 sq.ft.)</td>
</tr>
</tbody>
</table>

Net Forces

NACA 00-Series sections show no scale effect on lift-curve slope at Reynolds numbers between 3 and 9 million. The scale effect for maximum lift coefficient for 00-Series sections having thickness ratios less than 12% is very small (Figure 34). Figure 35 shows the scale effect for larger thickness ratios. The results are uniformly favorable, i.e., the model may yield a slightly lower lift coefficient than the full scale wing. Measurements at the Imperial College Aeronautics Department on a scale airfoil ship [11] show 2% variation in maximum lift coefficient over the Reynolds number range from 25 thousand to a quarter million.

![Wind Ship Wing Sail Model](image)

Fig. 34 Variation of maximum section lift coefficient with airfoil thickness ratio [10]
Scale Effects (cont'd)

**Fig. 35** Scale Effect On Maximum Lift [10]

At the lift coefficients of interest the drag is dominated by the induced drag, which is dependent on lift squared. Thus, for rig operation, if the lift coefficient is right, the drag should be right. However, the minimum drag coefficient is of interest in that we would like the windage force while the wing sail is feathered to be as small as possible.

The drag for small values of the lift coefficient is controlled by the skin friction drag. The skin friction drag is mainly a function of Reynolds number and boundary layer transition point. Laminar separation must be avoided to obtain consistent readings. Figure 36 shows that the NACA 65-418 experiences a substantial increase in drag at the lower Reynolds numbers; this is a result of laminar separation. Again, the model measurement will tend to be conservative with respect to the full scale.

Surface finish has an effect on the minimum drag. The factors to consider are:

- Roughness
- Waviness

**Fig. 36** Variation Of minimum drag coefficient with Reynolds number [10]

NACA [10] found that tests on wings of practical construction yielded drag coefficients of .008, regardless of section type. Thus, if the wing sail model is finished in the same way that the prototype will be, the model results should be slightly conservative.

The spanwise pressure distribution will differ between model and full scale for the same wind speed. The full scale prototype will operate in a more uniform velocity distribution, (Figure 37) and will thus experience less variation in loading over the span than the model.
Scale Effects (cont'd)

Fig. 37 Wind shear at 20 knots

Possible Range of Results

The lift/drag polar diagram as currently used in the Wind Ship Performance Model is shown in Figure 38. The feathered drag coefficient is taken as .02. Dependence of drag on lift below stall is:

\[ C_D = \frac{C_L^2}{A} + .005 C_L + C_{D0} \]

where \( A \) = aspect ratio, the second term is a curve fit to profile drag dependence ([8], p. 196), and

\[ C_{D0} = \text{minimum drag coefficient} = .02 \]

The maximum lift coefficient was obtained from data in NACA Report 661 [17]. The maximum drag coefficient is 1.2, a conservative estimate based on flat plate drag data [16].

If lift breakdown is forestalled as long as possible by:
- steady wind conditions
- fair leading edge
- tip vortices rolling up well downstream

then the maximum lift coefficient of 2.28 could be obtained at a flap deflection of 45° (Figure 38). The chances of obtaining a maximum lift coefficient of at least 1.9 are considered very good, based on NACA data at moderate Reynolds numbers [18] and the Wind Ship experiment as noted below confirmed this possibility.

There were two major chances for worse results than anticipated:
- Rough Leading Edge - Premature leading edge stall which was easily avoided by finishing the leading edge to prevent serious roughness.
Possible Range of Results (cont'd)

- Flap Gap Bleeding - Reference [17] showed the importance of sealing the flap gap of a plain flap. Flap bleeding decreased the maximum lift by 20%. A foam seal will be installed on the Wind Ship Wing Sail to prevent this bleeding. The porous foam will be compressed in the gap to prevent air from leaking from the pressure face to the suction face.

Actual Results

The realities of a limited budget, the inability to also test in a wind tunnel as planned and erratic winds at the test site led us to reduced expectations; much of the data we obtained was of a relative nature. The most important findings are summarized here.

Aerodynamic

Stall Angle of 25°

Stall angle is the angle at which maximum lift and flow separation occurs. The large nose radius of the NACA 0018 section makes occurrence of leading edge separation prior to trailing edge separation unlikely. Furthermore, low aspect ratio increases stall angle beyond that which would be expected in two-dimensional flow. Flow visualization tests indicate where on the wing and at what angle separation is occurring and, therefore, provide guidance in optimization of flap length.

Observation of the flow patterns in preliminary tests of the Wind Ship Wing Sail indicate that the stall angle is near 25°. (See Figure 39) In addition, there is evidence from studies on similar foils that the stall angle is at least 25°. Reference [15], from data for a systematic series of low aspect ratio control surfaces, shows a stall angle of about 24° for an effective aspect ratio of 2.86, without flap. Tests of the Patient Lady wing sail [16] resulted in a 30° stall angle.

![Fig. 39 Lift curve and stall angle](image)

**Fig. 39 Lift curve and stall angle**

For 300 ft² wing sail

Maximum Lift Coefficient ($C_{L\text{max}}$) of 2.0

This lift coefficient has been exceeded in several NACA tests with 20% plain flaps. Reference [17] reports a maximum lift coefficient of 2.3 for a 23012 section at 45° flap deflection, and reference [18] shows a $C_{L\text{max}}$ of 2.2 for a 66(215)-216 section at 45° flap deflection. Wind Ship's preliminary tests of the wing sail indicate a zero lift angle of -15° and a lift curve slope of 0.05/degree. From these data and a stall angle of 25°, we can deduce a maximum lift coefficient of 2.0, as shown in Figure 39.

Dynamic Response When Feathering

Passive Feathering - 5 Seconds in 20 Knot Wind

The expected result of 3 1/2 seconds was based on a theoretical model that uses the simplifying assumptions of a rigid wing in uniform flow to derive the unsteady feathering response. The wing response did damp out to zero after one cycle, as expected. The measured response time of 5 seconds may have been due to the bearing friction, which was not considered in the calculations shown in Figure 29.
Verification of other predicted aerelastic qualities such as flutter spread and vibration characteristics await further testing and the funding to implement it.

Operational

The operational characteristics of the wing sail were completely proven as a function of the testing program. Most importantly the concept and practicality of passive feathering was verified. With brakes released, the wing weathervanes safely in gusts of up to 60 knots. The drive system controls the wing easily and effectively. The drive system satisfied all design criteria. Test results show that the wing sail’s propulsive performance is indeed excellent based on maximum lift coefficient of 2.0.

WINDSHIP 3000 FT² PRODUCTION PROTOTYPE WING SAIL (MK II)

Taking advantage of the lessons learned from the construction and test of the one-third linear scale test wing the MK I design as previously described was subjected to one further complete design cycle with the basic objective of:

- Reducing weight and manufacturing cost.
- Development of a standard support structure which would be suitable with minimum modification to the greatest number of differing ship structural considerations.
- Provision for retrofitting an aspiration (boundary layer control) feature to improve lift characteristics if subsequent model tests showed such to be cost effective.

This work resulted in the production prototype MK II design of 3000 ft² planform area. The principal change from the MK I design (second iterations are shown in Table 9.

<table>
<thead>
<tr>
<th>Item</th>
<th>MK I I</th>
<th>MK II Production Prototype</th>
<th>Reason for Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast</td>
<td>Constant O.D., steel, rotating mast fitted over fixed stub mast</td>
<td>Tapered, cylindrical rotating mast of H oranges steel fitted over fixed stub mast</td>
<td>Reduce weight</td>
</tr>
<tr>
<td>Stub Mast</td>
<td>Constant O.D., steel, fixed stub mast extending 1/3 of wing span above wing base</td>
<td>Tapered, cylindrical fixed stub mast</td>
<td>Reduce weight</td>
</tr>
<tr>
<td>Support Structure</td>
<td>Mast foundation rigidly attached to ship structure</td>
<td>Mast foundation attached to ships structure through tension piles and foot cell</td>
<td>To allow direct measurement of sail thrust generated and reduce the loads at points of attachment to the hull and minimize alterations to hull structure to accommodate the rig. In turn reducing installation costs for rig retrofits.</td>
</tr>
<tr>
<td>Wing Structure</td>
<td>Laminated wood frame bolted to rotating mast</td>
<td>Cored fiberglass framing bolted to rotating mast</td>
<td>Reduce weight</td>
</tr>
<tr>
<td>Flaps</td>
<td>Laminated wood frame/oven cured plywood skins</td>
<td>Cored fiberglass framing/oven cured plywood skins</td>
<td>Reduce weight</td>
</tr>
<tr>
<td>Area</td>
<td>2,998 sq. ft.</td>
<td>2,820 sq. ft.</td>
<td>--</td>
</tr>
<tr>
<td>Span</td>
<td>62.25 ft.</td>
<td>62.5 ft</td>
<td>Reduce structural loads and weight</td>
</tr>
<tr>
<td>Chord</td>
<td>32.5</td>
<td>32.5</td>
<td>--</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>2.64</td>
<td>2.77</td>
<td>--</td>
</tr>
<tr>
<td>Section</td>
<td>NACA 0018</td>
<td>NACA 0018</td>
<td>--</td>
</tr>
</tbody>
</table>

A general arrangement drawing of the MK II wing sail on a MINI class tanker is shown in Figure 40.
Redesign of the wing structure and covering to include cored fiberglass frames and fiberglass skin resulted in a 77% weight reduction in these elements. The reduced weight of the wing structure and skin in turn reduced the inertia and gravity forces imposed on the rotating and fixed stub masts. This reduced loading, in conjunction with changes in material and geometry, led to a 40% reduction in the weight of the masts.

Modular construction of the main wing sections was provided for in order to decrease the cost of final assembly and the time required for installation.

The basic design criteria, including the maximum wind speed at which the rig was designed to operate and the ship roll characteristics, were the same for the production prototype MK II design as for the MK I design. However, due to the reduced weight of the MK II rig, inertia and gravity forces only equalled 37% of the total design loads for the MK II rig as opposed to 50% for the MK I design.

The basic principle of operation of the wing rotation drive system was not changed in the MK II design. However, several component elements were redesigned to simplify operation and reduce the weight and cost of the system and to increase its operational reliability.

In summary, the MK II "production" design resulted in significant improvements in weight and cost within acceptable aeroelastic stability and gust response values. The rotating weight of the MK II design was reduced from 31,700 lbs. to 15,840 lbs. and the total weight including hull reinforcements from 71,700 lbs. to 40,150 lbs. Detail cost estimates show it to have an excellent Return on Investment (ROI) when built in production quantities. U.S. patents have been granted on its unique features. Foreign patents are pending at this point in time. One of these promising rigs has yet to be built and tested in commercial service.

**DESIGN VARIATIONS & POSSIBILITIES**

**Wing Section Variations**

The primary variables under the symmetrical wing section designer's control are the thickness, location of maximum thickness, and nose radius of the section. These section parameters determine the point of leading edge stall, whereas the flap geometry determines the trailing edge stall characteristics. The designer's goal is to balance the two so they occur at the same angle of attack.

The influence of thickness ratio on maximum section lift coefficient is shown in Figure 41. Note that the optimum thickness ratio for the unflapped sections is in the range of 12% to 18%, whereas the range for the sections with flaps is 18% to 24%. At thickness ratios below the optimum, leading edge stall occurs before trailing edge stall, while at thickness ratios above the optimum, trailing edge stall occurs first and is aggravated by increased thickness. The influence of nose radius can also be seen here, for note that for the same thickness ratio (e.g. 18%) the 00-series section has a much higher maximum lift coefficient than section of the 6-series family. This is due to its nose radius of 1.78% of chord for an 18% thick section as opposed to 1.06% for a 66-series 18% thick section.
Only maximum lift coefficient has been considered in the foregoing. Increasing thickness will increase the section drag of the wing; but the wing will operate predominantly in high-lift mode, where the 3-D induced drag dominates and section drag is a second-order effect [18]. Increasing thickness will have a favorable effect on structural efficiency, giving the wing greater depth in the plane of highest bending movement. Larger nose radius also makes the wing more tolerant to angle of attack fluctuations, an important consideration for airfoils operating on a rolling ship in the earth's boundary layer.

![Graph](image)

**Fig. 41** Variations of maximum section lift coefficient with airfoil thickness ratio for flapped sections [10]

**Boundary Layer Control**

The maximum lift on a wing is determined by the point of flow separation from the surface. The longer attached flow can be maintained, the higher a lift coefficient can be maintained. On a thin wing section the flow separates near the leading edge first, in the region where the pressure increases aft of the suction peak. Leading edge slats are often used to delay leading edge stall. Thick wing sections tend to suffer trailing edge stall first, downstream of the minimum pressure point. Trailing edge stall is normally delayed by using trailing edge flaps.

However, the maximum lift coefficients that can be obtained with a wing that has a leading edge slat and a pair of slotted flaps is about 3.3. The complexity of flaps and slats at these higher lift coefficients makes it worthwhile to investigate the trade-offs involved in active control of the boundary to delay separation.

Active boundary layer control involves either removing low-energy air or adding high-energy air in the pressure recovery region. Low-energy air can be removed by suction through slots, or air can be blown over the surface through backward-directed slots. The air can be handled through blowers and the exhaust (or intake) located at the top of the sail.

For an indication of the benefits and costs of active boundary layer control, refer to the graphs of Figure 42. Incremental lift coefficients for a given throughput of air were estimated from test data for an 18% thick wing section [19]. An increase in lifting ability of 50% can be achieved for an airflow of 1700 ft/second and power input of approximately 85 kw.

The payoff is more obvious on thick wing sections. The problem of delaying leading edge separation on wing sections less than 25% thick becomes difficult, and some early investigations avoided it by testing very thick sections. One investigator obtained lift coefficients of over 5 with 40% thick sections [20]. The Cousteau Foundation has applied this arrangement on the Moulin A Vent, claiming lift coefficients of 6 achieved regularly, and 10 on occasion.

Taking the thick wing section to its limits, Southampton wind tunnel tests report a maximum lift coefficient of 8 on a circular cylinder section. A Magnus-effect rotor is thick wing section boundary layer control taken to the ultimate. Low-energy air is removed from the suction side and blown to the pressure side by way of surface friction, and lift coefficients up to 16 have been measured [21].
Automatic Control

Wind Ship currently has automatic control systems under development for both the wing sail and the cat rig. The microcomputer based control system for the wing sail will perform the following functions:

- Trim the wing sail to the correct angle for maximum sail thrust.
- Align the flaps to achieve low aerodynamic drag when sailing close to the apparent wind.
- Deflect the flaps to increase lift when sailing off the wind.
- Feather the wing sail automatically when the wing cannot be effectively utilized, or when design loads are exceeded due to high wind speed or extreme ship motions.

At this time there are three alternate types of controls that are envisioned as suitable:

- Passive control system would rely directly on instantaneous wind conditions for positioning the sail. This control system is designed to maintain a fixed relationship between the wing sail and the wind direction.
- Open loop control system determines sail adjustment from wind speed and direction measurement possibly combined with other readings then referenced against empirical or theoretical data. This type of control is only as good as the approximate model which describes ship and sail performance.
- Measurement optimized or closed-loop feedback control system operates on the basis of optimizing some measured performance index such as sail thrust, ship speed or fuel consumption.

Figure 43 shows the block diagram of a force measurement optimized automatic control system for the wing sail. For this system, control logic is organized into two levels. One level adjusts the sail to an approximate position based on apparent wind speed and direction. The second level operates from an initial setting to optimize net rig thrust by executing small changes in the sail position and comparing measurements of rig thrust from the load cell. Where large changes in wind conditions are encountered, feathering control will override all other sail trim functions.

The inputs and outputs of a force measurement optimized automatic control system used to control the wing sail are:

**Inputs**
- Apparent wind speed
- Apparent wind direction
- Wing angle relative to ships centerline
- Flap angle relative to wing centerline
- Sail Thrust

**Outputs**
- Electrical Power Required
- Blower Delivery
- Maximum Lift Coefficient
WING SAIL RESEARCH, DEVELOPMENT & DESIGN PROGRAM

DESIGN VARIATIONS & POSSIBILITIES

Outputs
- Rotate wing clockwise/counter-clockwise
- "Drive" brakes on/off
- "Hold" brakes on/off
- Rotate flaps +45°/-45°
- Feather wing (release both brakes)

Inputs would be supplied to the control unit in the form of analog D.C. voltages from the sensors or measuring instrumentation. Outputs from the central control unit are discrete signals suitable for interface with relays which in turn activate solenoid controlled directional valves in the hydraulic system.

The automatic control system used in trimming the wing sail could be tied in to an automatic load control system. In this case, the main engine revolutions and propeller blade angle would be varied to maintain a constant ship speed, since the required main engine output is dependent on the amount of power contributed by the wing sail.

The 300 sq. ft. scale model wing sail was mounted in a flexible support frame which was restrained by a load cell. This arrangement facilitated the measurement of aerodynamic forces and is representative of the input equipment required for force optimized closed loop control. Further development of automatic controls for this approach is subject to availability of funding. However, operation of the wing sail on a "manual" pushbutton control basis will provide significant and valuable data to insure the development of the most practical automatic control system.

Fig. 43 Block diagram - automatic control system for 3000 ft² MK II wing sail
VI. MAGNUS ROTOR TEST AND EVALUATION

Preface

In our introduction of this paper we have noted Anton Flettner's important work both on wing sails and rotors. The author and others have previously paid tribute to Anton Flettner's astounding and brilliant work of fifty to sixty years ago including his integrated research program with respect to the Magnus effect and the applicability of the phenomenon to auxiliary ship propulsion:

- Small scale tests of rotor propelled models.
- Wind tunnel tests of the rotor vs. conventional sail.
- Continuing tests of the rotor in an auxiliary ship propulsion mode in commercial service.

Flettner's findings have been exhaustively reported, including by himself [2] and we will not repeat them here. However, his account is inspirational, instructive and a model of objectivity in research and development. It should also be noted that the world's environmental degradation due to the cumulative effect of CO₂ in the atmosphere (and the resultant Greenhouse Effect) which is already too apparent, would have been significantly decelerated if the application of his rotors for auxiliary ship propulsion had not been held up over the last fifty odd years by the precursors of World War II which diverted Flettner's efforts back to aircraft. The coincident availability of dirt cheap oil and WW II itself sadly ended his effort to apply the rotor to ship propulsion.

Wind Ship started intensive research on the Magnus Effect Rotor in 1982. In 1983 we instituted a program to design and test a prototype Magnus Effect rotor and an association was formed with T. Hansen of Windfree, Inc. who had been systematically testing Rotors for wind mill applications since 1974 [23]. As a result of this joint effort, a Magnus Effect rotor was installed, instrumented, and extensively tested aboard the 16-ton, 42-foot motor vessel TRACKER from June - November 1983. An arrangement of this rotor as installed is shown in Fig. 44.

Fig. 44 Experimental Magnus Effect Rotor
General Arrangement

The results confirm the work done by Anton Flettner in the early 1920's and the potential of the Magnus Effect rotor as a reliable, economically viable sail-assist device which can provide substantial fuel savings for modern fishing vessels and commercial ships.
As a cylinder in a cross flow is rotated, the air is sped up on one side of the cylinder, creating a vacuum, and retarded on the other side of the cylinder. The flow speed change can be associated with a pressure change by way of Bernoulli's Theorem, and the pressure differential gives rise to a lift force. Although the viscosity is the primary mechanism by which the flow is altered, ideal fluid models have some usefulness in understanding the flow pattern. Taking the two-dimensional flow around a circular cylinder with circulation, the complex potential at any point in the fluid can be described by using a doublet and vortex model [22].

As the cylinder circulation increases, the stagnation points move closer together until they meet when the vortex velocity component reaches twice free stream velocity (Fig. 45). As the circulation further increases, the stagnation points move out into the flow (Fig. 45).
A result of the rotor force being independent of the angle of attack is ease of operation. The
tilt force will always be perpendicular to the apparent wind direction, and so no angle of attack
control is required (analogous to the boom trim of a conventional sail). An operator simply has
two controls to handle while underway on a given course - main engine throttle and rotor drive
speed. Tacking means reversing the direction of spin.

Design of Magnus Effect Sail Power Units (SPUs)

The advantages of the Magnus Effect rotor can perhaps best be summarized if we look at the problem
of designing a rotor for auxiliary ship propulsion through the designer's eyes.

Forces and Moments

In order to obtain the maximum feasible amount of thrust from the wind, the effective sail area
(projected area times lift coefficient) should be as large as the boat can safely accommodate.

Compared to a cat rig soft sail of equivalent area times lift coefficient, the Magnus Effect rotor
will be less than 1/2 as tall and the sail area centroid only about 2/3 as high above the deck.
Thus, if the design is limited by mast height due to bridge clearances, etc., the effective sail
area can be four times larger than that of a soft sail. If the design is limited by the vessel's
ability to accommodate heeling moment due to sail force, the effective sail area can be twice that
of the soft sail.

Structure

Soft sails and wing sails are like airplane wings in that the direction of the largest loads
coincides with the minimum available structural depth. Thus much of the structural weight and
complexity comes from collecting pressure loads that are distributed over large flat area and then
carrying them down to the hull through masts and rigging or cantilever spars of high aspect ratio.

The cylinder, on the other hand, is an ideal structural shape. The thin skins are stabilized by
their curvature so that they can carry both the distributed pressure loads and beam bending loads
with nothing in the way of substructure except a few ring formers to maintain their shape. As a
cantilever beam, the cylinder of aspect ratio 5 or 6 has excellent depth resulting in bending
stresses that are so low that even fatigue should not be a problem.

Deck Space Requirements

The cylinder diameter of a Magnus Effect rotor is roughly comparable to the thickness of a wing
sail. The wing sail chord would be perhaps six times the barrel diameter or about four times the
endplate diameter. A soft sail cat rig of the same effective sail area would have a boom length
about 5 times the endplate diameter. Thus, the Magnus Effect rotor involves far less deck space
and interference with cargo handling and other functions.

Control and Configuration Adjustments

Since the Magnus Effect rotor has no angle of attack or stall angle, the usual sail problem of
adjusting the angle of attack does not exist. There are no configuration changes of any kind
involved with operating a Magnus Effect rotor and thus no crew requirement. The helmsman can
start and stop the rotor and select the RPM and direction of rotation.

Crew Safety

The danger of swinging booms is eliminated. The barrel and endplates have smooth surfaces which
can be touched without injury while they are rotating. The lower endplate also has a guard rail
which prevents inadvertent contact with personnel or cargo gear.

Weight

The weight of a SPU subtracts from the vessel's payload. This weight times the height to the
center of gravity of the system directly subtracts from the vessel's static stability. Thus it is
advantageous that the SPU be as light and as low as possible. The rotor is by far the lightest
sail system that we know of. Flettner said that his rotor system for the BARBARA weighed only 22%
as much as a conventional sail system. The optimized design of the second generation rotor system
that we are now testing will weigh about 5 lb/square foot of barrel area which would translate to
about 1/6 lb/square foot of equivalent soft sail area.

System Costs

The cost of any manufactured item can be projected in terms of its weight times a cost/unit weight
figure based on its complexity: i.e., labor content/lb and raw material cost/lb. Since the
Magnus Effect rotor can be very light and its components (mast, endplates, and barrel) are very
simple to manufacture, this system appears to offer the lowest installed cost of any sail system.
Design of Magnus Effect Sail Power Units (SPUs)

Durability

Production units may ultimately be made almost entirely of fiberglass whose toughness, high fatigue strength, and corrosion resistance should provide a long, maintenance-free operating life. However, aluminum as used in the Wind Ship prototype is entirely feasible and may prove to be cost effective for many applications.

Most devices designed to utilize low speed winds are particularly vulnerable to damage by wind storms when they are not in use. However, the Magnus Effect rotor cylinder is much less vulnerable than other sail systems. The cylinders when not rotating have a drag coefficient of only about .4. Thus the equivalent non-rotating flat plate drag area (area times drag coefficient) is only about 1/32 of the equivalent rotating lift area (area times lift coefficient). The TRACKER rotor non-rotating drag force should be less than the design maximum lift force until the wind speed exceeds 110 knots.

Inherent Load Limiting

Perhaps the most unique feature of the Magnus Effect rotor is its inherent load limiting characteristic which can result in a virtually stormproof sail system. Sixty years ago, Anton Flettner discovered that in using the Magnus Effect to achieve a superior sail for sailing ships he had also created a virtually stormproof system. Fig. 46 shows that the total (sail) force exerted by the wind on the spinning cylinders did not increase as the wind speed increased from 35 to 80 mph. Thus Flettner's ship was able to sail through storms that conventional sailing ships had to ride out with "bare poles".

The fundamental aerodynamic fact that with any type of sail or airfoil the lift force can increase without limit as a function of the square of the increase in wind velocity, has always been a major problem in the design of aerodynamic devices intended to function at low air speeds. Sudden storms can shred the sails and break the masts of sailing vessels. Wind storms frequently damage light airplanes parked on airports.

The Magnus cylinder is not subject to this problem because the circulatory flow that is necessary to produce aerodynamic lift is not produced by directly converting a portion of the wind energy but through totally separate and independent means. This independent production of circulatory flow by spinning a cylinder can easily be limited in an absolute manner since an increase in spin RPM requires a linear increase in the torque being applied to spin the cylinder. Thus torque limit devices such as shear pins or slip clutches provide an absolute safeguard against cylinder spin overspeed.

Fig. 53 shows the relationship in the Magnus Effect between the lift coefficient and the ratio of cylinder surface velocity (circulatory or spin velocity \( \omega \)) to wind velocity \( (v) \). If the spin velocity is limited to some absolute maximum value, as was the case with Flettner's ship rotors, any increase in wind velocity results in a decrease in lift coefficient. Since the lift force is a function of both lift coefficient and wind velocity, the two changes tend to cancel each other, resulting in a stormproof sailing vessel.

Design and Construction of the TRACKER Prototype Rotor

The rotor system was fabricated by Windfree, Inc. in California and shipped to Massachusetts for installation. The barrel itself is aluminum skin supported by a series of ring frames. The barrel is 45.5 inches (1.16 m) in diameter, 284.5 inches (7.22 m) high, and weighs 180 lb. The endplates are of aluminum construction. The aerodynamic loads are transmitted to the vessel by way of a bearing at the top of an internal mast. The bearing point is midway up the barrel. The rotor is driven by a hydraulic motor directly connected to the barrel by a drive shaft and spokes. The mast is an angle iron trusswork, 27 inches square. The weight of the system is carried on the vessel's keel, and bending loads are transmitted to the hull by a set of radial arms. (See Fig. 43)

Other materials have been considered for the barrel; wood and fiberglass are two of the more appealing alternates. A prototype design for the wood barrel was carried out, and the major problems were the limited fatigue life and non-homogeneity. Four laminates appear to give good strength-to-weight performance, with the outer layer grain running circumferentially to carry the hoop stresses induced by the rotation. Fiberglass is the preferable choice among the three materials as the best performer in terms of fatigue life, strength-to-weight ratio, and corrosion resistance, but bears the disadvantage of being relatively expensive.

The decision whether to operate the system above or below the first cantilever bending frequency has a large impact on the weight and cost of the system. The TRACKER system was designed so that its first natural frequency in bending would be well above our maximum operating speed of 660 RPM; the reality of fastening the structure to a venerable wooden boat so that it would not suffer damage from the rotor operation decreased the foundation stiffness and therefore the natural frequency so that the actual critical frequency occurred at about 500 RPM. A mast and support structure or "soft" system designed so that the critical rotation speed is below the operating range of the rotor would weight less than half as much as the stiffer system employed on the prototype. Wind Ship and Windfree will test a production prototype rotor incorporating a "soft" support system in 1985.
Design and Construction of the TRACKER Prototype Rotor (cont)

Predictions

Wind Ship's Sail-Assist Performance Model was used to predict the effectiveness of the rotor sail on TRACKER. The main inputs to the computer-based model are the hull characteristics (upright resistance, dimensions, effective draft) and the rig force polar. The results are shown in Fig. 47 and 48. Fig. 47 shows the model predicted speeds for TRACKER with her main engine off, as a function of wind speed and wind angle. Another way of operating is to use the engine to supply the additional power to maintain a given "floor" speed, and the throttle setting for various wind speeds and directions is presented in Fig. 48. Floor Speed is the term that describes an engine use strategy primarily used to reduce fuel consumption. Under this strategy, horsepower is adjusted (down or up) as required to compensate for the rig horsepower input whilst maintaining the desired minimum ship speed. The modeled rig thrust is shown in Fig. 49.

Measurements

The performance of the rotor was arrived at through three independent sets of measurements:

- Direct measurement of rotor forces through use of strain gauges
MAGNUS ROTOR TEST AND EVALUATION

Design and Construction of the TRACKER Prototype Rotor (cont)

- Measurement of boat speed; the boat speed and main engine turns indicating the amount of thrust contributed by the rotor
- Anchored tests.

The direct force measurements were of the net bending moment through the internal (stub) mast using strain gauges. The output of these gauges was calibrated by applying a known force at the internal masthead which is located close to the vertical center of pressure of the rotor.

The boat speed measurements followed a method outlined by Goudey and Linskey [24]. TRACKER was towed in both her powered and unpowered conditions with a dynamometer measuring towline pull. The result of this test is shown in Fig. 50. The normal powering level lies along the x axis, and a lower engine speed for a given boat speed can be attributed to net rotor thrust. The effects of heel are not accounted for and the indicated rotor thrust must be corrected for the induced drag of the hull.

The anchored tests were conducted in calm, currentless water with wind speeds ranging from 9-16 knots. TRACKER was held beam to wind by mooring lines to anchors perpendicular to the axis of the vessel + 15°. A stern anchor incorporated a dynamometer - see Fig. 51. The rotor was then operated and force recorded when the apparent wind was 90° from forward and at different barrel and wind speeds.

Fig. 52 shows the lift coefficients reduced from the three measurement methods.
The lift coefficients are presented as a function of speed ratio, the ratio of the barrel peripheral speed to the apparent wind speed. The average of these data are compared to other research results in Fig. 52. The agreement is fairly good. The lift-to-drag ratios are compared to those previously measured as plotted in Fig. 54. Differences could be due to any one of a series of causes including endplate size, ambient turbulence, or unsteady boundary layer effects. More testing is proceeding in order to isolate the cause. However, low lift-to-drag ratios are relatively unimportant for sail-assist vessels, as opposed to pure sailing vessels where they are of prime importance.

The waters of Vineyard Sound where most of the TRACKER tests were conducted generally experience summer winds of 16-20 knots. For this range of uniformly distributed winds the Wind Ship performance model predicted savings ranging 50-66% based on a constant boat speed of 6.5 knots. Actual fuel consumption tests using precision fuel measuring equipment over a period of several weeks confirmed this range of savings.

The future potential of the Magnus Effect rotor, as with all sail-assist devices, lies with its ability to provide a good return on investment by reducing fuel costs. The operating costs of the rotor are of course higher than for conventional passive devices, since it requires a nominal continuous power input to operate. The potential advantage of the rotor is in reducing the initial investment. The far smaller size of the rotor may lower the first cost of the device, and therefore improve overall cost-effectiveness.

By way of illustrating the capabilities of the rotor relative to other sail-assist devices with which Wind Ship has done extensive work, predicted fuel consumption rates for MINI-ships are
compared in Fig. 55. Wind Ship has extensive data on these vessels, and the prediction for the cat rig has been correlated with the actual results of more than a year's service. The sizes are based on Wind Ship's standard nominal sizes of 3000 square feet for wing sails and cat rigs and Windfree's design for a barrel of 360 square foot projected area. Comparing average performance at 6 knots, the wing sail saves 32%, the cat rig 26%, and the rotor 20% (after deducting the fuel for spin drive power). Thus assuming maintenance costs are the same for each rig, the rotor must cost less than 63% as much as the cat rig and less than 63% as much as the wing sail to be competitive on an overall cost-effectiveness basis. Detail costs estimates based on manufacturing drawings for all three rigs indicate that the rotor more than meets the above test.

![Graph showing fuel consumption with various rigs.](image)

The outboard profiles of the MINI-ships are shown in Fig. 56. Operational advantages of the rotor due to its small size are better visibility, less interference with cargo handling, and better bridge height clearance. These characteristics combined with its simplicity, a low confirmed initial cost and the rotor's intrinsic fail safe operation may help to spur the shipping industry to incorporate rotor sail-assist as a commonly accepted means of auxiliary propulsion to reduce fuel costs.

![MINI Ship Arrangements with Various Rig Types](image)
In designing a sail-assist ship from scratch or considering retrofit of an existing ship, the first part of the design cycle— including sizing the ship for the service intended and the lowest required freight rate (RFR), in that service, and 'proving' that it is a significant improvement over an optimized motor ship — can be done economically on a parametric basis using a computer aided analytical model. By way of example we have discussed the use of the Wind Ship design and retrofit analysis program and its validation in section IV of this paper. In section IX we tabulate and discuss the answers which modeling has produced for a variety of ship and rig combinations — mostly on a retrofit basis. With the validation of the modeling by the MINI LACE performance, we have a fair degree of confidence in the process and the Wind Ship model. It continues to be available to ship owners and other naval architects for use in solving their particular applications. Other similar programs of merit are, no doubt, also available.

Thus through the use of modeling techniques a full spectrum of possible rig sizes and types can be analyzed for a given ship and service, and the optimum rig parameters for the intended service determined. Hopefully, standard rigs will be available and fulfill the requirements. Otherwise rig design cycles of the type described in this paper will be required. Satisfactory rigid wing sail designs will depend on iteratively confirming flutter and gust response characteristics and designing out those which are unacceptable (section V).

The computer aided performance analysis will have dealt with stability and heel angle for the purpose of determining performance. But detail stability calculations must also be made in order to specifically determine GM with and without the rig as well as heeling and righting moment curves which in turn must be reconciled with applicable regulatory body requirements. Design wind speed and survival wind speeds must also be considered and finalized. This will depend on a route wind analysis and the considerations of rig horsepower polars and average rig horsepower for the voyage scenarios in question. In the happy circumstance of a new ship design the rig horsepower polars will be the basis for reducing the installed horsepower and bunkering requirements for the conventional power plant. These reductions will have to be cycled through the stability analysis. The finalized design wind speed and survival wind speed will be major determinants in finalizing rig scantling, its effect on cargo deadweight, on rig cost and in the selection of suitable standard rigs.

Wind Ship rigs have all been designed on the premise that commercial ship owners want ruggedly reliable operation at sea with no increase in manning requirements. Thus they are designed for hydraulic operation and push button control from the bridge by the watch officers. Automation factors are optionally available. All of them are designed for ease of installation on either new or existing ships and have built-in devices for measuring thrust in the direction of travel and feeding that information to the bridge and optionally to a 'black box.' They are also designed for a minimum of (zero) maintenance at sea (Proven in the case of the MINI LACE cat rig). These criteria naturally are reflected in the cost of our rigs (section IX). Rigs of lighter scantlings and less exacting operating criteria can be, and no doubt are, being built. This can be at less capital cost per unit of thrust if sail handling is aided by manpower or greater cost if lofty soft sail rigs with mechanical operations and remote controls are for some reason specified. Most high lift devices will of necessity be mechanically operated, well instrumented and some will depend on sophisticated automation. As noted elsewhere the rotor or SPINS'L can have very simple controls and is intrinsically fail safe. If loose footed sails are fitted, control of the clew against flogging and control of sail shape for maximum thrust must be considered as well as safety.

All rig applications will require consideration of bridge height clearances in ports to be visited, and potential interference of the rig(s) with cargo gear both aboard ship and shore side. Also visibility from the bridge as it is affected by the addition of the rigs and the location of ship's lights, radar, communications antennas must be dealt with. Helm balance must also be considered.

Once naval architects have access to a data base on sail assist which they feel comfortable with they should have no problems in designing superior sail-assist cargo ships as a matter of course. Practical economic trade off come naturally to them and the novel aspects of sail-assist rig design such as speed and horsepower polars will be easily assimilated.

We think it apt to conclude this section by repeating from the introduction to Chapter II of ref [11] the words of Thomas Riley Blankley, a "Naval Expositor" who in 1732 had this to say on rig alternatives:

"sloops - are Sailed and Masted as Mens' fancys leads them, sometime with one mast, with two and three, with Bermudes, Shoulder of Mutton, Square, Lug and Smack sails, they are in Figure Square or Round Stern'd."

The common cause of all concerned with rational use of wind power must be to get to see a significant quantity of modern rigs in every potentially feasible configuration and show that indeed they will work well for the shipowner at enhanced profitability. This will also be to the benefit of mankind as a whole through the reduction of fossil fuel emissions and conservation of oil for better use.
Over the years many types of lift-generating devices have been designed, to utilize the wind for ship propulsion. Figure 57 shows the maximum obtainable lift coefficients of several of these devices.

Five types of modern rigs have been tested on a large scale, the test results of which are available in the open literature. These rigs have demonstrated their ability to withstand environmental conditions, confirmed the wind tunnel predictions of their performance and demonstrated their mechanical reliability to a greater or lesser extent. They are:

- The 3000 ft² Wind Ship Cat Rig as successfully tested on MINI LACE for over two years commencing in 1981
- The 1000 ft² mechanical wing sail rig as tested on SHIN AITOKU MARU commencing in 1980
- The Magnus Rotor or SPINS'L as tested in commercial at sea by Flettener on BADEN-BADEN and BARBARA over several years, without incident, [1922-1930] (results confirmed by Wind Ship 1983 TRACKER tests)
- The feathering wing sail (300 ft²) as extensively tested by Wind Ship in 1982
- The aspirated ellipse or TURBOSAIL as tested on MOULIN A VENT in 1983

Of the recently developed non powered lift generating rigs, the rig with the most at-sea experience is the square wing sail, promulgated by the Japanese firm Nipon Kokan KK and the Japanese Marine Machinery Development Association (JAMDA). On the SHIN AITOKU MARU, the log and bulk carrier USUKI PIONEER, and other vessels this rig has a proven record of reliability. It is also the least efficient of the modern rigs, at least in its current implementation. Sail handling gear impedes air flow on the high pressure side of the wing, increasing profile drag (Figure 58). More importantly, though, the low aspect ratio of about 80% leads to a very high induced drag.

On the other end of the spectrum is the wing sail with single flap, the most efficient of the group, but the one with the least operational experience. Its efficiency results from its low profile drag, high aspect ratio, and the movable flaps, which give it a maximum lift coefficient ($C_{L_{max}}$) of 2.
PERFORMANCE COMPARISONS OF ALTERNATIVE RIGS TESTED AT LARGE SCALE

Almost as efficient as the wing sail is the cat rig. The cat rig, a conventional soft-sail device, is second to the NKK rig in sea miles logged, and its mechanical functions and reliability operational features are well proven. Its efficiency results from high aspect ratio and the controllability of its sail shape.

This leaves the two powered rigs. The lift coefficients these rigs achieve are much higher than the unpowered rigs, and thus the powered rigs can be much smaller for comparable propulsive force. However, these rigs require a power input that varies with the local wind speed, reducing their fuel savings. The aspirated ellipse is somewhat more efficient due to its control of the surface boundary layer, but the SPINS'L is able to provide much more propulsive force from a given area and has a larger degree of controllability to suit wind conditions. The SPINS'L, being supported at mid-height, has shown itself in sea trials to be less prone to damage than the aspirated ellipse or TURBOSAIL, which is cantilevered from the deck.

The two primary measures of a rig's performance are its lift and drag coefficients. Sailing to windward, the rig should have a high lift coefficient with a low drag coefficient (i.e. high lift-to-drag ratio). This requirement is not as restrictive in a motor-sailing ship as it is in a pure sailing ship, however, since the forward speed caused by the propulsion engine significantly reduces the leeway caused by rig drag. With the wind abeam, the rig's lift coefficient should be as high as possible. With the wind astern, one would like to have as high a drag coefficient as possible. In motor sailing, though, stern winds are seldom experienced, since the ship speed produced by the main engine moves the apparent wind forward.

Lift and drag coefficients alone do not fully explain the performance of sailing rigs, however their sail areas must be taken into account to determine the actual propulsive power developed

\[
\text{Lift} = C_L \times \text{SA} \times \frac{1}{2} \times \rho \times V^2, \quad \text{where:} \quad C_L = \text{Lift Coefficient} \quad \text{SA = Sail Area} \\
\rho = \text{Air Density} \quad V = \text{Wind Speed}
\]

Thus, in a given environment (\(\rho\) and \(V\)), the total lift produced by sailing rigs will vary with the factor \(C_L \times \text{SA}\). Similarly, the total drag will vary with \(C_D \times \text{SA}\).

Figure 59 contains lift/drag curves for the five modern rigs, with the coefficients factored by the non-dimensional quantity \(\text{SA}/3000 \text{ ft}^2\). In other words, these curves show the non-dimensionalized forms of \(C_L \times \text{SA}\) and \(C_D \times \text{SA}\) explained above. The sail areas were non-dimensionalized over 3000 ft\(^2\) because that is a typical size for a conventional (non-powered) rig.

The 3000 ft\(^2\) wing sail is, aerodynamically, the most efficient, producing the highest maximum lift force and doing so at a relatively low drag. The SPINS'L also achieves a high maximum lift force but at a higher drag than the wingsail. The SPINS'L is thus aerodynamically somewhat less efficient than the wingsail, but it is so much cheaper to produce, easier to operate and smaller (as shown at the bottom of Figure 59) that it appears to be a very satisfactory rig.

The NKK rig achieves its maximum lift force at a very high drag coefficient, and thus shows no advantage over the aspirated ellipse or cat rig, both of which achieve close to the same maximum lift with much less drag.

![Fig. 59 Rig Polar Comparisons](image-url)
IX PERFORMANCE & ECONOMIC MODELING OF RIGS FOR SELECTED SHIP APPLICATIONS

Since 1981 Wind Ship has analyzed over seventy-five different sail-assist 'candidates' in its retrofit analysis model. We have selected several of these ranging in displacement from 50 tons to 51,000 tons and tabulated certain of their motor ship characteristics, their sail-assist rig characteristics, route wind data and highlights of their modeled performance. The data is shown in Table 10, the ships being listed in ascending order of length between perpendiculars. We have also included two ships which we modeled in the conceptual/preliminary design stage for their potential as sail-assist ships:

- the conceptual design of the 20,000 DWT, MARAD general cargo ship
- a Panamax Bulker of 99,000 tons

The latter are the only ships included in the table where the installed horsepower required for the motor ship was reduced in size, based on the average rig horsepower calculated for the routes and services for which they were planned, with consequential incremental benefit to their ship economics over the straight retrofit ship. It was assumed that the retrofits would not be repowered.

Since we are presenting the data for purposes of comparing different ship sizes, types and rig configurations, we have only set out performance figures for the ships in fully loaded condition. Ships which travel in ballast or less than full loads for part of their voyages would show somewhat lower % savings for those portions of their voyages. The ships which generally show the greatest percentage savings are, as might be expected, those whose sail area/displacement coefficient \([SA/Disp]^{2/3}\) are the highest.

We refrain from showing estimated yearly savings for these ships in their sail assist modes since they depend on the ships operating scenarios and the local current price of fuel. The most important of the ship operating conditions is of course the ship's route and the route wind characteristics. The best North Atlantic route by far for wind conditions is New York to Reykjavik, Iceland, and return, but there is a paucity of cargo traveling on that route. At the other end of the wind spectrum we have found many routes in the Mediterranean and certain inter-island routes in the Far East that do not have sufficient wind to support economics sail assist operations.

Rig prices are also an important 'variable' in evaluating the economics of sail assist. However, at this state in the development of the art we are faced with the "which comes first, the chicken or the egg" paradox. Economics based on production quantities and costs are bound to be more advantageous than prototype costs. International exchange rates and government subsidies also influence costs to the shipowner. So far, with the exception of the private MINI LACE effort, only the Japanese have seen fit to develop and put large ocean going rigs to sea for test in commercial service. The MINI LACE rig was only constructed, however, after a favorable payback analysis, based on the estimated prototype rig cost, had been performed and the fuel savings at the current fuel prices rendered a satisfactory payback to the owner. The cost of the Japanese rigs is not available and we cannot specifically quantify it, but they are obviously expensive (Fig. 58). Also Wind Ship estimates that the specific fuel savings at sea due to the USUKI PIONEER rig is in the range of 5%.

For the guidance of shipowners and naval architects and other rig builders we tabulate 1984 rig prices for U.S. built Wind Ship rigs in roughly the same rig horsepower range.

<table>
<thead>
<tr>
<th>Rig Type</th>
<th>Prototype</th>
<th>Each of 10</th>
<th>Each of 100</th>
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<td>198</td>
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<td>3000 Ft.² Wing Sail</td>
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<td>227</td>
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<td>450 Ft.² Rotor</td>
<td>156</td>
<td>112</td>
<td>95</td>
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</table>

We show the price for a U.S. built prototype and for production units in quantities of 10 and 100 based on conservative learning applied to the appropriate cost factors. These prices would be considerably lower if rigs were built (under license of course) in the Far East or perhaps in Europe.

Using MOBIL LUBCHEM as an example of a ship whose performance as a sail assist vessel has been predicted by others, we have, using our retrofit analysis model, developed some figures for the ship based on her actual routes, the wind conditions which she sees thereon, but using an optimistic 245 days at sea rather than her actual of 225. We have also optimistically used full load voyage displacements only. Three different rigs are analyzed based on their estimated installed costs (1984) as manufactured in the U.S. noted above, and alternately for UK manufacturing and Far East manufacturing. This data is presented in Table 11. We assume that an optimistic payback based on fuel savings of 3.0 would be acceptable to the shipowner as a basis for investment in the rig. None of the US built Wind Ship rigs meet this criterion but the rotor comes close with 3.2 year payback for one rig and 3.6 for two. Built in the UK the rotor improves to a 3.0 year payback for one and 3.4 for two but the latter is eclipsed by the walker wing sail at 3.1. If the assumptions we have used for rig cost estimates are correct. Built in Asia all of the Wind Ship rigs have fairly respectable paybacks but only the rotor comes in under 3.0 years. We assume the Walker Wing Sail would also. More sophisticated analysis must include...
<table>
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<th>LBP (ft)</th>
<th>Displ. (LT)</th>
<th>DWT (LT)</th>
<th>Beam (Knots)</th>
<th>Service Effy at Ser. Speed</th>
<th>SHP (MCR)</th>
<th>SFC Fuel Rate</th>
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</table>

Notes: 1 Conceptual ship designs for sail assist
2 As given by owner's otherwise value is modeled from other ship characteristics.
3 HP in Bench Mark Motor Ship
4 Reduced Installed HP in Sail Assist Ship
5 CP = Controllable pitch propeller ST = Steam plant
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<th>Line</th>
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<th>Rig Design</th>
<th>Wind Speed (knots)</th>
<th>Displ. 2/3</th>
<th>Route</th>
<th>Average Distribution</th>
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Note: Rig Horsepower based on following CLmax: Cat - 1.5, Wing - 2.0, Rotor - 8.6.
PERFORMANCE & ECONOMIC MODELING OF RIGS FOR SELECTED SHIP APPLICATIONS

volume of fuel saved, cost of money, etc. For volume of fuel saved two wing sails at $108,000 savings per year are the clear winners with two cat rigs next and two rotors and the Walker wing sail tied for third.

Table 11 Modeled economic return of various rigs on MOBIL LUBCHEM (based on rig manufacturing lots of 10)

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<tr>
<th>No. of Rigs</th>
<th>Type</th>
<th>No. of Total Savings $000</th>
<th>% Savings Benefit</th>
<th>$ Annual Shipowner's Rig Cost Based on US Rig/Est. Manufactured in</th>
<th>Simple Payback (Years) of Rig Cost from Net Yearly Benefits for Rigs Manufactured in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wind Ship Cat Rig</td>
<td>3000</td>
<td>.69</td>
<td>10</td>
<td>43125 37585 230.1 211.6 120.7 6.12 5.6 3.2</td>
</tr>
<tr>
<td>2</td>
<td>Wind Ship Cat Rig</td>
<td>6000</td>
<td>1.14</td>
<td>16.8</td>
<td>71250 60170 4602 423.6 241.4 7.6 7.0 4.0</td>
</tr>
<tr>
<td>1</td>
<td>Wind Ship Wing Sail</td>
<td>3000</td>
<td>.97</td>
<td>14.3</td>
<td>60625 57600 261.7 240.6 184.4 4.55 4.2 3.2</td>
</tr>
<tr>
<td>2</td>
<td>Wind Ship Wing Sail</td>
<td>6000</td>
<td>1.73</td>
<td>25</td>
<td>108125 101875 523.4 481.2 366.8 5.13 4.7 3.6</td>
</tr>
<tr>
<td>1</td>
<td>Wind Ship Rotor</td>
<td>450</td>
<td>.55</td>
<td>8.1</td>
<td>24375 24372 111.7 103.7 82.8 3.2 3.0 2.4</td>
</tr>
<tr>
<td>2</td>
<td>Wind Ship Rotor</td>
<td>800</td>
<td>1.07</td>
<td>15.8</td>
<td>166875 60875 223.4 207.4 165.6 3.6 3.4 2.7</td>
</tr>
<tr>
<td>3</td>
<td>WALKER Wing Sail</td>
<td>3258</td>
<td>1.053</td>
<td>15.5</td>
<td>66913 56913 180</td>
</tr>
</tbody>
</table>

Table 12 Modeled Economic Return for Rigs on MOBIL LUBCHEM (based on rig mfg. lots of 100)

<table>
<thead>
<tr>
<th>No. of Rigs</th>
<th>Type</th>
<th>$ Annual Benefit $000</th>
<th>Simple Payback (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>WS Cat</td>
<td>60.2 396 354 200</td>
<td>6.5 5.8 3.3</td>
</tr>
<tr>
<td>2</td>
<td>WS Wing Sail</td>
<td>101.9 454 406 310</td>
<td>4.4 4.0 3.0</td>
</tr>
<tr>
<td>2</td>
<td>WS Rotor</td>
<td>60.9 190 169 134</td>
<td>3.1 2.8 2.2</td>
</tr>
<tr>
<td>3</td>
<td>WALKER Wing Sail</td>
<td>56.8 166</td>
<td>2.9</td>
</tr>
</tbody>
</table>

We would have liked to add data for a 21% wing sail with flap as aspirated (C_{max} = 3.6) and the MOULIN A VENT with a C_{max} of 6) but have not developed the costs of the former or seen any published costs for the latter.

For proponents of fore and aft labor intensive rigs we can report that RAINBOW WARRIOR (formerly SIR WILLIAM HARDY), Figure 60, and the first vessel listed in Table 10, has now been rigged with a simple ketch rig designed to commercial specifications by Wind Ship Co. On sea trials off Jacksonville, FL on March 14, 1985 she attained 9 or more knots with the wind abeam at 18 to 20 K. Since the crew are volunteers and did much of the installation work, the cost of this labor intensive rig, in the neighborhood of $50,000, installed, will be more than paid back through fuel savings on the ship's proposed itinerary to the South Pacific over the next two years. The ship is instrumented, the data will be made available by the Greenpeace organization who own and operate her. Notice that RAINBOW WARRIOR has the highest sail area/displacement ratio of any of the ships listed in Table 11.

Oceanographic ships are another potential application for sail-assist. Indeed the most famous precursor of modern oceanographic ships, ATLANTIS, was a ketch rigged motor sailor built in 1930. She still earns her keep as a research vessel. An analysis of the oceanographic vessel KNORR was conducted by Wind Ship for the US Navy Office of Naval Research in 1983 [28]. She is listed in Table 10 and but for the small number of days in transit/year (110) in her operating scenario would have benefited economically from sail assist. More traditional hull forms such as
PERFORMANCE & ECONOMIC MODELING OF RIGS FOR SELECTED SHIP APPLICATIONS

R.V. OCEANUS, also operated by Woods Hole, would do much better under sail-assist. Her hull form is not unlike that of RAINBOW WARRIOR whose traditional British trawler hull form is well nigh perfect for a reasonably heavy displacement hull in a motor-sailing as opposed to a sail-assist mode (Fig. 1).

But naval architects are constantly seeking for innovative ways of doing things and this brings us to the SWATH type of hull which is currently, in contemplation at least, extremely fashionable in oceanographic vessel planning circles in the US. Wind Ship, through the courtesy of Alan C. McClure Associates of Houston, has analyzed what two 900 ft$^2$ rotors, operating in uniformly distributed winds would do for a 2970 ton swath vessel. The impressive results are shown in Table 13. A sketch of such a vessel underway is shown in Figure 61. Again the bottom line economics of rotors or other rigs on SWATH vessels will depend largely on the ship's operating scenarios and days at sea.

<table>
<thead>
<tr>
<th>SHIP SPEED (KNOTS)</th>
<th>14' DRAFT</th>
<th>28' DRAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QTY SAVINGS</td>
<td>% SAVINGS</td>
</tr>
<tr>
<td>5</td>
<td>.3 LT/DAY</td>
<td>21%</td>
</tr>
<tr>
<td>7</td>
<td>.5</td>
<td>37%</td>
</tr>
<tr>
<td>10</td>
<td>.9</td>
<td>19%</td>
</tr>
<tr>
<td>14</td>
<td>1.3</td>
<td>7%</td>
</tr>
</tbody>
</table>

NOTE: These values are probably understated due to the lack of data available about hull induced drag of swaths at the time of the evaluation.
Wind Ship's efforts to prove the economic viability of wind power commenced in 1978 when Arabian crude was $12/bbl. Our fundamental research on economics was done in 1980 on the basis of oil at $20/bbl. Subsequently the price of oil moved on up to a peak of $39/bbl in 1981. It now hovers precariously around $26-27. Some seers predict that the price will not hit the equivalent of $31/bbl in 1981's again until the year 2000 or so and will only reach $45.00 by the year 2010.

As noted in Section IV, MINI LACE economics in 1981-82 were outstanding based on gasoil of $327/metric ton. Gasoil is now $245/ton at best. The pressure this puts on rig economics is apparent in the MOBIL LUBCHEM analysis we have set out in Section IX. Rigs can be economic but only if the best aerodynamic and economic performers are built in the UK, Europe or Asia where manufacturing costs are lowest. The US is practically out of the picture as a rig manufacturer if not as a licensor of rigs for as long as the dollar remains strong.

Another major, if not absolutely controlling factor, is the economic health of shipowners worldwide. In 1981 when MINI LACE sailed proudly to sea a principal index of economic viability for the shipping industry - 12 month charter rates - stood at heights which in retrospect look like Mount Everest. 25,000 DWT bulkers, a prime target for sail assist rigs, commanded 12 month charter rates of $11.40/DWT/Mo. Other rates were $10.10 for 35,000 DWT, $7.30 for 85,000 DWT and $4.60 for 100,000 DWT. By mid 1982 these had dropped to $4.50 for 25,000 DWT, $3.00 for 35,000 DWT, $1.5 for 85,000 DWT and $1.00 for 100,000 DWT. At the time this paper is written (March 1985) a 25,000 DWT bulker built in 75-78 commands a charter rate of $4.60/DWT/Mo. Tanker charter rates are scarcely more glittering.

This stubbornly prevailing condition has forced many ship owners out of business and those who continue to operate portions of their fleets are, if not unprofitable, generally deprived of the excess cash flow which they might consider for investment in something new regardless of how good the projected forecast fuel savings and return on investment appear to be.

It is of interest in this regard that actual new construction of ships in the 25-40,000 DWT range has in the last few years exceeded by 50 percent or so, Wind Ship's private forecasts. This blip on the curve was largely due to Sanko Steamship Company's contracting for 100 or so new ships, some in the size range most advantageous for sail-assist. [Sanko has since become insolvent and has cancelled a number of these ships.]

In other words, as seen from the Atlantic Coast of USA there is in existence a worldwide shipping depression which has been in force since 1981 and for which there seems to be no end in sight. It would be presumptuous at this point in time to class sail-assist devices as established ship propulsion power plants along with diesel engines. But it is to be noted that even the leaders of the marine diesel business have recently suffered significant sales drops and unprecedented financial losses despite having outstanding products of proven reliability and fuel economics on the market.

The cause of the shipping depression and its cure is beyond the scope of this paper and may be beyond the scope of the combined governments and economic power structures of the world maritime nations to cope with in this century.

Narrowing back in on the prospects for sail-assist we can look back and conclude that sail-assist missed a good chance to establish itself in the 1980-81 period. The momentum for fuel conservation brought on by the oil embargo of 1972 was still tremendous. It had slowed down ships to economic speeds. It had accelerated the development of impressive improvements in diesel engine economics - of a magnitude not considered possible in 1970. It had led to shore side fuel economies and energy conservation. Most of all - shipping was profitable. Thus, had viable sail-assist rig designs been generally available to the shipping industry for retrofit in 1981 we believe they would have sold and sail assist would now be established in the marine industry. As it was, sail assist rigs were still under development and it is only since 1983/84 that they have been ready to release in quantity production anywhere in the world.

In the US sail-assist has never enjoyed tax credits or incentives of the kind which generated the California Wind mill business. In that case accumulative tax credit of 25% each from both the federal and state governments made ownership of windmills attractive to investors even if the windmills broke down after a day or two of operation. A new industry was created which may commercial ships under charter to the Military Sea Life Command.[29] Data on some of these ships in a sail-assist mode are noted in Table 10 and as will be noted nominal amounts of sail-assist on these ships produce significant savings. A recent proposal to install full scale rigs for continuing sail-assist research and testing on the government owned training ship GOLDEN BEAR has been put indefinitely on the back burner. Thus, today fuel savings is no longer a priority item either in the US Navy or in the US Maritime Administration. Neither is the sponsorship of advanced research in that area.

In Japan the combined weight of the government and the marine industry has kept up research into and investment in prototype ships incorporating fuel savings techniques on an ever increasing scale. In 1984 they put out individual rigs which finally exceeded the MINI LACE rig's 3000 ft
area if not its aerodynamic efficiency. It is of interest that there is to date little overt evidence of substantial Japan research on high lift devices. Their present rigs do not contribute more than 5-10% of the overall 50% fuel savings claimed and no figures are available on rig costs or return on investment for rigs alone. Nor has the sail assist concept has yet spread like wild fire through the Japanese owned shipping fleet.

The vigorous and well financed effort by Cousteau and the Pechiney organization backed by the French Government will yield interesting results including no doubt an intense marketing effort. At best, confirmed results from the use of the French sail assist rig(s) on commercial ships of substantial dead weight capacity are several months or years away. As of this writing we have no word of the British, Walker wingsail going to sea.

There is sadly a global trend noted elsewhere in this paper which will increasingly and adversely affect the sail-assist industry. It stems from the "Climate Crisis" caused by the exponential and irreversible CO2 build up in the earth's atmosphere. This in turn is a function of the world's energy oriented industrial society driven by both the bottom line syndrome and economic models neither of which give any weight whatsoever to factors inexorably destroying the world's environment and its vital natural eco-systems to say nothing of resources which man cannot replicate.

The CO2 build up, of course, creates the "greenhouse effect." The greenhouse effect induces global warming. Responsible scientists measuring build up CO2 in the atmosphere, decreasing thickness and disappearance of the polar ice pack and other symptoms over the last 30 years are universally alarmed and concerned for the future of mankind anywhere on earth [31]. Their concern has dented the armor of our political and industrial leaders scarcely one iota.

Why specifically is the exponential and irreversible build up of CO2 (20% since 1920) a threat to the future of sail-assist? Simply because one of the little studied, adverse effects of the build up (we will not go into the more dramatic and devastating ones here) is to decrease the temperature imbalances which generate the winds, cause ocean currents and create regional climates. Anyone who goes to sea can, if he thinks, identify his own private evidence that this is so and that it's happening before our very eyes. Trade winds don't blow when they're supposed to - or they blow weakly and often in untraditional directions. Average wind velocities measured consistently at the same geographic point drop 10% or so over a 6 year period (Boston). Violent weather still occurs but increasingly there are more and more periods of coastal calm that fall into no traditional weather pattern. Unprecedented tropical heat waves invade the temperate zones; interrupted by cold episodes. These are in both winter and summer and each year set new records for temperature levels and duration. Overall statistics will no doubt catch up with this trend and ultimately be reflected in a lowering of the present global average wind speed of 13.7 knots or so. But ship economics analysts should be alert to a continuing trend of decreasing wind velocities and therefore rig horsepower from a given size of rig as we approach the year 2000. And, if we believe the oil price predictions noted above, the price of oil will not have increased sufficiently in real $'s to make the necessarily larger rigs robust economic performers.

This is not a pleasant aspect of sail-assist future for the authors to report on - particularly since the prime motivation in our own sail-assist enterprise has been the possibility that a significant dent (1 or 2%) in the world's CO2 generation could be made by putting auxiliary sailing rigs on commercial ships at net economic benefit. We hope our warning will be taken seriously by those whom we address with this paper. Perhaps those sincerely interested in sail-assist as a potential benefit to mankind will collectively help to generate awareness of the CO2 problem amongst the general public. This could in turn help stimulate the responsible government and industry actions to avert an environmental disaster more surely devastating to life on earth than the threat of nuclear holocaust. The latter currently is less certain of happening than a climatic disaster simply because there is a chance that buttons will not be pushed to send nuclear weapons flying. Only a worldwide change in human perceptions, values and lifestyles can avert the climatic holocaust. On the other hand, the solution in the form of a drastic change to an environmentally oriented social system and set of values would most certainly create an unprecedented and badly needed economic boom.
XI Recapitulation

It has now been proven at sea that the hypotheses of 1981 are valid. Sail-assist does yield significant fuel savings on almost any hull form from barge like configurations to catamaran type hulls.

Properly engineered rigs do not require additional crew, or on board maintenance and will provide a safe, trouble free form of auxiliary power.

Past prejudice against sail-assist with respect to maintenance of schedule and reliability has been proven as unfounded by the MINI LACE and Japanese full scale tests in commercial service.

Ship performance can be modeled accurately for a wide variety of hull forms using existing analytical techniques. Therefore, ship designers and shipowners can with confidence reduce installed horsepower by average rig horse power expected. But rigorous analysis is required both for new construction and retrofits before proceeding.

A variety of rigs work well and are now available for the quantity production which will yield lower rig prices and satisfactory returns on investment.

Development of the sail-assist business has, since 1981 been impeded by a stubborn worldwide depression in the shipping industry which has inhibited investment by shipowners in capital improvements of any kind.

High lift 'power assisted' sail-assist - devices such as the Flettner rotor and the aspirated ellipse show economic advantage over unaspirated wings and soft sails for all ship sizes at the present rig cost relationships. But the latter have several advantages. Their potential should not be discounted and prototype test cost engineering of them should continue.

Oceanographic vessels are good candidates for sail-assist but the market is limited.

The geometry of the Flettner Rotor, its fail safe characteristics and its inherent simplicity, make it ideal for application to fishing vessels of any size.

More research on sail-assist as called for in [1] and [30] would be extremely useful to the marine industry but it is not a real prerequisite to getting more working rigs to sea.

Sail-assist is not a universal answer as to how to achieve fuel savings. Slower ship speeds, vastly improved diesel engine fuel economics and improved hull forms yield good results. Nevertheless, sail-assist works best at the optimum point for economy on the speed power curve and will pay for itself even when considered for use with modern power plants on new construction.

Retrofit of existing ships with less than optimum power plants will pay out for owners thereof, subject to specific prior analysis.

Modern sail-assist rigs can easily be retrofitted and even transferred from ship to ship for a useful economic life equivalent to that of a ship.

Sail-assist rig economics are sensitive to oil prices which currently are weak. Responsible forecasts of future oil prices do not indicate spectacular increases. This is contrary to logic since known oil reserves are dropping.

Wind patterns and wind velocities are adversely affected by the CO2 induced 'climate crisis'. If the present exponential rate of growth in the amount of atmospheric CO2 is unchecked, there will be a significant adverse effect on sail-assist rig economics by the year 2000 - when the 'climate crisis' will have become fully established. Mitigation of this adverse trend will require a convulsive world wide change in values and western pattern life styles including concerted government actions world wide. The prospects for engineering such a change are not good but must be pursued with vigor.

Fuel savings through sail-assist is economically viable, socially and morally on target and should be pursued with renewed vigor. The governments of all maritime nations should be encouraged to support it as part of the solution to the 'climate crisis'!

Progressive shipowners who do have cash reserves to invest in rigs should, after careful analysis, do so - thus contributing their leadership toward rational use of energy and mitigation of environmental decay even as they profit.
REFERENCES


4. Letter from Seagroup, Inc., dated December 2, 1982, reporting the performance of the MINI LACE vs. two sisterships. Motor ship fuel use was reported as 2.79 tons/day on the average. Generator fuel was observed from at-sea data to be .3 tons/day, so the main engine fuel rate used was 2.49 tons/day.


REFERENCES


ACKNOWLEDGEMENTS

This paper could not have been written without the prior outstanding work by the many who contributed to Wind Ship's basic research and engineering analyses on sail assist as reported in "Wind Propulsion for Ships of the American Merchant Marine"[1]. This group included, notably, my co-authors of that report:

George L. Clemmer  
A. P. Bates, Jr.  
John E. York  
Dr. James M. Mays  
Maurice A. Glucksman

Other major contributors to the research were Dr. P. A. M. Spierings, John G. Lord, William P. Carl and Dr. Henry S. Marcus.

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The Wind Ship Company would not have been formed without the enthusiastic urging and generous financial support of the late Philip S. Weld.

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John M. Bradley  
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Paul D. Cavanagh  
Albert Pratt  
Forrester A. Clark  
Nicholas S. Schauss  
Allerton Cushman  
Barbara D. Schauss  
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Frank Simon II  
Beatrice B. Frantz  
John J. Wilson, Jr.

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For all of the above as well as the unstinting contribution of my co-author I am deeply grateful.

Lloyd Bergeson
APPENDIX A

SYNOPSIS OF WIND SHIP’S BASIC RESEARCH FINDINGS ON SAIL-ASSIST

ABSTRACT

A systematic assessment of the technological and economic feasibility of sail power for commercial ships was conducted by the Wind Ship Company in the period 1979-1981. This work was partially funded by the U.S. Department of Commerce, Maritime Administration (MARAD). A full report of the work, “Wind Propulsion for Ships of the American Merchant Marine”, L. Bergeson et al was published in March 1981 as MARAD Report #MA-RD-940-91034. Various sailing rig concepts were considered, and a wing sail, similar to an airplane wing mounted upright on the ship’s deck, appeared to offer better overall performance than cloth sail rigs. Based on parametric studies in which required freight rate is used as the economic measure of merit, sail-assist ships are found to compete favorably with conventional ships over a wide range of ship speeds. Sail-assist ships have sailing rigs of moderate size and in comparison with conventional ships, power plants of fractionally reduced size. The cost of such ships is found to be similar to the cost of conventional ships, since the saving in power plant cost offsets rig cost. At sea these ships burn 15 to 25 percent less fuel than conventional ships, and thus enjoy reduced voyage expenses. This advantage can be further enhanced by ship routing which makes use of real time weather information. The conceptual design of a 20,000 DWT multi-purpose wing sail ship indicates no major technical barriers to the development of sail assist hardware. Based on the overall findings of the study, an aggressive sail assist hardware development program seemed warranted.

INTRODUCTION

The world shipping fleet consumes 730 million barrels of petroleum annually at a cost of approximately 30 billion dollars. This is about 3% of world petroleum demand. The price of marine fuels has multiplied more than 15 fold during the last decade and has become the largest component of operating costs for maritime shipping. Even in the face of these fuel cost increases, international oceanborne trade gives every indication of continued expansion. Shipowners, naval architects and governments of nations around the world have been moving rapidly to cut marine fuel costs through conservation or the use of alternate fuels. Wind propulsion is an alternate source of motive power, and the focus of this report.

RIG ALTERNATIVES

In order to focus attention on sailing rigs showing the most merit, a first order evaluation of the eight wind propulsion alternatives shown in Figure 1 was made. The wind turbines and Flettner rotor were eliminated from further consideration in the present study based on the following rationales: Wind turbines of the size required for marine propulsion have not been proven reliable in land based applications. When longevity problems which currently plague large wind turbines have been overcome, further examination of marine applications will be warranted. The Flettner rotor does show substantial potential for marine propulsion. However, the paucity of reliable aerodynamic data related to power input requirements provides little basis for system design and performance analysis and the development of such data was beyond the scope of the present study.

Conceptual designs were developed for the five sailing rigs shown in Figure I. Based on these designs, weight, cost and aerodynamic performance were estimated, and the rigs were ranked according to relative merit. The wing sail was found to be superior in terms of aerodynamic performance. It also ranked highest in operational and safety considerations. Of the other rigs examined, the stayed fore and aft, square and unstayed cat rigs ranked second, third and fourth in terms of initial cost effectiveness. The unstayed cat rig ranked best in terms of aerodynamic effectiveness, operational and safety considerations, but has slightly higher weight and maintenance costs.

The five rig concepts considered in the rig design study were all found to be technically feasible. Development can be accomplished through the adaptation and application of design, testing and analysis techniques which are presently available. The cat and wing sail rigs were chosen as representative of rigs likely to be built in the near future.

INTEGRATED MODEL

A major part of the research conducted with the assistance of MARAD was the development of an integrated model; the objective being to systematically quantify the overall economics of sail propulsion so that the impact of ship size, ship speed and other primary parameters could be studied. This model comprises two sub-models, performance analysis and ship syntheses.

The performance analysis model applies to the full range of sail powering levels from conventional motor ships to pure sailing ships. It derives average ship speed and fuel consumption with the following procedure: Models of the hydrodynamic and aerodynamic forces and moments acting on the ship are developed; ship speed and engine power setting for given wind conditions are determined; finally a statistical model of the route wind is applied to yield average voyage speed and fuel use.

Note 1. This synopsis is drawn from a paper presented by L. Bergeson & G. Clemmer at the Fifth Biennial Wind Energy Conference, Washington DC, October 5, 1981.
APPENDIX A
SYNOPSIS OF WIND SHIP'S BASIC RESEARCH FINDINGS ON SAIL-ASSIST

The ship synthesis procedure synthesizes principal characteristics of hull and sailing rig, and estimates weight, stability, building cost, and operating and voyage expenses. These are combined with the performance predictions to determine the economic merit of the ship using required freight rate (RFR).

RFR is the freight rate that a shipowner must charge to cover operating expenses and provide an appropriate return on the capital invested. The RFR's used in the study are based on shipbuilding and operating costs prevailing in the U.S. These costs are two to three times those prevailing elsewhere in the world, and in fact most U.S. flag shipowners receive substantial subsidy from the U.S. government. Since the fuel costs in the U.S. are at or below those prevailing elsewhere, these RFR's show less sensitivity to fuel savings than world fleet RFR's. Thus the results of the study should be a conservative indication of the potential benefit of sail assist for world shipping economics.

The performance and ship synthesis models are fully described in Chapters III and IV of the MARAD report along with a discussion of their perceived limitations and areas meriting further refinement, extension and development.

PARAMETRIC STUDY

Using the integrated model, a parametric study was performed to determine the general effects of ship size, ship speed, and hull and rig parameters. Motor ships, cat rig ships and wing sail ships ranging in size from 2,000 to 38,000 CDWT (cargo deadweight, long tons) were analyzed. Based on an analysis of opportunities for sail assist in the U.S. fleet, a ship size of 20,000 CDWT was chosen for detail study. Hull and rig parameters were optimized for a 20,000 CDWT wing sail ship, as were hull parameters for an equivalent motor ship. Given these two ships, the sensitivity of the relative economics to various parameters was determined. The principal findings developed in this exercise are presented below.

Ship Size and Rig Type. Figure 2 presents RFR versus average speed for three ship sizes. The wing sail ships have lower RFR's than the cat rig ships. This result is consistent with the merit ratings reported earlier. The economic advantage of sail-assist is greater on the smaller ships. This is primarily due to the fact that sailing rig cost per unit area increases for larger rigs, while cost per horsepower and specific fuel consumption decrease for larger engines. At present fuel prices, (based on $20/bbl for Arabian crude) cat rig ships are competitive up to 20,000 CDWT, while wing sail ships are competitive up to at least 40,000 CDWT.
APPENDIX A

SYNOPSIS OF WIND SHIP'S BASIS RESEARCH FINDINGS ON SAIL-ASSIST

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Average Speed (KTS)</th>
<th>Fuel Cons. (LT/Year)</th>
<th>RFR ($/LT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Ship</td>
<td>10.5</td>
<td>1,335</td>
<td>24.73</td>
</tr>
<tr>
<td>Cat Rig</td>
<td>10.9</td>
<td>1,098</td>
<td>24.28</td>
</tr>
<tr>
<td>Wing Sail</td>
<td>10.0</td>
<td>1,005</td>
<td>23.69</td>
</tr>
</tbody>
</table>

Figure 2: Required freight rate and fuel savings for three ship sizes. RFR is in dollars per long ton per round trip. Since RFR is sensitive to ship hull form, these have been optimized to minimize RFR. Sailing rig parameters are not optimized, thus RFR savings shown are conservative estimates. All ships operate in a wind distribution with 16 knot average speed and equal directional probability.

Ship Speed. The study considered motor and sail-assist ships with powering levels suitable to achieve average speeds ranging from 10 to 20 knots. Over this speed range, sail-assist ships show a nearly constant economic advantage over motor ships. Thus, there is no economic barrier to the viable operation of sail-assist ships at speeds competitive with conventional motor ships. RFR versus average speed for 20,000 CDWT motor and wing sail ships of optimized hull form are shown in Figure 3.

Figure 3: RFR vs. average speed for 20,000 CDWT motor and wing sail ships of optimized hull form. The impact of rig parameter variations is shown in the dashed box.
SYNOPSIS OF WIND SHIP'S BASIC RESEARCH FINDINGS ON SAIL-ASSIST

Fuel Savings. As shown in Figure 2, the sail-assist ships save 18 to 25% of the annual fuel consumption. Optimization of rig parameters to minimize RFR saves 2 to 5% more fuel at present fuel prices. If a sail-assist ship is designed to have an RFR equal to the motor ship and save the maximum amount of fuel, the fuel savings are greater.

Engine Size. In addition to fuel savings, the power generated by the sailing rig allows a reduction in engine size similar to the percentage fuel savings. For a given vessel size and sailing rig, the rig power output remains essentially constant, independent of average ship speed. Thus, as higher fuel prices force lower average speeds and smaller engines in both motor ships and sail-assist ships, the fuel savings and engine size reduction will be proportionately greater.

Ship Cost. The cost of sail-assist ships is not substantially different from that of the same size and speed were found to be essentially offset by the savings associated with a reduction in machinery size. The extent to which this offset occurs depends on ship size and rig efficiency, but the 20,000 CDWT wing sail ships were found to cost essentially the same as the equivalent motor ships (Figure 4).

Hull Form. The economically optimum hull forms of sail-assist ships and motor ships of equivalent size and speed were found to be essentially the same. Thus no extreme excursions of hull form from current practice are indicated. When a motor-sailing ship and a motor ship are both subjected to the same draft limit, the economic advantage of sail propulsion is not diminished. Also, cargo density does not have a significant impact on the economic comparison between the motor-sailer and the motor vessel.

Optimization of Rig Parameters. Figure 3 shows RFR vs. average speed for 20,000 CDWT motor ships and wing sail ships. The wing sail ships have a 210 foot air draft measured above the ballast waterline. Shown within the dashed box are the effects of rig parameter variations used to determine the optimized rig parameters. For a 14 knot average speed, the minimum RFR is $16.26/LT and 4 wings of 9000 square feet each designed to operate in winds up to 40 knots. The RFR of the 14 knot motor ship is $16.93/LT. Thus the economic advantage of the wing sail ship is $.67/LT or 4% of total ship cost. The wing sail ship burns 26% less fuel, and has a main propulsion engine which is 30% smaller than the motor ship's 6018 horsepower engine.

Air Draft. At present fuel prices, economically competitive sail-assist ships do not require excessive air drafts. The optimum air draft was found to be 210 feet for the 20,000 CDWT wing-sail ship. However, an air draft limitation of 170 feet (which allows access to most major ports) only increases the RFR to $16.31/LT and retains most of the advantage of sail-assist. For the 170 foot air draft ship, the power output of the rig has been kept close to the output of the taller rigs by maintaining most of the sail area on shorter masts, and by increasing the operational design wind speed to 45 knots. This ship has five wings of 6000 square feet each, and forms and basis for the conceptual design presented later in this paper. It saves 24% of the motor ship fuel consumption and has a main engine 27% smaller.

Figure 4 presents RFR and construction cost breakdowns for the 170 foot air draft ship and the motor ship.

Wind Conditions. Sail-assist preserves its economic advantage at surprisingly low average wind speeds. For instance, the 170 foot mast height ship described above maintains an economic advantage down to an average wind speed of 10 knots, even though it was designed for an average wind speed of 16 knots.
APPENDIX A

SYNOPSIS OF WIND SHIP'S BASIC RESEARCH FINDINGS ON SAIL-ASSIST

Manning. The economic viability of sail assist is sensitive to increments in ship manning levels. Given U.S. labor costs, a 20% increase in manning would at present fuel prices negate the economic advantage of a 20,000 CDWT wing sail ship. It is clear that any relaxation of the requirement for low maintenance and automation in the sailing rig would have an adverse effect on the economic advantage of sail-assist.

CONCEPTUAL DESIGN

In order to study the implications of fitting a sail rig to a merchant vessel of popular size and application, the conceptual design of a 20,000 CDWT multi-purpose dry cargo vessel was developed. Such a ship illustrates the co-existence of sailing rig and cargo handling gear. The 170 foot air draft ship from the parametric study served as the starting point, and the design effort concentrated on novel features and constraints associated with the presence of the rig. Elements of ship configuration not related to the sailing rig were not treated in detail, and would vary depending on the particular application. On this basis the design should be indicative of how sail-assist could be applied to merchant vessels in general.

Figure 5 illustrates the design that was developed. The ship has five wing sails totalling 29,280 square feet of sail area, and an air draft of 171 feet. One of the principal design compromises necessitated by the wing sail installation in in the arrangement of cargo handling gear, which must be located clear of the tail-swing circles of the wings. Consequently, the derricks which would typically be positioned at the ends of the cargo hatches are situated on each side. Such an arrangement still allows all parts of each hatch to be served, and both ends of all hatches to be worked simultaneously. When handling cargo, the wing sails will be locked in the athwartship position.

Figure 5: General Arrangement and Outboard Profile of the Conceptual Design: Length, B.P. 523', Beam 81.1', Draft 32.4', Displacement 28,565 LT, CDWT 20,000 LT, Bale Capacity 1,000,000 cu. ft., ME horsepower 5,060, Average rig horsepower 1629, Average Speed 14 knots.
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Figure 6 illustrates the conceptual arrangement of the wing sails. The wings have a NACA 0015 airfoil section, with a 25 percent chord plain flap divided into three spanwise segments and adjustable through plus or minus 40 degrees. The sails are stepped in bearings which allow unconstrained 360 degrees rotation. The center of rotation is forward of the quarter chord point in order that the sails be self-feathering when allowed to rotate freely in their bearings. In normal operation, trimming gear and flap actuators operate in concert to trim the wings for optimum sail-assist. When winds exceed the design wind speed of 45 knots, the trimming gear is allowed to free-wheel, the flaps are set to neutral position, and the wings feather passively into the wind. The wing sails are remotely controlled from the bridge, and there should be no difficulty in designing a control system which is sufficiently automated that no increment in manning would be necessary. The total rig weight of 240 tons (including hull reinforcing, etc.) is offset in part by the reduction in propulsion machinery weight. The ship's stability is only slightly affected by the rig, and no problem with achieving sufficient stability is foreseen.

A controllable pitch propeller and bow thruster are commonly installed on conventional vessels of this size, and are specified for this ship. The controllable pitch propeller should accommodate the range of speed thrust conditions anticipated. With the bow thruster, low-speed maneuverability should not be a problem.

Table I shows the ship characteristics for the conceptual design and the parametric designs from which it was developed.

WEATHER ROUTING

Sailing ships have long taken advantage of knowledge of winds and currents to improve passage performance. A weather routing study was performed to determine the benefit achieved by applying weather routing to a sail-assist ship. Two 20,000 CDWT ships were selected from the parametric study for this analysis: the 170 foot mast height wing sail ship and the equivalent motor ship. North Atlantic weather was simulated using a Monte Carlo simulation technique with statistics following those given by pilot charts. A dynamic programming approach was used to select the optimal route for each passage from a grid covering most of the navigable waters between New York and the English Channel. The yearly average voyage statistics derived from these simulations indicated that by using weather routing, a sail-assisted vessel may expect to increase its effective voyage speed by three percent over the course of a year contributing to a decrease in RFR from $16.31/LT to $15.96/LT. The weather routed motor ship will experience only a marginal improvement in RFR from $16.93/LT to $16.92/LT. Thus, the RFR spread between the two ships increases from $.62/LT to $.96/LT when both make use of weather routing; and the combination of sail assist and weather routing can be expected to save about 6% of total shipping cost of 20,000 CDWT ships.
APPENDIX A

SYNOPSIS OF WIND SHIP'S BASIC RESEARCH FINDINGS ON SAIL-ASSIST

TABLE 1

SHIP CHARACTERISTICS
FOR CONCEPTUAL AND PARAMETRIC DESIGNS

<table>
<thead>
<tr>
<th>Parametric Designs</th>
<th>Conceptual Design</th>
<th>Sail Assist Ship #973</th>
<th>Benchmark Motorship #963</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length O.A. ft</td>
<td>550.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Length B.P. ft</td>
<td>523.0</td>
<td>522.9</td>
<td>520.0</td>
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<tr>
<td>Beam ft</td>
<td>81.1</td>
<td>81.1</td>
<td>81.2</td>
</tr>
<tr>
<td>Depth ft</td>
<td>49.9</td>
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<td>49.9</td>
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<tr>
<td>Draft (full load) ft</td>
<td>32.4</td>
<td>32.4</td>
<td>32.5</td>
</tr>
<tr>
<td>Displacement (full load) LT</td>
<td>28,565</td>
<td>28,557</td>
<td>28,573</td>
</tr>
<tr>
<td>Cargo Deadweight LT</td>
<td>20,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Fuel LT</td>
<td>520</td>
<td>516</td>
<td>638</td>
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<tr>
<td>Misc Deadweight LT</td>
<td>255</td>
<td>254</td>
<td>251</td>
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<tr>
<td>Total Deadweight LT</td>
<td>20,775</td>
<td>20,770</td>
<td>20,889</td>
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<tr>
<td>DWT - Displ. Ratio</td>
<td>0.727</td>
<td>0.727</td>
<td>0.731</td>
</tr>
<tr>
<td>Light Ship Weight LT</td>
<td>7,790</td>
<td>7,787</td>
<td>7,684</td>
</tr>
<tr>
<td>Bale Cubic cu ft</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Stowage Factor cu ft/LT</td>
<td>50.0</td>
<td>50.0</td>
<td>50.0</td>
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<tr>
<td>Length/Beam</td>
<td>6.45</td>
<td>6.45</td>
<td>6.40</td>
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<tr>
<td>Beam/Draft</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>Depth/Draft</td>
<td>1.54</td>
<td>1.54</td>
<td>1.54</td>
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<tr>
<td>Block Coefficient</td>
<td>1.727</td>
<td>1.727</td>
<td>1.730</td>
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<tr>
<td>Prismatic Coefficient</td>
<td>0.734</td>
<td>0.734</td>
<td>0.737</td>
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<tr>
<td>Max. Section Coefficient</td>
<td>0.990</td>
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<td>0.990</td>
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<tr>
<td>L/T 1/3</td>
<td>5.23</td>
<td>5.23</td>
<td>5.20</td>
</tr>
<tr>
<td>Accommodations</td>
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</tr>
<tr>
<td>Crew</td>
<td>20-32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spare</td>
<td>0-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed Horsepower (MCR)</td>
<td>5,060</td>
<td>4,288</td>
<td>6,017</td>
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<tr>
<td>Shaft RPM</td>
<td>155</td>
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<td></td>
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<tr>
<td>Fuel Consumption @ .9 MCR 1/2/day</td>
<td>17.7</td>
<td>15.5</td>
<td>20.9</td>
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<tr>
<td>Propeller - Type &amp; Diameter ft</td>
<td>C.P. 19.5</td>
<td>C.P. 19.5</td>
<td>C.P. 19.5</td>
</tr>
<tr>
<td>Average Speed knots</td>
<td>14.0</td>
<td></td>
<td>14.0</td>
</tr>
<tr>
<td>Sailing Rig Type</td>
<td>Wing Sail, NACA Sect. 0015 (360° rotation)</td>
<td>25° Flap, ± 40° max. flap trim</td>
<td></td>
</tr>
<tr>
<td>Number &amp; Size of Sail Units</td>
<td>3 @ 6048 ft²</td>
<td>5 @ 5946 ft²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 @ 5668 ft²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Sail Area ft²</td>
<td>29,280</td>
<td>29,730</td>
<td></td>
</tr>
<tr>
<td>Clearance Height ft</td>
<td>171</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Effective Rig Horse Power HP</td>
<td>1,629</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Rig Horse Power HP</td>
<td>24,943</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Speed (true wind 48 KTS, 130°)</td>
<td>21.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SAIL ASSIST OPPORTUNITIES

An evaluation of U.S. Merchant Marine fleet forecasts indicates that the majority of ships to be constructed in the next decade would benefit from sail propulsion. Small and medium size tankers are the best candidates, as sail would cause little or no complication in normal operation. General cargo ships are also good candidates and the number of these ships forecast should provide incentive for development of sailing rigs which double as cargo handling gear. Container and partial container ships might benefit from sail-assist, but the potential of sail propulsion in liner trades will remain uncertain until the effects of sail assist on passage time variance are quantified.

Of the U.S.-foreign grade route, the North Atlantic and North Pacific routes have the highest average wind speeds. Caribbean trade routes show wind conditions only slightly above average, but a large quantity of trade in small ships and favorable wind direction make these routes candidates for sail assist as well.
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SAIL ASSIST OPPORTUNITIES (cont'd)

While the topic of retrofitting sailing rigs to existing vessels was not treated directly, some
inferences can be made. The similarity between optimum motor and sail-assist hull forms indicate
no major problem with a mismatch between rig and hull. Many existing ships have older power
plants whose specific fuel consumption is higher than those in the study. Such considerations
work to the advantage of an existing motor vessel that is retrofitted with a sailing rig. A
factor working to the disadvantage of retrofit is engine size. Because of the additional power
provided by the sailing rig, a retrofitted ship will probably be somewhat overpowered for its hull
form.

This should not be a major problem as an engine use strategy which takes cognizance of the problem
can be developed. A review of present merchant fleets indicates that significant opportunity
exists for the retrofit of existing vessels.

OVERALL CONSIDERATIONS

Fuel Savings. Assuming it practical to apply sail-assist to 50% of the world fleet, the circa
1980 potential annual savings would be on the order of 70 million barrels and over $2 billion.
The savings for the U.S. flag fleet would be 2.8 million barrels and approximately $85 million
annually.

Technology. The findings of this study indicate that no major technical barriers exist to the
introduction of sail-assist for the world's shipping fleet. In addition, sail-assist is
compatible with the present technologies of ship hull and machinery design.

Development. Sailing rig development, including testing at sea of a full spectrum of rigs can be
budgeted in terms of millions of dollars and two to three years as opposed to the billions of
dollars and longer time frame associated with other high technology energy projects. The
potential benefit for the U.S. fleet alone would justify a multi-million dollar development
program.

Regulations. Current rules and regulations do not provide for commercial sailing ships. Since
the economic benefits are clear it is certain that the application of sail-assist to commercial
ships will spread. Therefore, consideration should be given by classification societies,
regulatory bodies and professional societies to addressing the problem of developing appropriate
rules. This should be done in such a way that rule development will proceed in concert with the
spreading application of commercial sail.