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WIND-ASSISTED SHIP PROPULSION

B R Clayton

The erratic fluctuations in price and supply of oil over the past decade have led to a reappraisal of wind assistance for ship propulsion as a means of saving fuel. This article reviews the devices currently considered as potentially viable and other factors that have recently been appreciated.



Dr Brian Clayton is Reader in Mechanical Engineering at University College London where he has special responsibilities for research and teaching in marine hydrodynamics related to naval architecture. He is a director and founder member of the British Wind Energy Association and has been able to bring together his research interests in aero/hydrodynamics within the single topic of wind-assisted ship propulsion.

The sudden escalation of oil prices in the early 1970s followed by disruption of supplies through various Middle East conflicts, including the present risks to oil tankers in the Iran–Iraq war, has led to a general policy of energy conservation. Notwithstanding the current low cost of crude oil, at about $18 a barrel, substantial efforts are being made in the manufacturing and service industries in the UK to increase savings by making, often modest, capital investments. We thus see more sensible operating policies for space heating, improvements in boiler efficiencies, better lighting techniques and buildings erected with energy conservation measures included at the initial design stage.

In common with this national concern shown by manufacturing and service industries and domestic consumers the shipping industry has considered what it can do to reduce energy costs. Indeed, in the Efficient Ship project, involving the Department of Trade and Industry, consultants and shipbuilders, attention has been paid to all possible methods by which running and operating costs can be reduced without compromising the principal functions of the ship. Naturally, propulsion systems play a vital role in any consideration of a ship's running cost and cargo capacity. It is in this context that the assessment of wind assistance techniques has now emerged as a factor that should be included in the evaluation of both existing and new cargo-carrying ships. Not that wind propulsion for ships has ever ceased to exist in some parts of the world as a primary power source for the transportation of cargoes and people. However, apart from a few rather special holiday cruise vessels, wind power has, until now, tended to be adopted only for pleasure craft in most of the industrialised countries. Although the

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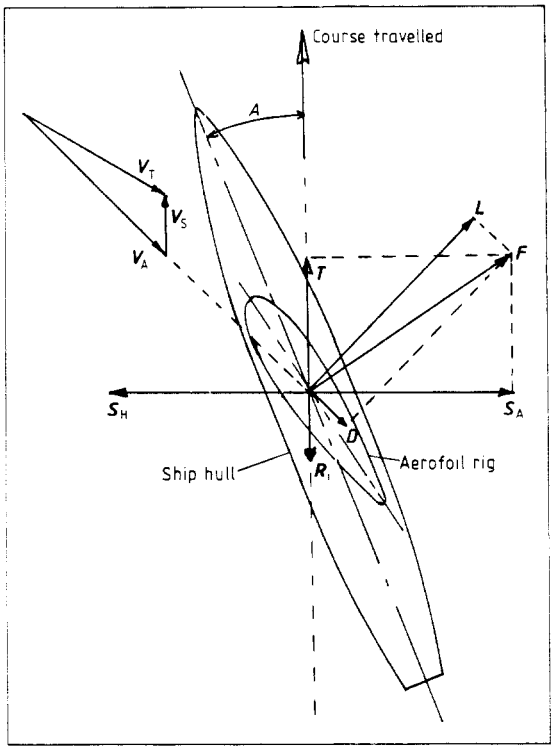
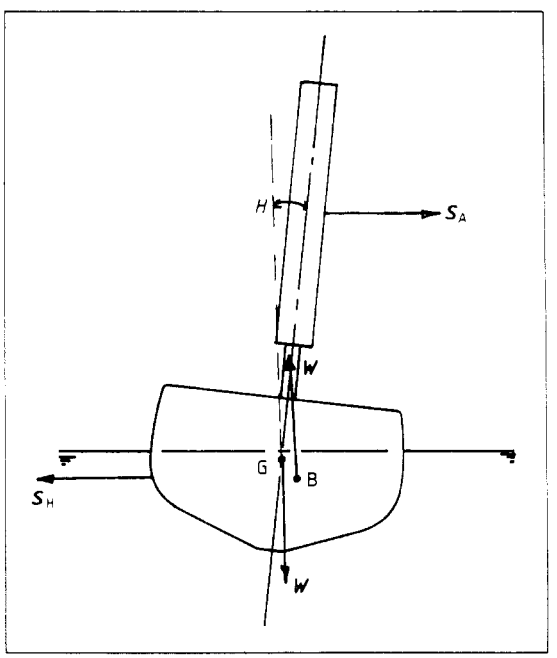


Figure 1. Forces and velocities on a wind rig attached to a ship.

Figure 2. Equilibrium of hull and rig transverse forces giving rise to the angle of heel H. The centre of gravity is at G, the centre of buoyancy at B.



leisure market offers substantial and competitive business it is, perhaps, astounding to realise that the potential market for the conversion to wind assistance, say, one quarter of ships over 100 gross registered tonnef, could amount to £2 billion and so even a small fraction of this is big business indeed.

In this article the various viable types of wind assistance devices for application to motor ships are described and their main characteristics analysed. The general operational criteria of ship and rig combinations are discussed and attention given to weather routeing, economics, design and technology development.

Aerodynamic and hydrodynamic forces

When there is a wind relative to a rig used for assisting ship propulsion, that wind experiences at the device a change in its direction and magnitude resulting in a reduction of momentum and a consequent reaction force on the device. It is this force that is optimised for the purposes of efficient propulsion.

The essential features of the aero/hydrodynamics of a generic rig and ship are shown in figure 1 and it is assumed (unrealistically but for simplicity) that steady conditions prevail. The vector diagram to the left shows that the true wind velocity relative to earth, V_T, adds vectorially to the ship velocity, V_S, to yield the apparent wind velocity, V_A, and it is this velocity that is 'felt' by the rig. In various ways each rig deflects the apparent wind and in doing so yields a force F, the magnitude of which depends on the area and effectiveness of the rig. A second process takes place in the case of a wind turbine in that the force F gives rise to rotation of the turbine rotor and usually power is then extracted from the rotating shaft connected to it. In figure 1 it is seen that F may be resolved into a crosswind force L, the 'lift' force at right angles to V_A, and a downwind force D, the 'drag' force parallel to V_A. The lift and drag forces can be obtained theoretically and experimentally for aerofoils and a considerable body of graphical and tabulated data already exists, although unfortunately much of it is inappropriate in the present context.

For the powering of ships, however, the more useful resolution of F is into thrust T parallel to the course travelled and the side force S_A perpendicular to the course. For steady course-keeping the aerodynamic side force S_A must be balanced by an equal hull hydrodynamic force S_H in the opposite direction. This is why the course travelled is not in the direction of the longitudinal axis of symmetry of the ship but inclined at some angle A. The existence of the forces S_A and S_H along with the weight and buoyancy forces (each W) of the floating ship, with its rig, means that equilibrium in the vertical plane

can only be attained at the expense of a heeling angle H as shown in figure 2. For large ships this angle may only be up to 5° and up to 10° for smaller inter-island vessels under 1000 tonnef (10 MN) displacement. Extreme angles of heel are, of course, seen in racing yachts, where movable mass (the crew) is often required to adjust the location of the centre of mass of the boat to restore equilibrium and prevent capsizing.

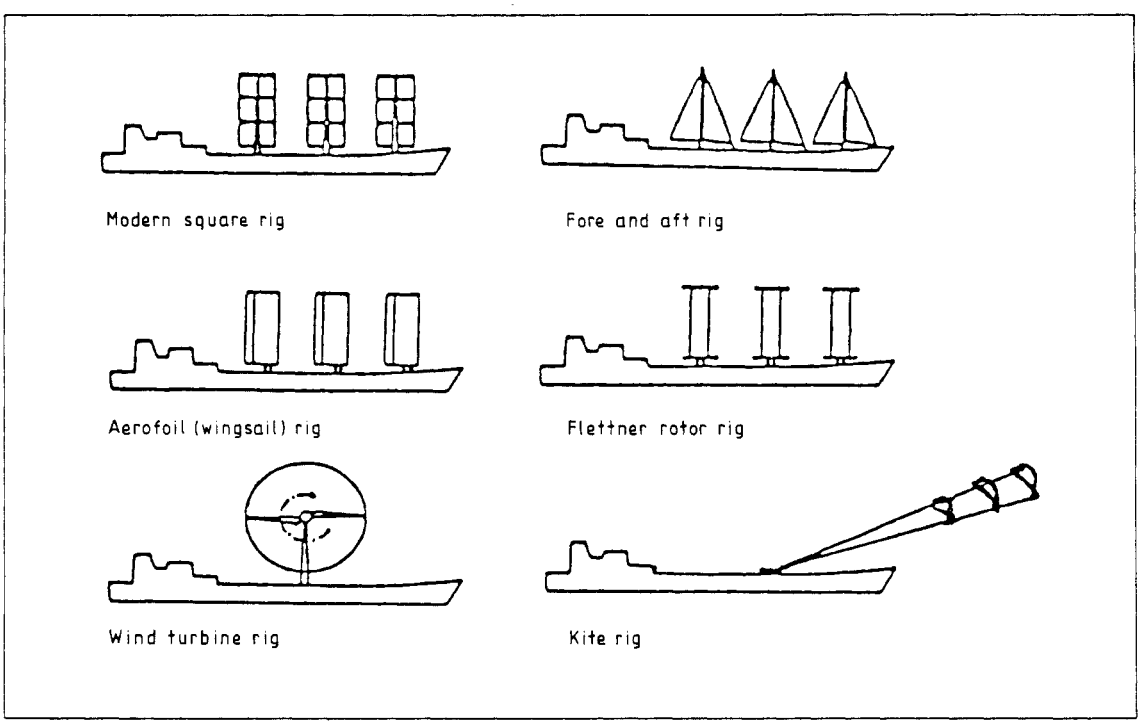
A penalty to be paid for the installation of a wind rig on a ship is the induced resistance $\boldsymbol{R}_i$. This force is a measure of the increased resistance of the ship arising from the presence of the rig by virtue of increased weight displacement and therefore increased submergence of the hull, interaction with the aerodynamics of the superstructure and the presence of the side-slip angle A. One clearly expects $\boldsymbol{T}-\boldsymbol{R}_i$ to be positive for useful assistance with propulsion. On the other hand, considerable attention is now being paid to the potential of rigs as ship stabilisers in a seaway and it is possible that this feature may outweigh the overall propulsion requirement.

Wind assistance devices

There are essentially five different groups of wind assistance device for ships although, in most cases, there are many variants within each grouping. Indeed, there is such a variety of rigs adopted for different hull and superstructure configurations that a comparative assessment between them is virtually impossible. Fortunately for the designer, operator and builder of wind-assisted motor cargo ships, in which conventional sources still provide the major proportion of propulsive power, there are relatively few that would merit detailed consideration. The main groups are as follow and examples are shown schematically (but not necessarily to scale) in figure 3.

Soft sails. There are two main subdivisions under this heading. The square rig form, epitomised by a three-masted barque, presents an almost irresistible romantic element. Modern versions of the square rig form seek to improve the aerodynamics of the sails by providing clean lines, using cantilever masts and having fore and aft stay-sails. These rigs were historically employed, and would still be so, on long routes with continuous and predictable wind regimes. There is now less demand for cargoes to be sailed on such long routes. The second category is the fore and aft rig, which is more suited to shorter routes where there are many applications and, not surprisingly, less predictable wind characteristics. The leading edge of the fore and aft sails and of the unstayed cat rig can be accurately shaped for sailing close to the wind as would be necessary for good

Figure 3. Schematic drawing of different wind rigs for ships.



windward performance on short routes. In summary, soft sails can be reefed at sea, are served by an existing industry and have reasonably low capital cost. They can, however, hinder the use of dockside cranes, have high maintenance costs, often have suspect structural integrity and are generally incompatible with automation systems.

Aerofoils (wingsails). The Japanese, through the Japan Marine Machinery Development Association (JAMDA) and Nippon Kokan KK (NKK), have designed, built and operated at least ten aerofoil-rigged ships since 1980. The rig designs follow the same basic geometry in which a central mast supports a vertical, rectangular, steel framework with horizontal aerofoil-shaped ribs, the rectangular planform being covered by a laminar-flow-type sail canvas. These aerofoils are of variable geometry, in that they can be opened or closed by a mechanism somewhat similar to that used by an umbrella, and differ in number and location according to the ship on which they are mounted. Two important developments have taken place in the UK. The so-called 'Gallant' rig is also a sailcloth-covered aerofoil but the ribs are not rigidly constrained vertically. The spacing can thus be adjusted vertically for reefing or stowage and examples have been built for fishing vessels. On a larger scale, and employing high-technology materials and computer control systems, is the Walker Wingsail rigid aerofoil system. This rig consists of a vertical triplane of flapped aerofoils interconnected with a trimming vane for fast, low-power control and performance optimisation. In general, aerofoil systems have high lift coefficients compared with soft sails, use 'high-tech' materials, work well in motor sailing mode, and multiple forms can be made light, strong, compact and free-standing. At sea, 'weather cocking' capability is required, capital costs are higher than equivalent soft sails but would be outweighed by lower running costs. There is the possibility of high rolling moments but also the potential for motion damping; however the technology is still in the early stages of validation.

Mechanical high lift systems. Devices in this group use an external energy supply to control the boundary layer (i.e., the low-energy air layer close to the outer surface of the device) in order to enhance useful propulsive forces. The rotating cylinder, used with considerable success by Anton Flettner in the 1920s on the 'Bachau' (or 'Baden-Baden') and the 'Barbara', is well known and utilises the Magnus effect whereby large cross forces are developed relative to the instantaneous wind direction. Forces can be very large at high rotational speeds and considerable support for such a system built of modern materials has been voiced in the USA and at least one example has been constructed in the UK. A different system has been designed and tested by the Cousteau Foundation of France. Boundary layer control is exercised by a suction fan set atop a hollow elliptical cylinder, which draws off low-energy air through a porous part of the cylinder wall extending the entire span. Control of forces relative to changing wind velocity and direction can be obtained by partially blocking the porous region with an adjustable cover. Briefly then, these rotating or suction cylinders are compact, made of 'hi-tech' materials and use technology familiar to ship operators. Flettner rotors require a modest investment for a given fuel saving, which makes them suitable for retrofitting to slow vessels operating in beam winds. These systems appear to offer smaller fuel savings than aerofoils, possibly have higher maintenance costs, require an external and significant energy source and develop high drag forces when sailing to windward.

Wind turbines. These devices are now becoming generally familiar owing to their use on land as electrical power generators and in pumping and irrigation schemes. Applications to ships have, to the present author's knowledge, been used only on a small scale and with the horizontal axis rotor geometry. The unique feature of wind turbines is that they can propel a vessel at all directions to the wind including directly to windward. Vertical axis wind turbines have the advantage of being omni-directional, i.e. insensitive to the wind direction, but are somewhat less efficient. A number of small mono- and twin-hull craft in the UK, USA and New Zealand have been fitted with wind turbines connected through gearboxes to a marine propeller. Large ships, which would certainly require megawatt size machines driving an electric generator–motor set at the present limit of land-based technology, have not been considered so far. Wind turbine rotors can also be operated in a freely rotating autogyro mode but at lower lift-to-drag ratios compared with soft and rigid sails. Present-day limits on the efficiencies of components in the power train indicate that applications are best suited to the low ratios of ship speed to true wind speed applicable to tugs and fishing boats. Net thrust can be very high at low ship speeds. Complex engineering is required, structural responses on ships in waves need investigation and high deck weight and safety problems could be severe.

Kites (elevated sails). These systems probably represent the least conventional wind propulsion application, yet in a number of ways offer extremely high potential gains. By using manoeuvrable kites high relative wind speeds can be tapped to give large tensile forces in the attachment lines. However, there are significant problems associated with the launch and retrieval of these large and costly devices

as well as the control techniques needed to handle the figure-of-eight movements of the kite. Nevertheless, inflated forms have encouraging aerodynamic performance, and, since air movements at altitude do not necessarily follow those at sea level, it is possible to get good downwind propulsion. Although some experiments on a small scale have been undertaken in the UK, with mixed success, there have to date been no systems built for commercial operations other than a few racing craft. Deck space required and visual obstruction are minimal and kites can be made of lightweight materials with cheap frameworks of short life. There is the possibility of stacking as with parachutes and launching from compressed air guns or with drogues.

General assessment

It is a complex matter to assess accurately the benefits and opportunities for wind-assisted ship propulsion since many variables are present, not all of which are reliably predictable. A simple illustration of some of these problems can be demonstrated by reference to figure 4, which attempts to show the effectiveness of the devices described above relative to the same ship unrigged. The ship is considered to be travelling at constant speed in a wind of given strength.

Curve A shows the unrigged ship with the implication that more fuel power is needed when heading into the wind, with a maximum at about 35° off the bow, than when sailing downwind. All rigs, except the wind turbine and the kite system, require extra power from the ship when sailing into the wind and this condition lasts for various angles off the bow, with the Flettner rotor type ship being the worst. The wind turbine is the only rig that can generate sufficient useful propulsive power to reduce that required by the motor ship when heading directly into the wind. The kite can, of course, be stowed below decks when the ship is heading into the wind and so no change in power is recorded. If the kite can be operated at sufficient altitude it could pick up winds in a different direction to the surface winds and so may afford assistance in surface headwinds. A particularly important behaviour is that of the aerofoil wingsails represented by curves D and E in figure 4. Slightly more power is required than the unrigged ship when sailing into the wind, owing to windage or drag, but thereafter substantial savings are possible and this system is probably the best until beam winds are reached. Even then it is possible to devise wingsails of variable geometry that allow efficient sailing for winds aft of the beam and even sailing before the wind as shown by curve E.

The most important feature to notice about figure 4 is that the curves cross each other at different wind angles and so one could expect the optimum rig

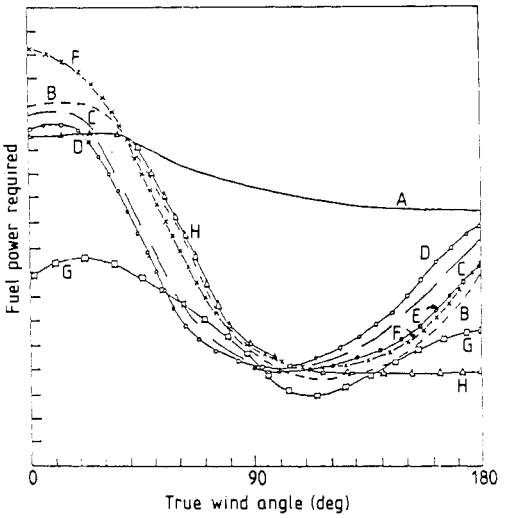


Figure 4. Relative effectiveness of different wind rigs compared with unrigged motor ship as a function of true wind angle. Key: A, unrigged ship; B, square rig; C, fore and aft rig; D, E, aerofoil rigs; F, Flettner rotor; G, wind turbine; H, kite system.

configurations to differ from one operating location to another, with even the use of more than one type on a given ship. It may be that the rig with, say, the highest lift coefficient is not necessarily the best choice. On the other hand, for general trade and for return journeys, it is hardly likely that a ship will carry two sorts of rig for optimum operation in reversed wind directions. Essentially, then, what power the ship gains in one direction could be lost in the other and so detailed consideration must be given to weather routeing and ship speeds. Another factor that is now being appreciated is that the ship propeller becomes more lightly loaded since part of its thrust requirement is supplied by the wind assistance device. Hence the propeller efficiency rises and an additional fuel saving accrues. It is also noticeable that ship motions can be significantly reduced by the aerodynamic damping characteristics of wind assistance rigs. The hydrodynamic resistance of the ship reduces if roll, yaw and pitch motions are reduced, and this represents a substantial contribution to power savings.

An economics assessment of a wind-assisted ship must take account not only of fuel costs but of many other factors. Operational requirements, such as cargo handling, routeing, crewing, types of cargo, maintenance policies, first costs, technology transfer to other ships and so on, need careful consideration. It is then possible, by using curves such as those in figure 5, to determine the most economical service speeds. The curve of net revenue (gross revenue

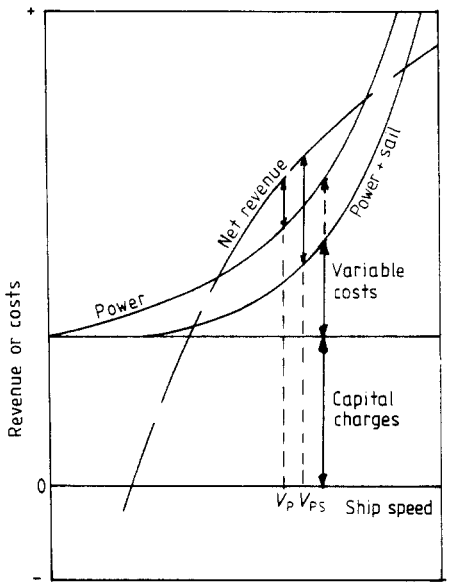


Figure 5. A graphical technique for determining the most economical operating speeds.

minus capital charges on cargo) intercepts two curves of costs, one for fuel only, the other for the wind-assisted ship. The speed that gives the greatest financial return is that which corresponds to the largest vertical distance between them. Examples have been found where the most economic speed may be greater or less than that for the equivalent all-fuel ship. There are also various benefits that tend to be lost in a simple analysis, such as comfort, romance and duration, which may all be important elements. The essential economic decision in choosing between different devices involves appraising the impact of a device on the overall economics of particular ship operations.

Apart from the complexity of supply and cost fluctuations of oil, another problem in determining an accurate picture of costs concerns the unit capital charges on rigs. Many so far have been one-off devices of high cost and so quantity prices have not been assessed with confidence. Even wind turbines, of which there are now significant numbers for land-based operations, have not been costed for quantity production in a maritime role. Indeed, a series of calculations in respect of wind turbine applications, carried out at Glasgow University, has shown just how difficult it is to predict, with any certainty, satisfactory payback times within the life of the rig. On the other hand, detailed analyses conducted at Southampton University in respect of rigs with the performance expected from computer-controlled wingsails on ships travelling several thousand miles with weather routeing details have shown more encouraging results. The Japanese operators are convinced of the viability of wind assistance and report fuel savings of 25% for many of their ships.

Some examples

A few examples of the many wind assistance systems that have been built are briefly described here to give an indication of current developments.

The UK system that has, perhaps, received the most publicity and certainly the greatest financial support is the Walker Wingsail, developed over a number of years by John Walker. Despite many difficulties, particularly from doubting venture capitalists, the first complete version is now installed above the 'castle' of the MV Ashington, a 6800 tonnef dry-cargo bulk carrier operated by Stephenson Clarke Shipping Ltd and shown on the cover of this issue. Standing above the funnel, the triple, flapped-aerofoil rig and connected trimming tailplane is some 13.5 m high. The whole set is pivoted and turns freely on a rigidly mounted pillar. A centrally placed, forward-projecting probe detects wind speed and direction, which are fed to the computer that controls a motor to trim the tailplane, thus swinging the wingsail to take up the optimum direction to the apparent wind. An additional, ingenious facility is that, at the same time, the tailplane connection also adjusts the aerofoil and flap combinations to optimum camber. Forces required to control the wingsail are minimised since the mounting locations of the wingsail and tailplane are close to the respective aerodynamic centres, thus keeping aerodynamic moments small. Considerable use has been made of glass-reinforced plastic (GRP), aluminium and foam sandwich as well as steel for strengthening the centre aerofoil.

Although the application may not necessarily be ideal, the test programme should yield valuable results during its first six months to January 1987. In particular, the expected 10% fuel savings are likely to be achieved with the added facilities of docking without tugs and improved motions in all but following winds in a quartering sea (i.e. when waves overtake the ship from a rearward sector).

An example of the soft sail rig, in this case a ketch rig with manually operated roller furling on all three sails, is that designed and installed by MacAlister Elliott and Partners on behalf of the Asian Development Bank for the Fijian Government fleet of inter-island ferries. Two ships have so far been fitted out and operated, each employing a novel standing wishbone construction on the mainsail to give a quadrilateral sail that could be furled on luff spars. The first ship completed was the Na Mataisau, shown in figure 6, constructed with a steel hull some 27 m long overall, 274 gross registered tonnef, and used as a passenger cargo vessel with a single diesel

engine. Conversion to auxiliary sail was carried out at a Fijian shipyard and completed in September 1984, whereupon the ship operated normal schedules with a continuous log kept to record performance data. Good performance was obtained in both sailing and motor–sailing modes with substantial speed enhancement in the combined mode. Tragically, the ship foundered on a reef and was lost after an engine breakdown when running for shelter before a tropical cyclone in January 1985. Only two deaths occurred and matters could have been far worse had sails not been fitted and the ship been unable to sail close enough to a lee shore for the remainder of the crew to make land. It is well known that JAMDA also support the incorporation of wind assistance devices as a back-up system in just such circumstances.

The rig of Na Mataisau was rescued virtually undamaged and has subsequently been installed on a somewhat larger ship, the Cagidonu. This ship was completed in December 1985 and has shown fuel savings of 20–25% on its inter-island schedules.

Although much has been made of the aerodynamics of wind assistance devices, the correct choice of materials is vital for a cost-effective, structurally sound product to be accepted. Composite Technology (previously Gifford Technology) has investigated a whole range of materials from traditional timber, steel and cotton to alloys and plastic composites. Some of this experience has been applied to wind turbine blades for use on land and also to the construction of a Flettner rotor. The latter device was built as a one-off rig for installation at the stern of a 670 tonnef general cargo vessel for Caribbean routes. The rotor is 11 m high and 1.6 m in diameter with the rotor skin formed from a GRP inner and outer thin skin enclosing a foam core. Timber was used as the framework to support the rotor skin using longitudinal rails and ring frames attached to a series of wooden discs, in turn fixed to the main steel centre tower. Evaluation of the device is now awaited. In the meantime, an economic comparison has been made of a number of wind assistance devices with the conclusions that soft sails are ideal for inter-island shipping whereas, for compactness and automation, rotors are as cost-effective as rigid wingsails, a decision also reached by designers in the USA.

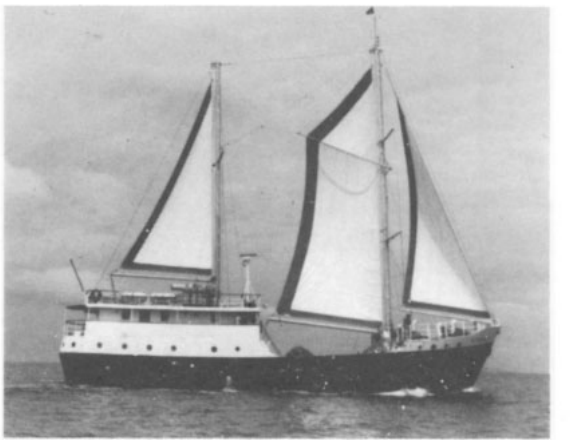


Figure 6. Na Mataisau, an inter-island ship running on passenger/cargo schedules in Fiji. (*Permission of MacAlister Elliott and Partners.*)

The Japanese have led the way in sea-going wind-assisted vessels. These have been operating successfully for the past six years, having been constructed at several yards for a number of different operators. The first ship was a 1600 tonnef deadweight tanker,



Figure 7. Shin Aitoku Maru, the first of the Japanese wind-assisted cargo ships. (*Permission of Nippon Kokan.*)



Figure 8. Aqua City, the largest wind-assisted cargo ship now trading. The sails are now undergoing a thorough structural examination for the purpose of improving future design techniques.
(*Permission of Nippon Kokan.*)

the Shin Aitoku Maru (see figure 7), which has been thoroughly evaluated. The fuel savings were due only in part to the somewhat crude wingsail, the remainder being the result of both fitting a new propeller and improved hull motions, dramatically recorded on film during a parallel cruise with her unrigged sister ship. In 1984 two large ships put to sea, the Aqua City of 31 000 tonnef deadweight (see figure 8), operating as a bulk carrier, and the 26 000 tonnef deadweight Usuki Pioneer, designed at the outset as a wind-assisted log and bulk carrier for Pacific Ocean routes. Unfortunately, the latter ship has since been impounded in a South-East China port as a result of a collision with a dock, resulting in the temporary closure of ship movements there.

Despite the various trepidations experienced by the designers and operators of wind-assisted ships, the successes so far in the UK, Japan, USA, France, Germany, Scandinavia and elsewhere should still ensure exciting progress ahead, especially so once the economics again become more favourable.

Future prospects

It is a widely held view that oil prices will again increase and/or sources of supply will become increasingly uncertain. Economically, a good case for wind assistance can be made in many parts of the world, although at the present time the most immediate applications may lie in the developing regions and possibly in the pleasure cruise market.

There are a number of technical areas needing further work. It has been stated already that motion damping can be a valuable attribute of wind assistance devices and so deserves to be examined. Indeed, significant groundwork on this aspect has been covered at Southampton University, and a wide-ranging examination of rig/hull combinations is now underway at University College London. Materials of value to wind assistance rigs should be kept under review and related to cost, reliability, strength and maintenance. The strategies for the combined engine/sail operation must be further developed, in the light of improved weather routeing techniques. Since 75% or so of the total propulsive power must come from conventional sources, it is vital that this should not be compromised in terms of efficiency by the installation of a wind rig.

Finally, ship operators must be persuaded to consider wind assistance on an equal standing with their concern for the latest applications of high technology in rather more familiar roles. This, one suspects, might well prove to be the most difficult problem to overcome.

Further reading

Proc. Symp. on Wind Propulsion of Commercial Ships (Comsail '80), Royal Institution of Naval Architects, London, November 1980 (London: RINA)

Proc. Int. Symp. on Windship Technology (Windtech '85), Southampton, April 1985 ed. C J Satchwell (Amsterdam: Elsevier)

Proc. First British Wind Energy Association Symp. on Wind Assisted Ship Propulsion, Glasgow, November 1985 ed. B R Clayton (London: British Wind Energy Association)

Wind Assisted Ship Propulsion – A Development Strategy, British Wind Energy Association, November 1985 (London: British Wind Energy Association)

Proc. Asian Development Bank Conf. on Sail Motor Propulsion, Manila, November 1985 (Manila: Asian Development Bank)