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FONDATION COUSTEAU AND WINDSHIP PROPULSION

1980 - 1985

SYSTEM COUSTEAU - PECHINEY

by

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THE FONDATION COUSTEAU AND WIND ENERGY

A WIND DRIVEN CALYPSO

Various crises in the supply of raw materials and energy over the past ten years have completely changed our conception of the exploitation of the earth's natural resources. At the same time, the idea of conserving resources and respect for the environment have asserted themselves in nearly every corner of the world, giving rise to the concept of responsible management of the planet. Implementing such ideas raises enormous political, legal and economic problems, but man has at his disposal an extremely powerful technology which he develops unceasingly and which will surely allow him to overcome these difficulties progressively.

Concerning maritime transport today, this mood can best be described by profound changes such as the return to "economic speed" for many ships, which allows us to hope for the end to an era of ease and waste. The return to using sources of renewable, clean energy, like wind energy which our forefathers tried to harness, is becoming conceivable. As Captain Cousteau emphasised in one of the editorials written for the "Calypso Log", the newspaper of his Fondation, "we shall soon be able to celebrate the marriage of hydrodynamics with aerodynamics as we improve our methods for managing natural resources".

In fact the idea of a wind-propelled ship is not new to him nor to members of his team. In addition, the "Calypso", whose exploratory expeditions are known the world over, is no longer young and it is time to start thinking about her successor : a fine occasion to apply these beneficial improvements judiciously, wherever possible, from the propeller system to the hull, from auxiliary engines to general services : navigation, integration of meteorological data received by satellite, scientific equipment, centralised networks of electronic control, fresh water supply, waste disposal, etc. To this end, "Calypso II" dreams of becoming no less than the most beautiful itinerant ambassadoress of French technology and innovation and one of the first genuinely ecological ships in the world (see figure 1).

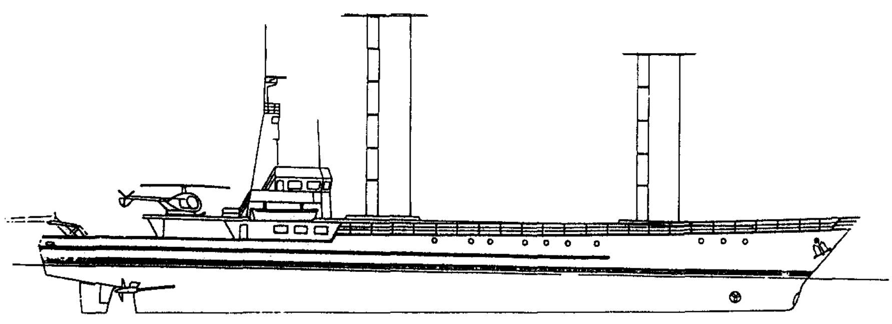

Fig. 1 : Sketch of Foundation Cousteau's future oceanographic ship : Calypso II - ship equipped with two Turbosails, 1,000 tons deplacement, cruising speed: 12 knots.

It is in this context that the Fondation Cousteau undertook to study the possibilities of wind energy for the propulsion of ships. A first bibliographic study led by M. Jacques Constans, scientific director of the Fondation Cousteau, made it possible to locate the man in France best placed to direct future studies : Professor Lucien Malavard member of the Academy of Sciences. Once contacted, the professor accepted to supervise the research with enthusiasm, bringing with him, Bertrand Charrier who had just completed a doctoral thesis (Ph. D) on the aerodynamics of Flettner's rotating cylinder.

Studies carried out into the idea of a ship with rotating cylinders, a modern replica of "Buckau" and "Barbara", rapidly veered towards a new system, much simpler and more reliable: the orientable aspirated cylinder, named Turbosail. Mention must be made here of the exceptional assistance received from the French Government, who have shown interest in the project from the outset, not only by making an important financial contribution, but also by offering unflagging moral support, in particular on the part of the Ministry of Industry and Research, the Secretary of State for the Sea and French Agency for Harnessing Energy.

MOULIN A VENT I

Wind tunnel tests made it possible to validate the concept of a Turbosail. They resulted in a simple system, remarkably efficient, consisting of a vertical aspirated cylinder along the total height of a generatrix orientable with respect to the direction of the wind. These wind tunnel tests, carried out inevitably on a reduced scale, were complemented by the construction of a large-scale propeller, mounted on to the hull of a catamaran, "Moulin à Vent" (Fig. 2). Trials on this experimental ship were carried out over a period of several months in varying wind conditions, first of all on the Berre lake near Marseilles, then cruising in the Mediterranean. The results, conforming perfectly to those achieved in the wind tunnel were so satisfactory that Captain Cousteau decided to attempt a transatlantic crossing during the Autumn of 1983. This ended off the American coast after the mast broke at an assembly point weakened following several storms at sea. All the same, the remarkable qualities of the propeller had already been sufficiently demonstrated to convince our Fondation that it could look forward with confidence to developing the project over several years.

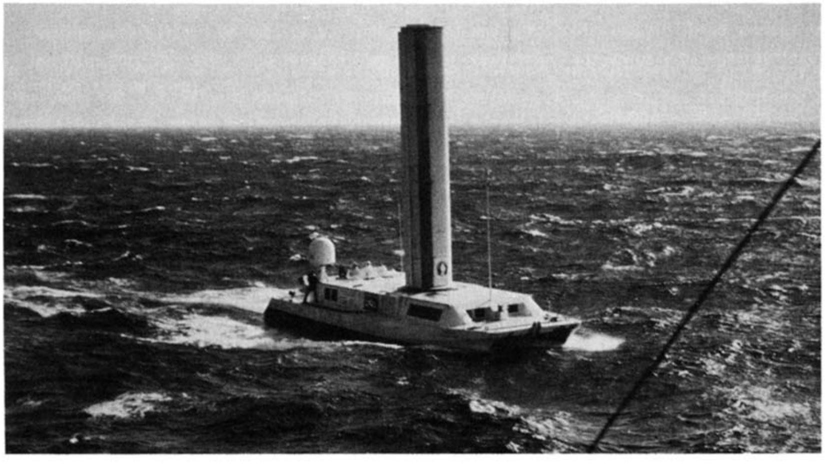

Fig. 2: The "Moulin à Vent" under way

ALCYONE

Since 1984, a specific experimental ship, "ALCYONE" (30 metres overall length, 9 metres wide and a little more than 60 tons light deplacement) has been under construction by the Société Nouvelle des Ateliers et Chantiers de la Rochelle-Pallice. Made of light alloy, this ship will be equipped with diesel-engine propulsion, coupled with supplementary wind propulsion by "Turbosails". The two cylinders with which the ship is to be equipped are also made of light alloy, following the mechanical specifications of Cegedur-Pechiney and are being made in the workshops of the firm Pourprix at Lyons. Launching is scheduled for April 1985. Without entering into details, the plan of use for the "ALCYONE" will consist of three stages:

- a transatlantic crossing, Europe-USA, May-June 1985;
- a period of about two years for the demonstration/promotion of the system on seafaring routes;
- the use of the ship by the Fondation Cousteau for worldwide scientific, exploratory and filming missions.

"CALYPSO" AND "ALCYONE" REDISCOVERING THE WORLD

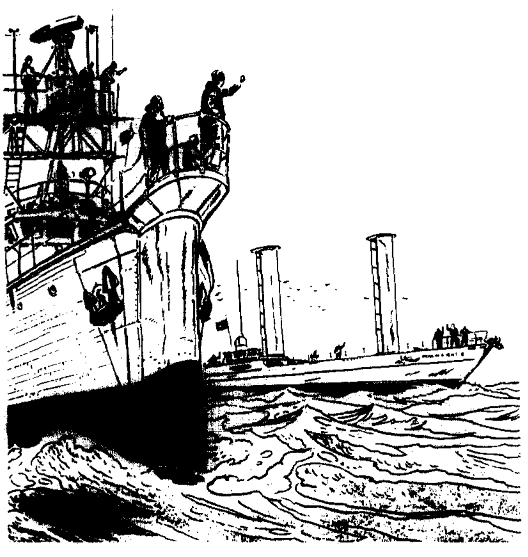

Fig. 3: "While filming the wonders of the Caribbean, the Pacific, of Asia and the southern lands, we study relations between the nations concerned, we look for ways in which different human communities can use renewable energy and exploit the biomass in order to improve living conditions and reduce rivalry between peoples. In this spirit, we are actively preparing an ambitious four-year programme in the course of which our specialists aboard the "Calypso" and the "Alcyone" will set out in 1985 to discover the world." Said Captain Cousteau in "Calypso Log" in October 1984.

COUSTEAU-PECHINEY AGREEMENTS

On 14th September 1984, Monsieur Jean-Pierre Ergas, on behalf of the Pechiney group, and Captain Cousteau concluded an agreement on the industrial and commercial exploitation of Turbosails used as auxiliary propulsion on ships. This transfer of licence agreement was signed after several months of negociations. The determination of both partners - a major industrial group and the government - to give effect to the idea that protection of the environment and a better use of the earth's resources does not run counter to economic development. In fact, quite the contrary!

For its first industrial application, Turbosails will be fitted on to a chemical carrier of about 3,000 DWT. The system is designed to operate in addition to the ship's main engines, the power of which can be regulated depending on wind conditions encountered on route with a view to reducing fuel consumption by between 15 and 35 %.

The project is included in the demonstration programme of the Directorate-General for Energy of the European Communities. Its aim is to show to a significant degree, within the context of normal commercial exploitation what fuel savings can be accomplished using Turbosails. This ship will be operational at the start of 1986. Its programme of use will include a period of demonstration lasting two years, during which time all data on the technological and economic conditions for exploiting the system will be collected and processed to enable the commercial and industrial phase of the project to be reached as soon as possible.

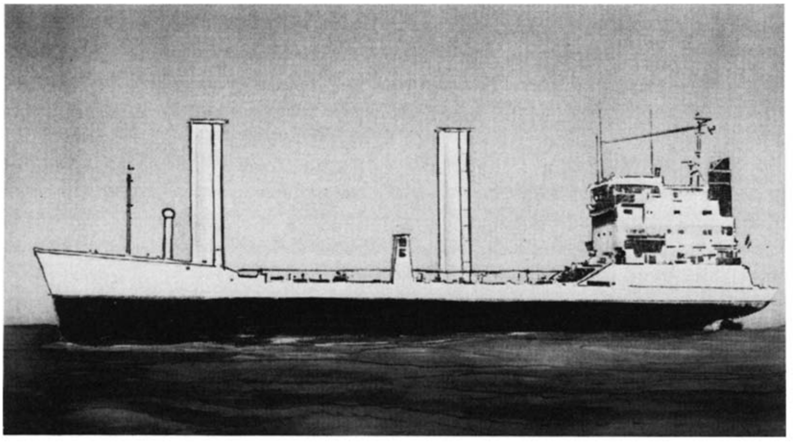

Fig. 4: Outline of the chemical carrier equipped with two Turbosails 22m. high for 4.5m. of chord. Anticipated energy savings are expected to be between 15 and 35%.

AERODYNAMICS AND WIND PROPULSION SYSTEM

PROPULSIVE FORCE AND MAXIMUM LIFT

Action of wind on wings

In considering a wing profile, placed in a wind W (fig. 5) and inclined to an angle of incidence α, the action of the wind results in effort F proportional to the surface S of the wing and to the square of speed W.

F is decomposed into an effort of drag D in the direction of W and an effort of lift L which is perpendicular to it. In passing around the profile, the air is deflected with local increased speeds on the outer surface (extrados), accompanied by reduced air pressure, while on the inner surface (intrados), the air is slowed down and produces compressions.

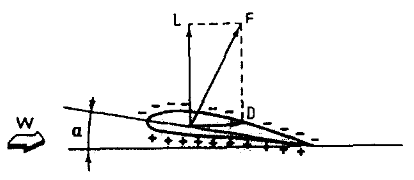

Fig. 5: Action of wind on a wing profile. Force F is broken down into drag against forward movement D and lift L.

In aeronautics, the lift L of a wing balances the weight of the aicraft in horizontal flight and the effort D corresponds to its resistance to forward movement. To illustrate diagramatically the aerodynamic performance of a wing, a curve called a "polar" (fig. 6) is traced by placing drag D on the x axis (abscissa) and its lift L on the y axis or, more precisely the dimensionless coefficients:

of lift: $C_L = L/(\frac{1}{2}\rho SW^2)$ and of resistance: $C_D = D/(\frac{1}{2}\rho SW^2)$

in which ρ designates mass density of air. Each point of the polar corresponds to an incidence α, in joining the original 0 to this point one has the corresponding effort F, or rather the coefficient: $C_F = F\ (\frac{1}{2}\rho SW^2)$

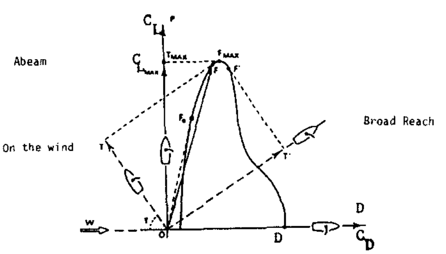

Fig. 6: Diagrammatic determination from the polar of the propulsive force T for various directions of the ship's movement (angle τ between the course and apparent wind).

The curve bends inwards to attain a maximum C_{Lmax}which corresponds to the start of the separation of air streams on the outer surface and to the formation of a turbulent wake which increases which the increase in incidence.

Propulsive effort

Given the polar, it is possible to estimate very easily the propulsive effort T for various direction of the wind. Projecting F according to the ship's route provides the propulsive effort T.

Vectorial analysis of the polar shows that for working courses, the most interesting part of the latter is found around its maximum. At a first estimation, propulsive effort T may be written :

$$T \approx \frac{\rho}{2} W^2 S C_{Lmax} \left(\sin\tau - \frac{C_D}{C_{Lmax}} \cos\tau\right)$$

where $C_D \ll C_{Lmax}$ and τ represents the angle between the ship's route and the direction of apparent wind.

For τ and W given, it is the product SC_{Lmax} which determines T: given equal action, an increase in C_{Lmax} allows a corresponding reduction in sail surface S, that is to say, of the dimension of the system. This is a general observation: the performance of a wind propulsion is even greater when its C_{Lmax} is right.

High lift systems

Devices for obtaining high lift may be divided into two categories: those which operate using no energy (UNE) and those using energy (UE). The first category (UNE) include hyperlifting devices mounted on wings to facilitate landing: profiles with single or multiple flaps: these may give C_{Lmax} to the order of 3. At the same time, their use for wind propulsion on ships is delicate as the base profile must necessarily be symmetrical since the flaps must be orientable in both directions to ensure the course of the ship either starboard on port tack. Profiles with reversible curvature have been imagined for particularly special use, the mini America Cup for example. The mechanical complexity of these devices rule out their commercial application. Only the simple flap with symmetric profile may easily be used. That is the choice made by Lord Bergeson of the Wind Ship Company.

The second system (UE), includes all wings hyperlifted by control of the boundary layer with a view to delaying the separation of the air stream of major angles of incidence α thus increasing C_{Lmax}. This control can be obtained either by blowing or by suction.

With classical profiles of moderated thickness with which aircraft are equipped, control of the boundary layer is only carried out during the landing phase when the speed of the aircraft is low. In these flight conditions, the energy expended comes from the reactors at a time when power on board is plentiful. For wind propulsion, energy expended in controlling the boundary layer is deduced from energy recuperated of the wind and used to displace the ship.

Also to be included in the UE category, is the Magnus rotor (1853) studied successively by Lord Rayleigh (1857) concerning the effect on a tennis ball, then on a rotating circular cylinder by A. Lafay (1910-1935) and L. Prandtl (1925) and by many searchers since then. This effect was effectively used for the propulsion of ships at the end of the '20s by A. Flettner. Two ships were equipped with rotors: the "Buckau" and the "Barbara". The "Buckau" crossed the Atlantic at the end of 1926. Despite the efficiency of the system, its development was abandoned as a result of the decline in sailing ships in favour of steam propelled ones.

Originally we suggested that J.Y. Cousteau should use on "Calypso II" rotors of the Magnus effect which permit the creation of high lifts, especially since Bertrand Charrier had recently carried out a thorough study of them, closely analysing the effect of aspect ratio, the presence of rotating end-plates, reciprocal interactions between the two rotors, etc... After careful consideration, we decided however that this ingenious system presented serious practical disadvantages: the necessity to have the cylinders rotate at peripheral speeds in an order three or four times that of the apparent wind W, involving more serious mechanical problems and posing security problems difficult to solve in the case of the use of rotors of large scale dimensions. Another system had to be found, eliminating the disadvantages inherent in rotating cylinders, but capable of producing comparable results. That is why Professor Malavard proposed a study or cylindrical wings, fixed, orientable, with thick aspirated profiles with a flap.

AERODYNAMICS OF THICK PROFILES

The theory of wing profiles shows that with a perfect air stream, that is one without viscosity, the lift coefficient C_L increases with the relative thickness of the profile expressing the ratio of the maximum cross-section to the chord . Thus the coefficient C_L varies from simple to double when one passes from a very thin profile to a circular profile. The strong vacuums created on the outer surface of these thick profiles by their own form and by the angle of incidence are at the origin of this high lift.

With a real air stream, the presence of viscosity engenders the separation of air streams in areas where pressure gradients are positive and significant. Control of the boundary layer by suction, in the area favourable to separation, permits the reconstruction of a flow around the profile as close as possible to that allowed for by the theory of a perfect air stream.

A group of profiles, whose relative thicknesses vary between 50 and 100% has been defined. The flap placed in the wind separate inner and outer currents in simulating the start of a line of current arising from an imaginary fixed point. This flap is mounted on a mobile section which covers one of the permeable perforated lateral vents, thus permitting easy passage from one side to another by simple rotation. The rear of the profile is circular in order to facilitate movement of the flap.

The cost of aspiration in energy

Energy expended in controlling the boundary layer depends on the output of sucked air and on the vacuum prevailing in the profile; those being a function of the shape of the profile, of the thickness of the boundary layer, of the position, the width and of the permeability of the suction area.

It is customary to define a coefficient of output: $C_q = \frac{Q}{SW}$

Where Q is the output of sucked air, S the wing's surface of reference, W wind speed.

Pressure measurements were carried out in the interior of the model. In designating the average pressure in this depression chamber by p_c and by p_s the static pressure of the uniform air stream, it is possible to define a pressure coefficient :

$$K_p = (p_c - p_s)/(\frac{1}{2}\rho W^2)$$

This coefficient K_p is, in magnitude, always superior to the pressure coefficient: $C_p = (p - p_s)/(\frac{1}{2}\rho W^2)$ of local pressure p which prevails upstream of the suction area: the difference being due to the drop in pressure across the permeable wall. Given C_q and K_p enables the minimum power $\mathcal{P}_a$ necessary for suction to be calculated; this minimum is obtained by assuming that the air is discharged into the outer flow at a speed close to that of W. Thus a coefficient for the power C_a of aspiration can be defined.

$$C_a = \mathcal{P}_a / (\frac{1}{2}\rho W^3 S) = C_q (K_p + 1)$$

The value of this power coefficient C_a is essential to qualify an UE system. Experiment has shown us that the power coefficient C_a must not exceed 0.2 for naval applications.

First wind tunnel tests

Tests in a wind tunnel were carried out rapidly after the concept had been elaborated. Figure 7 gives the shapes of some of the thick profiles tested in the wind tunnel.

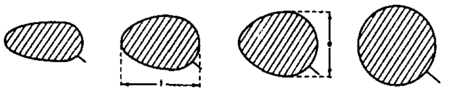

Fig. 7: shapes of some of the thick profiles studied:
AVP - forward parabolic type
AVE - forward elliptic type
CIR - circular profile

The principal features of the wind tunnel are:

- vein dimensions: 2 m x 2 m
- speed of flow: 12 to 40 m/s
- number of Reynolds: 300 000 to 500 000

Early experiments carried out on a group of forward elliptical or parabolic and circular profiles for a large range of suction output made it possible to specify the best positions, types, areas and permeability of the suction areas, as well as the influence of the position of the flap.

After these tests carried out in quasi-bidimensional flow following the technique of the model between panels, all the many other experiments were carried out tri-dimensionally. The models had an aspect ratio (ratio of their length L to the chord 1) taken to be between 4 and 6; one of their extremities was placed against a wall in order to obtain the image effect well known in aerodyna - mics, the said effect allowed for an effective aspect ratio almost twice the geometrical aspect ratio. The other extremity could be fitted with an end disk with its circular opening facing the fan to expel sucked air into the outer flow.

For a wing of infinite aspect ratio,figure 8 shows the curves of C_L according to the incidence α and the polars for certain values of the suction output C_q. For the C_q still further moderated, to the order of 4%, the C_{Lmax} reached is between 7 and 8. For weak C_q, the C_L obtained exceeds 5.

The profile selected for MAV I (Moulin à Vent I) was with forward elliptic and 66% for relative thickness. The position of the flap was 45° and the permeability of the porous skin was about 35%.

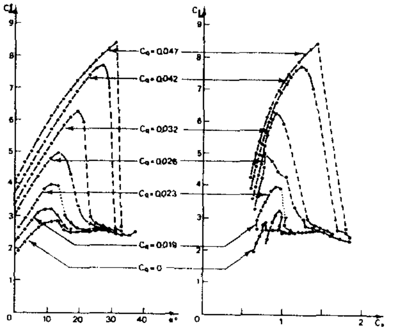

Fig. 8: Infinite aspect ratio:

- Variations of the lift coefficient C_L according to the angle of incidence α for different values of the suction coefficient C_q (the points are experimental)
- Polars of a thick aspirated profile for various C_q (the scale of C_D is double that of C_L)

Figure 9 gives the results obtained in the case of a threedimentional air stream with a model placed at the wall. Aspect ratio of the wing was 4, I.E. an effective aspect ratio of 8. The results obtained suggest that the theory of the finished wingspan of Prandlt has once again been verified in the case of profiles of high lift. Indeed, one notices the proximity of the experimental curves to the induced parabola:

$$C_{Di} = \frac{C_L^2}{\pi\lambda_e}$$

This means that drag of the profile's form is negligible compared with induced drag.

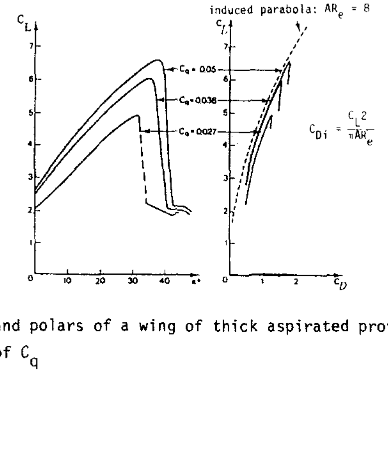

Fig. 9: Curves $C_L(\alpha)$ and polars of a wing of thick aspirated profile of aspect ratio AR = 4 for three values of C_q

Visualisations

A series of visualisations of flow around a thick, aspirated profile was organised by ONERA (OfficeNational d'Etudes et de Recherches Aerospatiales) in M. Verlets's hydrodynamic tunnel. Photographs taken of these tests show the significant deflection of air stream from the suction area (fig. 10). Aspiration reduces turbulence behind the profile.

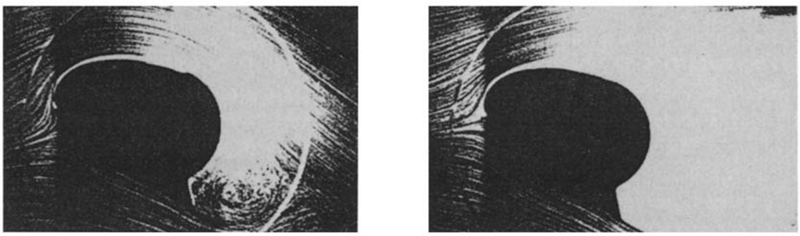

Fig. 10: Views of flows around a thick profile with indicences of 0 and 25°. On the left, without aspiration, one notes the importance of the wake behind the obstacle -on the right, with aspiration, the air streams pass around the rear and the importance of the wake is greatly reduced.

THEORETICAL CALCULATIONS AND EXPERIMENTAL VERIFICATIONS

An important part of the basic research has been carried out by M. Abdallah Daïf, in the aerodynamic laboratory of the ESEM (Ecole Supérieure de l'Energie et des Matériaux) of the University of Orleans, under the control of M. Michel Mudry and M. Roger Roucous.

Standard transformation

The modelling of the flow around the profile based on the standard transformation of the profile on a circle with a fixed point β fixed by experiment, permitted a representation of the movement of C_L according to the incidence α and of the distribution of pressure coefficients C_p on the profile according to the curvilinear axis s.

When the gradient dC_p/ds is too great, the flow separates from the profile. First results in the wind tunnel gave a limited value to this gradient.

Systematic calculations have been carried out for different groups of thick, or very thick profiles, so that it was possible to select a new profile whose foreseeable results seemed more interesting than those obtained on the profile of the MAV I (Moulin à Vent I).

Figure 11 shows the changes in C_L according to the incidence α, as well as the polar obtained in infinite aspect ratio on the profile of MAV I and on the new. This theory/experiment comparison enabled us to choose this new profile for the "Alcyone".

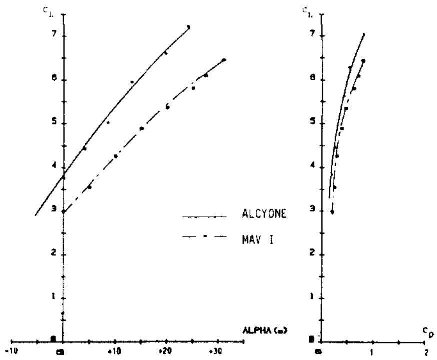

Fig. 11: Aerodynamic differences obtained with the profiles of MAV I and Alcyone by the calculation of the standard transformation. The points and crosses correspond to experimental measurements obtained in infinite aspect ratio.

By calculating the standard transformation, it is possible to determine the distribution of pressures on the outer and inner surfaces of the profile, that is to say, to know the reduction in pressure or vacuum prevailing in the suction area. This vacuum must be overcome by the fan placed at the top of the Turbosail.

Figures 12 et 13 show the distrubution of pressure coefficients on the profiles for the MAV I and Alcyone. One notes the outstanding experimental verification of the theoretical calculation for C_{Lmax} and C_L at zero incidence. The most recessed position of the suction area for Alcyone profile leads one to believe a reduction in aspiration power may be possible.

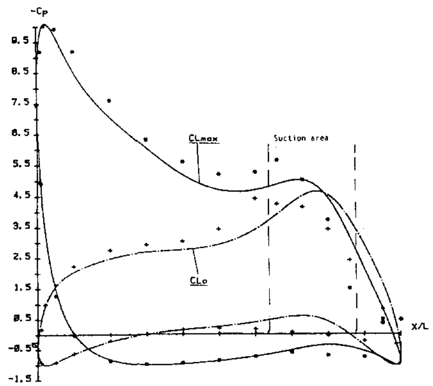

Fig. 12: Distribution of pressure coefficients on the profile of the MAV I - Comparison between theoretical calculations and measurements for C_{Lmax} and C_L at zero incidence.

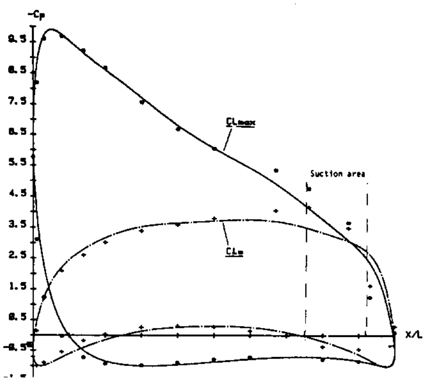

Fig. 13: Distribution of pressure coefficients on the profile of the Alcyone - Comparison between theoretical calculations and measurements for C_{Lmax} and C_L at zero indidence.

Experimental verifications

The aerodynamic performance of thick aspirated profiles is directly linked to the pressure coefficient C_A. The aim is to obtain coefficient of lift C_L as high as possible for minimum C_A. Systematic tests have been made to find the best position in the suction area. Different types of permeable skin have been tested, those consisting of circular holes, oblong holes, longitudinal and transversal slots.

After having found the best compromise in the wind tunnel of small dimensions (0.4 m x 0.4 m) at the University of Orleans, in infinite aspect ratio, a final set of tests was organised in June 1984 at the wind tunnel of Institut of Saint Cyr l'Ecole (dimensions 2 m x 2 m).

These global results are set out in fugure 14. One observes that the new profile requires less energy for the same performance. Differences in C_L of approximately 5% which appear in the results obtained at Orleans and at Saint Cyr, are due to the difference in the number of Reynolds. At Orleans, R_e = 130 000 and at Saint Cyr, R_e = 350 000; an increase in the number of Reynolds always accompanies an improvement of C_L.
The passage to a finished aspect ratio of 8 results in a slight decrease in the value of C_L from one C_A of 0.08. For a C_A of 0.15 the C_L reached is 5.4. By contrast, without aspiration, the passage to a finished aspect ratio results in the loss of one point of C_L.

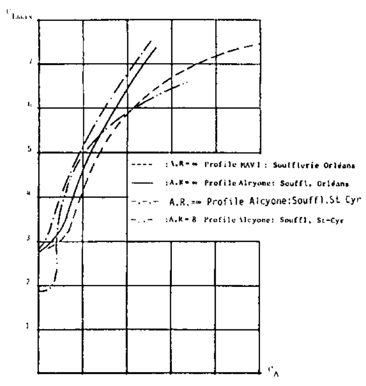

Fig. 14: Aerodynamic performance or the profiles of the MAV I and Alcyone obtained in wind tunnels at Orleans and Saint-Cyr.

On the close hauled course, it is important that the aerodynamic drag C_D of the wind propulsion system should be as low as possible. This is possible by increasing either the span of the wind propulsion system or by improving the aerodynamic properties of the profile. Figure 15 shows changes in the ratio C_L to C_D (fineness) of the profile to the point of C_{Lmax} by infinite and finite aspect ratio for the MAV I and Alcyone profiles. Reduction in fineness during the passage to aspect ratio 8 is due to an increase in induced drag which is limited by the presence of extreme disks placed at the top of the Turbosail.

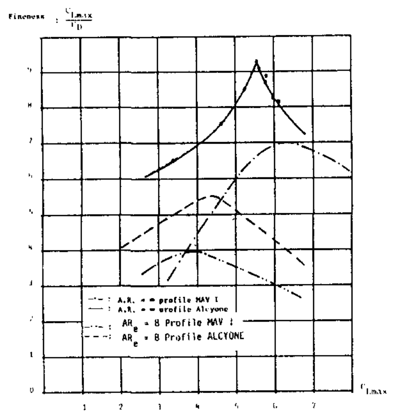

Fig. 15: Changes in the ratio of C_L to C_D of MAV I and Alcyone profiles with infinite and finite aspect ratio obtained in the Saint-Cyr wind tunnel (R_r = 300 000).

Aspiration of the boundary layer

Power expended to control the boundary layer depends on the voluminal output in the boundary layer upstream of the suction area.

Calculation of the boundary layer is based on knowledge of the flow around the profile in perfect air stream.

The numerical programme set up for this calculation uses global methods of calculation of the boundary layer. For the laminar boundary layer, Karman's equation was used and to solve it, it is assumed that the speed inside the boundary layer is represented by a polynomial of the fourth degree (Polhausen's polynomial).

For the turbulent boundary layer, the solution of this equation is obtained by taking Ludwig and Tillman's coefficient and a plausible estimation of the growth coefficient of the boundary layer.

Transition is fixed by experiment, in general on the leading edge of the profile.

Calculation show that air output effectively aspired is between 40 and 70% of the output calculated in the boundary layer, with the same Reynolds. This indicates that it is not necessary to aspirate the entire boundary layer in order to control separations.

Experimental verification of the profile of speeds in the boundary layer obtained by global methods or possibly the replacement of these methods by methods of resolution with finished differences, should permit relating the output in the boundary layer to the aspirated output, according to unfavourable pressure gradients. Thus the criteria of separation and forms will be better controlled.

Comparison between Turbosails and Flettner rotors

It is interesting to compare energy expended in creating the Turbosail effect and maintaining the rotation of a rotating cylinder, with performances of equal lift of course. The Flettner rotor and its extreme disks lead the air by friction, this friction creates a resistant couple which has been assessed during tests carried out by NACA and SNIAS. As with aspiration, a coefficient of operating power C_a can be defined.

In figure 16, curves C_L according to C_A of two elongated rotors with an elongation of A.R. = 6 C_a with or without rotating end-plates of double diameter are traced. Graduations marked on these curves correspond to the ratio of peripheral speed of rotation to the speed of flow. The rotor with rotating end-plates very high C_L but at high C_a : with low C_a the rotor without end-plate is more efficient. The wing of even AR = 6 of circular, aspirated profile is practically equivalent to a rotor with rotating end-plates up to $C_a < 0.5$. The Turbosail with an aspect ratio of AR = 4 is finally the most advantageous for the least expense of C_a. The superiority often attributed to Flettner's rotors thus proves to be ill founded.

Theoretical and experimental research is at present under way to improve the internal flow of the Turbosail, to modelise the working of the aspiration fan, to optimise distrubution of the permeability surface.

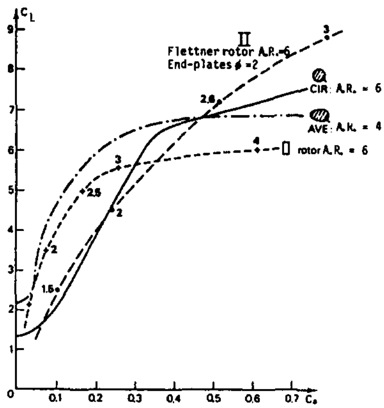

Fig. 16: Comparison of the power necessary (coefficient C_a) for the working of Flettner rotors and thick aspirated profile wings.

TESTS AT SEA

MOULIN A VENT I

Despite all the results obtained in the wind tunnel, it was important to verify, on the scale of one, the Turbosail's surprising performances. To this end a catamaran, 22 meters long, and 7.4 meters wide, found abandoned in the port of Marseilles was refitted to serve as an experimenta platform. This ship was equipped with a floating laboratory and had on board the measuring instruments necessary for learning about the behaviour of the new rigging which consisted of a Turbosail 30 m² by 13.50 m hight, 1.5 m thick for 2.25 m of chord. Two AIFO marine engines of 68 h.p. each were installed for the experiment using mixed propulsion.

The first tests consisted of measuring aerodynamic efforts on the Turbosail using a dynamometric method for a fixed point. In fact, the ship was moored at a fixed point on a bank and could oscillate around this point like a pendulum under the action of aerodynamic forces. Once balance had been obtained, the computer recorded the data. Analysis in deferred time allowed to find lift coefficients according to wind incidence.

The results for wind propulsion alone confirmed the prededing performances.

The speed limit of nine knots for this catamaran with a heavy displacement did not allow tests using mixed propulsion to be carried out in very favourable conditions.

These tests at sea proved the Turbosail's exceptional manoeuvribility. Tacking into wind was carried out in a very short time. In strong wind, reducing the wind force means reducing the speed of the fan before reducing the wind incidence. The Moulin à Vent lost its Turbosail three days from New York, after having endured three storms with winds of more than 60 knots. The poor seafaring qualities of the catamaran in heavy seas destroyed reinforcements made to the base of the Turbosail.

ALCYONE

At the start of 1984, Captain Cousteau decided to built a new ship, truly oceanic, equipped with two Turbosails. This project, presented by the naval architects André Mauric and J. Charles Nahon was chosen: half catamaran half monohull, this ship had a most unusual silhouette (fig. 17); 30 meters long, exceptionnally wide -9 meters- ensuring excellent stability in water. Its displacement with load approximates 70 tons.

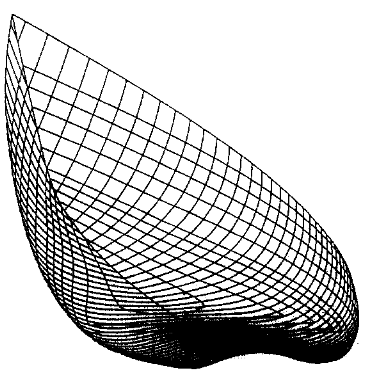

Fig. 17: Perspective view of Alcyone hull designed by naval architects André Mauric and Jean-Charles Nahon.

Each Turbosail has a surface of 21 m², 10.25 m height for 2.05 m of chord. Despite a displacement for the Alcyone twice that of its predecessor, the sail surface has only been increased by 25%. The reduction in height of the Turbosails will reduce catching the wind, which is important when manoeuvring in ports or in storms.

Turbosails begin operating as soon as the true wind attains 5 to 8 knots. When the wind on the beam attains 20 knots, l'Alcyone will travel at more than 10 knots. Between these two wind speed values, the ship will travel on mixed propulsion.

A micro-computer is on board to collect information from weather-wind anemometers, speedometers, pressure sensors, Wattmeters, couplemeters, thrust sensors, consumption-meters, and rotation speed sensors. In total, 33 analogical and 10 numerical sensors will be installed, not counting the 32 strain gages which equip the rear Turbosail. These informations will be processed and analysed by the Analog Devices computer, a multi-task machine which will act on the hydraulic centres of both Turbosails, so as to regulate rotation of the aspiration fan, orientation of the Turbosails and the position of the flap. The computer can also act on the engines which drive the marine propellers (fig. 18).

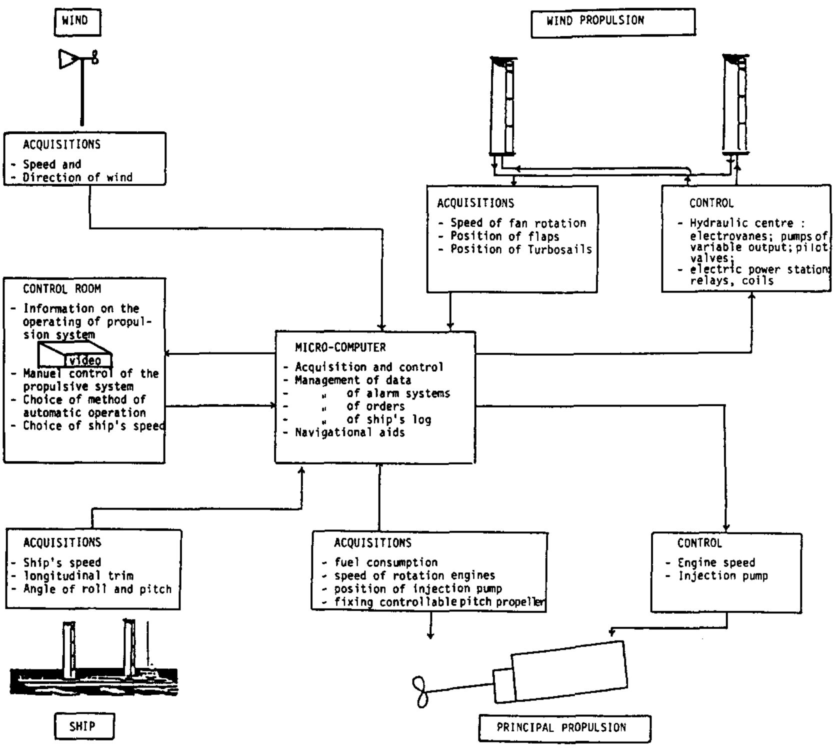

Fig. 18: Propulsive equipment of Alcyone is controled by a multi-task micro-computer, allowing the action and the control of parameters essential to the operation of the ship.

The Alcyone has been conceived as an experimental ship employing all the latest technological developments. Apart from the system of telephonic communications, telex, facsimile by satellite, already installed aboard the Alcyone, a system of positioning by satellite (coupled with a more classic device Loran) will give the position of the ship to within 0.5 of a mile. The route will be projected on to a graphic monitor on to which marine maps will have been recorded. Another colour monitor placed in the ship's wheelhouse will give, continuously, the different operating parameters for the ship: speed, course, fuel consumption, expenditure of electrical power...

SIMULATION OF PERFORMANCE OF A SHIP WITH SUPPLEMENTARY WIND PROPULSION

NUMERICAL PROGRAMME

In association with the firm Péchiney, Jean-Luc Quinio of the Fondation Cousteau has developed a numerical simulation programme for the performance of a ship with supplementary wind propulsion. The main object is to provide a shipowner with facts to enable him to decide whether or not to equip his ship with Turbosails. Indeed, from the detailed features of the ship to be equipped, this simulation determines:

- the dimensions of the sails to be installed on the ship
- the power expended for operating the Turbosails
- the performance to be expected from such equipment
- the economic cost of this solution and its profitability.

Thus, a shipowner can rapidly form an objective idea of the system and decide whether or not to call for a more detailed study.

The hypotheses taken into account in this programme will be verified by the results obtained on the Alcyone.

The principle of the programme is to compare the working of two ships identical in every way except:

- one is driven by its own propellers
- the other, has Turbosails in addition to its propellers.

For each value of wind intensity, its direction variant from 0 to 180°, with an increment of 10°, is calculated for this ship equipped with sails:

- the thrust provided by wind on the Turbosails
- the power expended for aspiration and associated fuel consumption;

for both ships:

- the thrust provided by the propellers
- the power developed by the engines
- the fuel consumption realised by the engines.

From these results, it is possible to calculate on a well-determined route, the consumption of diesel fuel, the time taken for the crossing, etc. given the statistical meteorological data (Pilot chart or global compass card).

For the solution of equations of longitudinal transversal and vertical equilibrium, of the ship's movement, the programme takes into account:

- the resistance of the ship's advancement R in a straight line
- the increase in R according to sea conditions encountered (sea wind)
- increase in R according to the leeway heel of the ship
- increase in R according to the rugosity of the ship's hull
- true efficency of the propeller and of its variation according to the thrust to be provided
- variation of the specific consumption of the propulsion engines and of electric groups according to their charge/load
- aerodynamic efforts on the superstructures
- effective aspect ratio of the Turbosails
- dimension of the end-plates
- interaction between several Turbosails
- wind gradient over open water (classical curve)
- efficiency of the energy system of the fan's

Simulation on a ship of 5 000 D.W.T.

A complete simulation has been carried out on a typical ship, the main features of which are as follows:

- overall length (m) 106.6
- displacement (t) 6,200
- full load (t) 5,000
- 2 propulsion engines (h.p.) 1,550 x 2
- type of fuel DO
- specific fuel consumption (g/hp.h) 158
- controllable pitch propellers 2
- cruising speed (knots) 10.5
- number of days at sea per year 200
- daily consumption (t) 9

The table below sets out the principal results obtained with 15 and 25 knots of true wind, when the ship is equipped with 100 m² then 200 m² of Turbosails.

WIND speed / TURBOSAIL surface	Loss of Head Wind	Maximum economy of power/ Direction of true Cross Wind	Sector where the speed of service is exceeded	Maximum speed/ Direction of True Cross Wind	Economy of average Power with Wind in equiprobable direction
15 knots / 100 m²	- 3.1%	+ 14.8%	0	10.5	6.6%
25 knots / 100 m²	- 4.9%	+ 32.4%	100°-110°	10.6	16.9%
15 knots / 200 m	- 5.6%	+ 28.1%	0	10.5	12.4%
25 knots / 200 m²	- 10.0%	+ 61.4%	60°-150°	10.7	30.7%

With a cross wind of 25 knots, and 200 m² of Turbosail the ship sails using only one engine: under these conditions economy of energy attains 61%. In considéring a directional equiprobable wind, the ship economises 30 % of its energy taking into account the energy expended in aspiration of the boundary layer.

Figure 19 shows the distribution of economies of energy according to the direction of true wind.

Due to the excellent aerodynamic fineness of the profile, wind traction becomes positive for angles of route below 30.

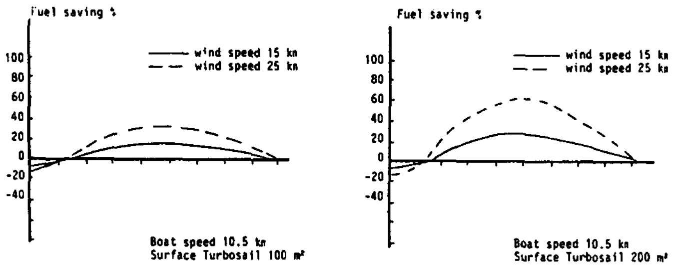

Fig. 19: Distribution of energy economies according to direction of true wind for a ship of 5 000 DWT equipped with 100 m² or 200 m² of Turbosails.

The simulation programme used on the same ship shows that three times the sail surface of the type developed by Nippon Kokan K.K. is necessary to obtain the same average power saved by directional equiprobable winds.

ECONOMIC RISKS OF WIND PROPULSION

Thanks to the French government, the Turbosail concept has been rapidly developed scientifically. Following licensing agreement reached between the Fondation Cousteau and the firm of Cegedur-Pechiney, industrial development should follow at the same pace; however a certain number of economic risks concerning wind propulsion for ships appears on the horizon.

Indeed, the success of the renewal of wind propulsion for ships, seen from the angle of economies of energy, is essentially the result of political and economic factors, the analysis of which, on several occasions, has defeated the best international specialists. Thus, the price of a barrel of oil is an important element in the share of the fuel cost of the running costs of a ship. From 50% two or three years ago, this share now represents no more than 30 - 35% under present conditions. This fact is not without influence on the economic efficiency of a wind propulsion system on a ship especially when the installation is aboard an old ship.

Moreover, notable advances have been made recently in the technique of marine propulsion engines whose specific consumption in several years has passed for 170/180 gr/h.p. x hr to 120 and even 110 gr/h.p. x hr. The use of selfsmoothing paint on hulls, polished propeller blades, etc. are other factors which reinforce even further the economy of exploitation for ships today.

The case of ships at the planning stage is quite different: then it is possible for the supplementary wind propulsion system to be truly integrated into the structure of the ship to be built. In addition, the presence of Turbosails on board can influence the choice and number of main and auxiliary engines, thus rendering the wind system particularly attractive.

CONCLUSIONS

From April 1985, the Alcyone, experimental ship, will take to the sea on a mission lasting many years . At the start of 1986, a chemical carrier of 3,000 tons equipped with two Turbosails, each of 100 m², will sail in European waters. These two experiments conducted at the same time will a low a definitive qualification of the Turbosail concept of supplementary wind propulsion of ships with respect to its foreign competitors.

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N O T E

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