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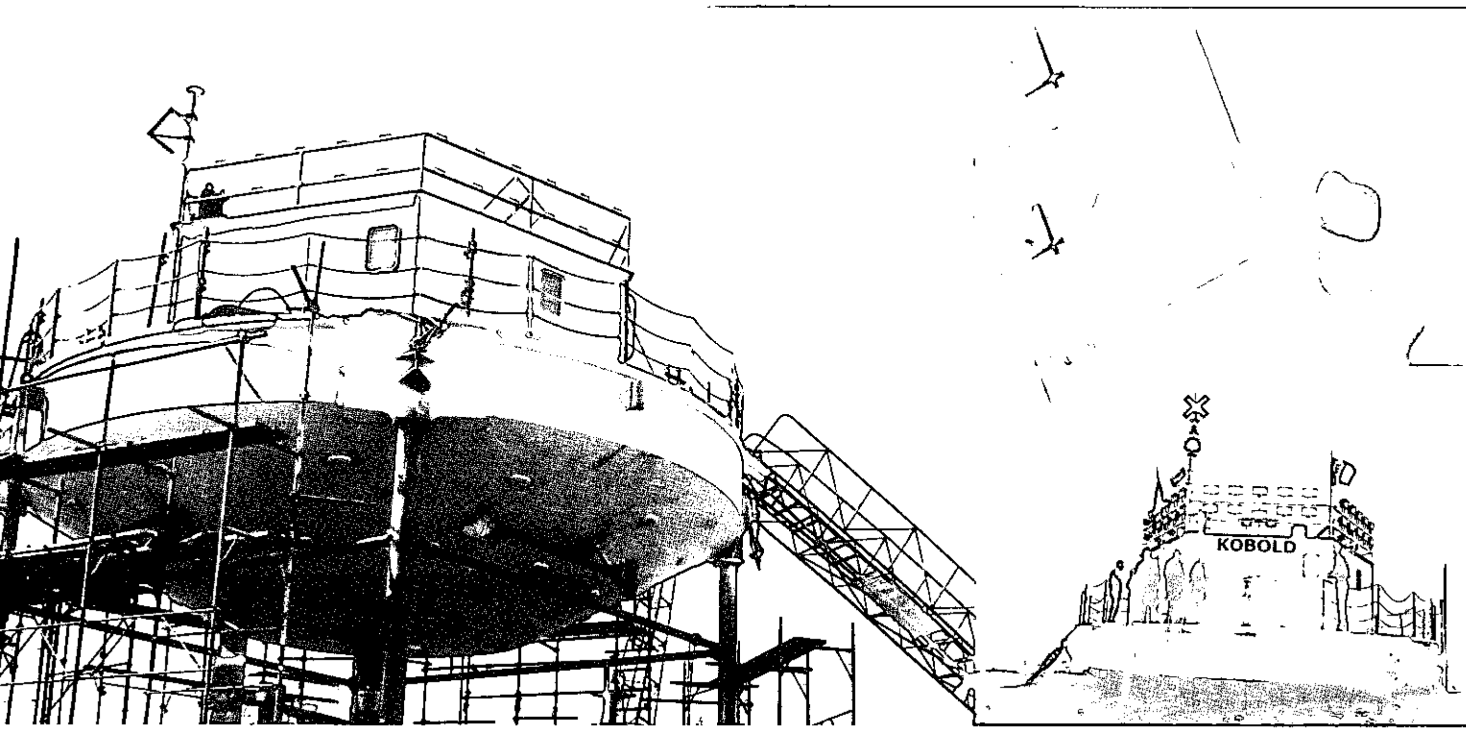
UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org



Kobold Technology, Innovation and Research

Technical Papers

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allo Sviluppo
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The Innovative Kobold technology has been promoted by UNIDO
with the financial support of the Italian Foreign Ministry.

Kobold Technology

Innovation + Research

Technical papers

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna, 2005

The timely compilation of this document was thanks to the dedicated work of Daligault Julien and Ritin *Koria, intern at UNIDO, Vienna*

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Technical Papers

Assessment of the ENERMAR technology, investigating viability and efficiency of a Kobold turbine prototype

Alfredo Cigada, Alberto Zasso Dipartimento di Meccanica,
Politecnico di Milano

1. INTRODUCTION

According to Project: US/RAS/04/069, Politecnico di Milano was charged by UNIDO to start an improvement assessment process for the Kobold water turbine.
The object of the present contract is to give the aerostatic coefficients for a single vane of the same kind as those equipping the already built prototype. Tests have been performed in Politecnico di Milano wind tunnel: results are easier to be obtained in the wind tunnel at a high reliability level and later they can be scaled to water according to well known similitude criteria. This procedure has been often performed by the research team of the wind tunnel in Politecnico di Milano, always with satisfactory results.

The final report will go through the following points:

- o the wind tunnel
- o the testing strategy
- o the model and preliminary calculations
- o the balance
- o the calibration procedures
- o results

2. POLITECNICO DI MILANO WIND TUNNEL

To the purpose of supporting by a state-of-the-art facility the world-wide recognized excellence of Politecnico di Milano research in the field of Long-Span ridge Wind Engineering, as well as general Aerodynamics, in the late 90's it was decided to design and build a new large Wind Tunnel, having a very wide application spectrum, very high flow quality standards and a number of testing facilities. The Wind Tunnel, being a reference all over Europe for

Wind Engineering applications as well as for flowstructure interaction, has been working at its full capability since September 2001 and in the four years of operations it has been fully booked for applications in both fields of Wind Engineering and Aerospace applications. In addition to the already mentioned Wind Engineering projects, several Aerospace applications have been dealt with: Helicopters aerodynamics (Agusta), Air intake aerodynamics, Flying model aeroelasticity, etc..

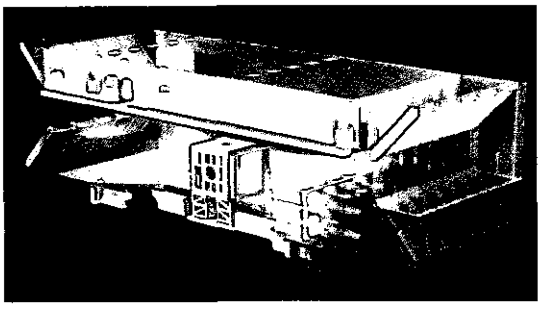


Figure - 1: Politecnico di Milano Wind Tunnel

Figure 1 shows an overview of the Wind Tunnel: it's a closed circuit facility in vertical arrangement, having two test sections, a 4x4m high speed low turbulence and a 14x4m low speed boundary layer test section. The overall wind tunnel characteristics are summarized in Table 1; the vertical arrangement and flow circuit are sketched in the vertical section of Figure 2 and Figure 3.

Politecnico di Milano Wind Tunnel				
Tunnel Overall Dimensions			50×15×15 $[m]$	
Maximum Power (Fans only)			1.5 $[MW]$	
Test Section	Size $[m]$	Max Speed $[m/s]$	$\Delta U/U$ %	Turb. Int. I_u %
Boundary Layer	14×4	16	$< \pm 3$	< 1.5
Low Turbulence	4×4	55	$< \pm 0.2$	< 0.15

Table - 1: Overall wind tunnel characteristics

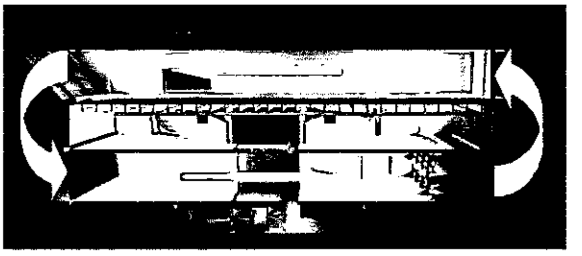


Figure - 2: Wind Tunnel section

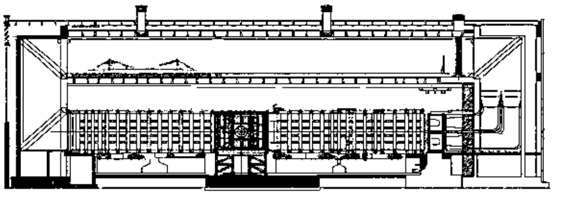


Figure - 3: Wind Tunnel section

The presence of two test sections of very different characteristics is peculiar to this facility, offering a very wide spectrum of flow conditions from very low turbulence and high speed in the contracted 4x4m section (I_u<0.15% - V_{Max}=55 m/s) to the earth boundary layer simulation in the large wind engineering test section. Focusing on the boundary layer test section, its overall size of 36m length, 14m width and 4m height allows for very large scale wind engineering simulations, as well as for setting up scale models of very large structures including wide portions of the surrounding landscape. The relevant height of the test section and its very large total area (4m, 56m²) allows for very low blockage effects even if largetopographic models are included.

The flow quality with smooth flow shows a 1.5% along wind turbulence and ± 3% mean speed fluctuations in the measuring section. A very large 13m-diameter turntable lifted by air-film technology allows for fully automatic rotation of very large and heavy model fitted over it (max load 100.000N). The device is specifically suited for very quick and easy change of wind exposure of very long span bridge aeroelastic models, avoiding all the problems related to the repetitive assembly and disassembly of those complex models (Figure 4).

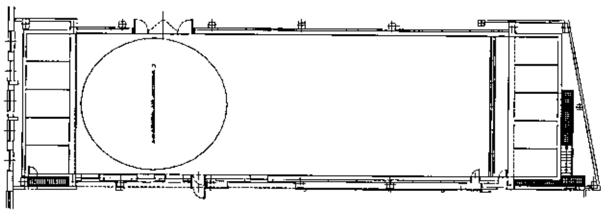


Figure - 4: Wind Tunnel top view

The wind tunnel has a floating floor, allowing for a very clean model set-up, leaving all the instrumentation cable connections out of the flow. The very long upwind chamber is designed in order to develop a stable boundary layer and the flow conditions are very stable even when parameters like temperature are considered, due to the presence of a heat exchanger linked to the general control loop of the facility. The Wind Tunnel is operated through an array of 14 axial fans organised in two stacks of seven 2x2m independent cells. 14 independent inverters drive the fans allowing for a continuous and independent control of the rotation speed of each fan. This fully computer controlled facility can help in easily obtaining, joined to the traditional spires & roughness techniques, a very large range of wind profiles simulating very different flow conditions and very different geometrical scales. The wind tunnel process is fully controlled by a PLC and a computer network (ABB control system), monitoring through more than 100 transducers all the most important flow parameters in terms of wind speeds, pressures, temperatures, humidity, vibrations of the fans and of the structure, door opening etc., and allowing for feedback control on the flow temperature and speed.

The flow conditions were found to be very stable and a confirmation of this fact is the very low turbulence level in smooth flow. All the typical various set of spires have been developed in order to simulate the different wind profiles and an original facility has been recently installed allowing for active turbulence control in the low frequency range.

Concerning the low-turbulence high-speed section, positioned in the lower arm of the circuit, the large dimensions (4x4m) and the quite high wind speed (55 m/s) enable toreach Reynolds numbers in the order of Re = 4.5 E 6 . The very low levels of turbulence reached in this section (0.15%), give the facility a very wide spectrum of possible applications. A number of transducers, instrumentation and data acquisition systems are available, allowing for all the typical boundary layer wind tunnel measuring applications in the wind-engineering field.

3. THE TESTING STRATEGY

Prior to starting a wide range activity, a research plan has to be outlined. The leading idea is to start with the existing Kobold turbine. The overall process, which could lead to the optimal adaptation of the technology to local conditions, could be planned in different phases.

These could be:

- o *Assessment of the present technological development;*

- *Mathematical modelling*
- *Experimental tests on the complete turbine*
- *Optimisation*

The first phase , that is the evaluation of the existing situation, may be split into different tasks:

- Setting up of a single vane model to be tested in the wind tunnel
- Setting up of a suitable load cell to measure forces
- Wind tunnel measurements
- Data analysis

This first phase deals with the experimental tests on the single vane.

The aim of the initial phase is to deal with the wind tunnel tests on a single vane. The key activities involve an in depth evaluation of the turbine wing profile in the wind tunnel, measuring both the flow field in the surrounding of a vane and the global forces given by the stream. This enables to derive the aerostatic coefficients. Of course the leading role of such a big wind tunnel is that of working with rather high scale (that is 2/3 the real profile chord in the present case), though preventing form the typical load effect problems of small test sections and related to the blockage effect.

To achieve these measurements it has been necessary to develop a dynamometric model of the turbine blade and run the necessary tests in the wind tunnel, prior to come to the final elaboration of the collected data and to the overall evaluation of the existing equipment efficiency. In more details, the first phase has consisted in setting up a vane model, for the wind tunnel testing operation. This is an important step of the evaluation phase, as, according to the usual adopted procedures, the wind tunnel features should match those needed for the specific test to be performed.

4. THE MODEL AND PRELIMINARY CALCULATIONS

The vane model has been designed as light as possible in order to limit the dynamic effects on the recorded measurements and at the same time it has been built very stiff, in order to reduce any wind-structure dynamic interaction.

Therefore this operation has required particular skills in the model construction (Figure 5 and Figure 6); the model has been built using carbon fibre, with a very smooth surface painting. The adopted shape is that of the existing Kobold turbine, the so called "high lift 018".

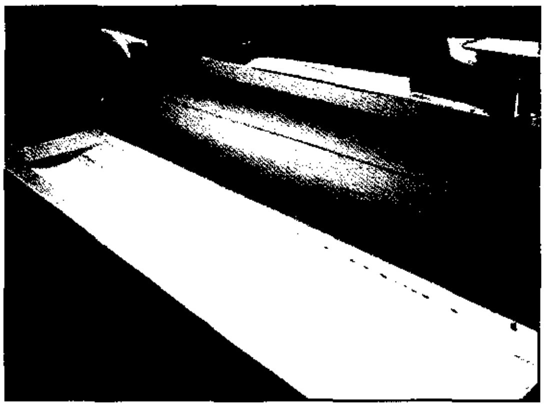


Figure 5: building the vane model

Special care has been devoted to similitude scaling, as the real structure will operate under water, which implies very high Reynolds numbers.

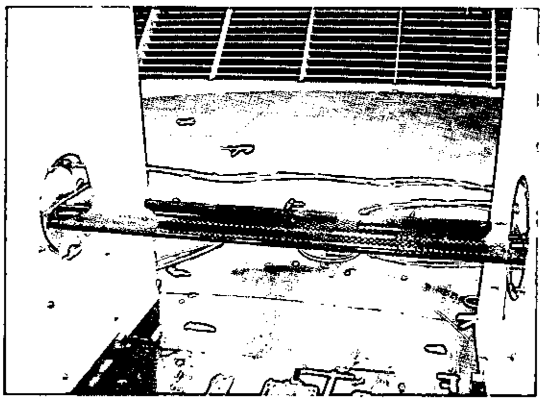


Figure 6: the vane in the wind tunnel

Testing has been performed at the highest possible Reynolds numbers (high speed, large models). It is remembered that Reynolds number is the ratio between the fluid forces and the friction forces exerted by the fluid on the body exposed to the fluid stream. Working under similitude conditions means that this ratio is the same for the model being tested in the wind tunnel and the full-scale prototype.

Advantage of large scale (close to full scale) wind tunnel tests is that the air cinematic viscosity is just 15 times lower than the water cinematic viscosity so that at Wind Tunnel air speed about 15 times larger than the corresponding full scale water flow Reynolds numbers very close to full scale can be achieved. This is the case of the studied Kobold turbine vane Wind Tunnel tests, where air speed much larger than the full scale water current can be applied on a close to unity scale ratio model.

With reference to the following symbols and corresponding values: ρ V and μ the fluid density, velocity and viscosity, B the vane chord, having indicated with the suffix "P" and "M" the quantities related to Prototype and Model, with reference to the standard I.S. values $\mu_{Air} = 1.83\ 10^{-5}$, $\mu_{Water} = 1.0\ 10^{-3}$, $\rho_{Air} = 1.23$, $\rho_{Water} = 1.0\ 10^{3}$, the ratio between prototype and scale model Reynolds Number can be represented as follows:

$$\mathrm{Re} = \frac{\rho V B}{\mu}$$

$$\frac{\mathrm{Re}_P}{\mathrm{Re}_M} = \frac{\rho_{Water}}{\rho_{Air}} \frac{\mu_{Air}}{\mu_{Water}} \frac{V_{Water}}{V_{Air}} \frac{B_P}{B_M}$$

$$\frac{\mathrm{Re}_P}{\mathrm{Re}_M} = 14.87 \frac{V_{Water}}{V_{Air}} \frac{B_P}{B_M}$$

Having selected a scale ratio of the model in the order of 2/3 or in other words $B_P/B_M = 3/2$, the Reynolds Number ratio prototype to model is in the order of $\mathrm{Re}_P/\mathrm{Re}_M = 22.3\ V_{Water}/V_{Air}$

Being the typical current speed in the order of $V_{Current} = 1 \div 2\ m/s$, but with a relativespeed under steady-state conditions around 2 times the current speed, then it has been assumed $V_{Water} = 2 \div 4\ m/s$, and being the tests performed at a wind speed $V_{Air}=12 m/s$ the typical Re ratio will be in the order of $\mathrm{Re}_P / \mathrm{Re}_M = 7.5$ in the worst case. In other words the wind tunnel tests will be rather closely representative of the full scale Reynolds Number. Special care will be taken to the surface roughness problem. In fact it is well known that a large roughness on the wing surface can lead to earlier flow detachment at large angles of attack and consequently to lower maximum lift allowed by the lifting surface. On the other hand a larger roughness surface is typically representative of larger Reynolds number conditions. The true vane surface, under operating conditions in the sea environment will very quickly experience a growth in its, so that it is believed that the very smooth surface tests could be representative just of laboratory conditions or brand new equipment. For these reasons *both conditions were tested: smooth* and rough surface Kobold turbine vane applying a very rough coating to the wing profile, (see Figure 7).

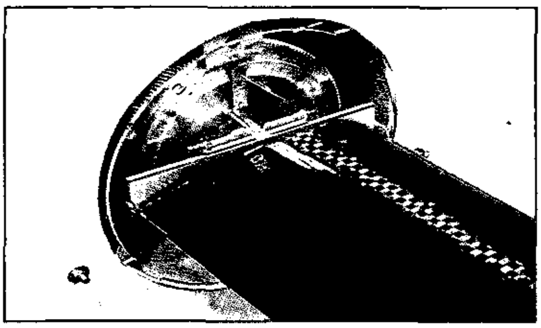
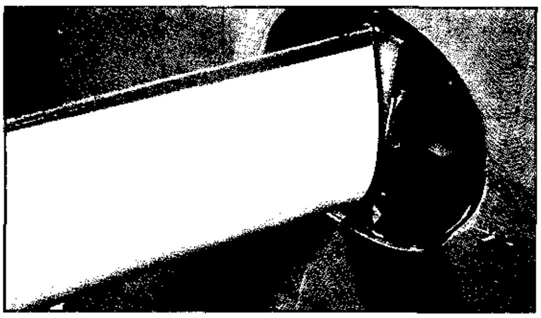


Figure 7: the smooth and the rough wing coating



5. THE BALANCE

The next step has consisted in setting up a special wind tunnel balance to get the aerostatic vane coefficients. Forces on the vane are directly measured, together with the flow speed, in order to get the aerostatic coefficients for the chosen vane profile. Force measurement in wind tunnels is for sure a critical aspect. The overall accuracy of the measurement, is strongly influenced by different factors:

- the *transducer sensitivity and* full scale, according to the expected static and dynamic loads;
- the independence of the measurement from the actual load distribution along the section model, allowing for easy and effective calibration;
- load effects, if the dynamometers are not sheltered from the oncoming flow;
- "border effects", that is the reduction of the total load due to 3-D effects at the model sides;
- if dynamic measuring is asked for, both mass and stiffness have to be properly tuned to allow for a natural frequency high enough not to affect measurements; this need usually fights against the search for high sensitivity.

Two kinds of dynamometers are used to build balances for wind tunnels: those working with box models, capable of hosting the sensing elements inside of them; then those working with section models of trussed or anyway very thin structures, when it is not possible to fix any sensor inside the model, but only at the two side ends. Details about the sensors, specially designed at Politecnico di Milano wind tunnel, are given in the following; the projects and the choices to get the best measurement performances will be analyzed, with special attention paid to those points, which may lead to too large uncertainties or to systematic effects, needing for corrections. However the dynamometer alone is not enough for getting reliable data: the supporting structure has been suitably projected to allow for rotation of the model to the desired angle of attack, though not affecting the overall performances. In the end, static and dynamic calibration will be considered. The check on border and load effects, which cannot be taken into account in laboratory calibration, but which are an essential part in the overall measurement accuracy, has also been accounted for, to complete the calibration and to assess reliable results.

The whole dynamometer set is made up of two sensors to give the global force resulting on the model under test: this force is split into the drag lift and pitch components. These components are measured in a local reference system, as the dynamometers are fixed to the model under test, and this is turned to the desired angle to change the relative windto- model position. To go to the "global" reference system, with components parallel and normal to the relative wind speed axes, a transformation matrix must be considered, and therefore the relative angle between the wind speed and the model reference axes must be known and measured too.

The sensors are of the strain gage kind: the choice has been led by the need of having small and easy to-handle sensors and to allow for dynamic testing at least in the range 0-10 Hz. Special attention has been paid to the strain gages thermal sheltering, to prevent from output drift. This is a critical aspect, especially due to the fact that the sensor has to be exposed to the wind flow which may cause ventilation effects. These may lead to non uniform temperature fields inside the sensor, therefore making strain gage temperature compensation useless. A sketch of the dynamometer concept is given in Figure 8.

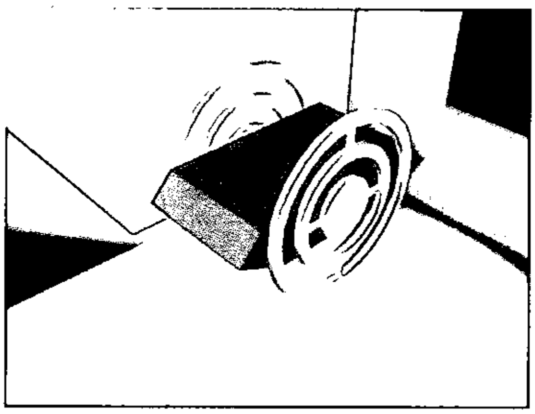


Figure 8: external dynamometer set

The first attempt has been for a strain gage sensor, already known in literature and made up by a number of plates (which can be considered rigid) joined by thin beams, which are the sensing elements: a force, whichever oriented in the sensor's plane, is detected through two normal components. However, a solution like the first in Figure 9 is not fit, as the thin beams mainly react in tension and compression: the modified final solution of Figure 9 improves sensitivity, as the load mainly causes bending strains (with strain gages it is better this latter solution also for thermal compensation). The strain gages have been glued according to the theoretical scheme of Figure 10 and Figure 11, for pitch and for each force component. In this case strain gage sheltering from the wind has been provided by suitable side screens to prevent from both load and "border" effects (non confined flow) and ventilation effects (forcing bad temperature compensation).

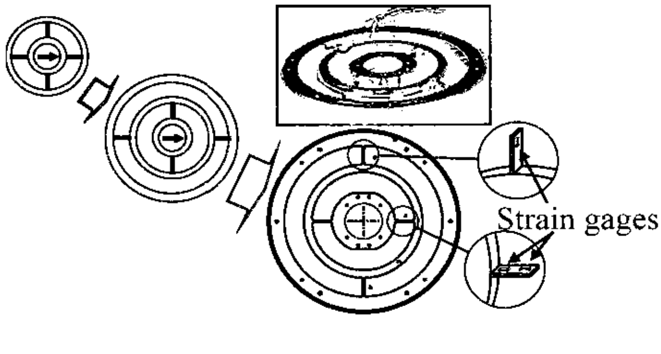


Figure - 9: external dynamometer

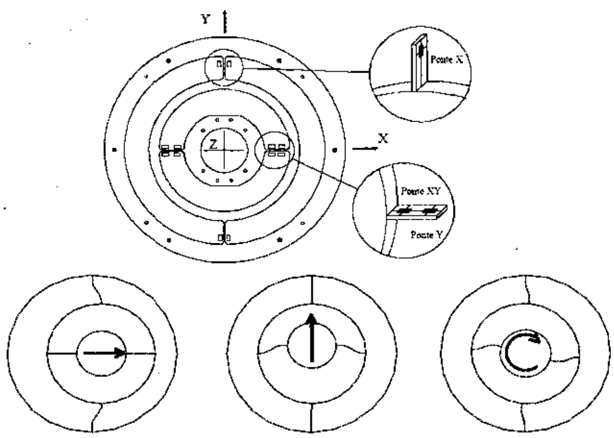
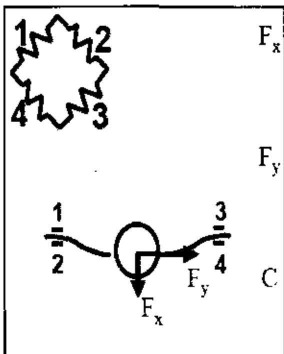


Figure - 10: details on the dynamometers

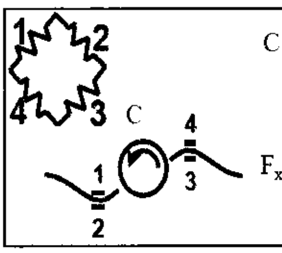
For a correct dimensioning in terms of sensitivity and full scale, the dynamometers must withstand the expected loads in the wind tunnel: these have been estimated for some typical tested models. The maximum load has been estimated through considering the model weight (comprising the supporting elements), the stationary wind forces (fixed model, static coefficients), non stationary wind forces (moving model, dynamic actions) and the inertia forces; the relative weight of the four named forces on the overall loads have been considered: they are more or less comparable. Some preliminary dimensioning has been performed, a prototype has been built and a F.E.M. check has been carried out on the final design before building the real dynamometer. It has therefore been possible to foresee the beams behavior due to all the possible loads, and to look for the best strain gage positions, in order to achieve a compromise in terms of linearity and sensitivity, full scale and rigidity, not forgetting dynamic measurements too.

The mentioned preliminary dimensioning has been performed on a simple analytical model, assuming a thin beam with restrained joints at the ends and working on the theory of elasticity. The strains due to a force and a moment applied to the central plate have been considered (see Figure 13). Concerning the two measured force components, the dynamometer exhibits the best sensitivity when strain gages are glued



F_x	$\Delta R_1 = -\Delta R_2 = \Delta R_3 = -\Delta R_4$ $\frac{\Delta V}{V} = \frac{1}{4}\left(4\frac{\Delta R_1}{R_1}\right)$
F_y	$\Delta R_1 = \Delta R_2 = -\Delta R_3 = -\Delta R_4$ $\frac{\Delta V}{V} = 0$
C	$\Delta R_1 = -\Delta R_2 = -\Delta R_3 = \Delta R_4$ $\frac{\Delta V}{V} = 0$

Figure - 11: external dynamometer: main idea



C	$\Delta R_1 = -\Delta R_2 = \Delta R_3 = -\Delta R_4$ $\frac{\Delta V}{V} = \frac{1}{4}\left(4\frac{\Delta R_1}{R_1}\right)$
F_x	$\Delta R_1 = -\Delta R_2 = -\Delta R_3 = \Delta R_4$ $\frac{\Delta V}{V} = 0$

close to the beam ends (not too much to prevent from notch effects).

The sensitivity to torque is still greater for strain gages close to the extremities, but the bending moment in the thin beams is not symmetric as in the case of force, being greater at the internal side. This strain is also a function of r, that is the distance from the dynamometer center (where the moment is applied), being higher where r is lower [2]. So it comes out that the best position to glue the strain gages to sense torque is on the beams between the inner and the mid ring plates, close to the inner one. On the same beams, close to the mid ring, two other gages sense one component of the global force, while the two beams between the second and the third ring carry the strain gages to sense the other force component, normal to the previous one. A first check on a simple one component prototype has put into evidence that the estimated values for sensitivity, full scale and natural frequencies were correct within a 5% limit.

The final stage has been the numerical simulation via a FEM model of the whole dynamometer (by means of beam elements) and of the sensing beams alone (by means of brick elements) Figure 12 and Figure 14 show a sample of this kind of calculations. The aim was not only to have a more refined check on the dimensioning calculations, but also to foresee the sensing element behavior to different complex load conditions, such as a combination of forces with different directions superimposed to a torque. Also Kobold loads normal to the sensing plane have been considered (Figure 14): these loads shouldn't happen, but they might. A number of tested cases have then been checked through experimentation. Table 2 shows the comparison between the results of the analytical pre-dimensioning and the FEM simulations for 3 different sensors: they are in good agreement, and this

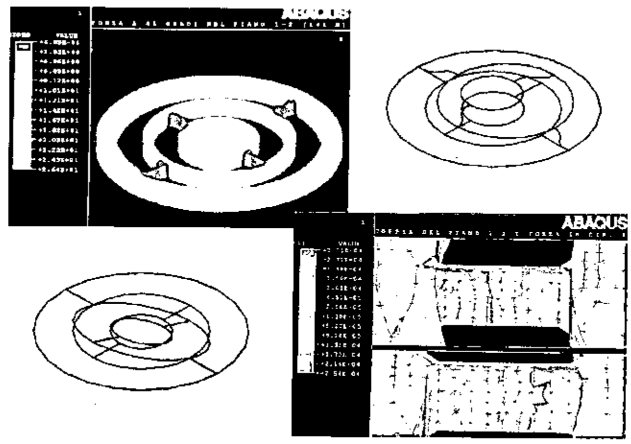


Figure - 12: the FEM model

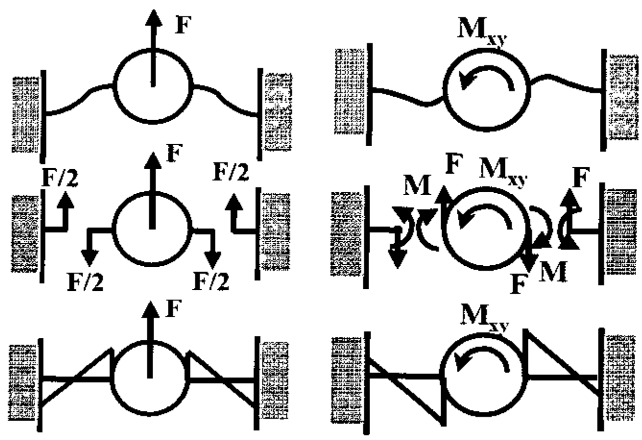


Figure - 13: internal dynamometer: dimensioning

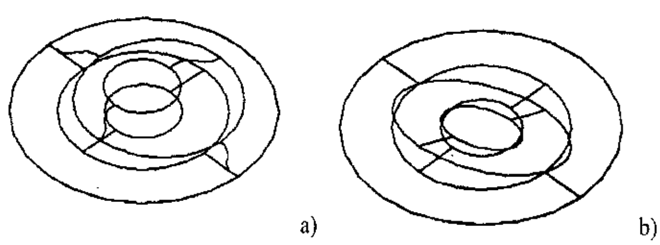


Figure - 14: a) general plane load b) out of plane load

Sensitivity Lift [με/N]	Dyn 1	Dyn 2	Dyn 3
Experim.	4,37	3,63	4,73
Analytical	4,57	4,57	4,57
FEM	4,49	4,49	4,49

Sensitivity Drag [με/N]	Dyn 1	Dyn 2	Dyn 3
Experim.	5,15	3,94	5,67
Analytical	4,57	4,57	4,57
FEM	4,56	4,56	4,56

Sensitivity Pitch [με/Nm]	Dyn 1	Dyn 2	Dyn 3
Experim.	114,46	87,70	100,98
Analytical	98,50	98,50	98,50
FEM	102,53	102,53	102,53

Table 2: Sensitivity: measured and calculated

has permitted to go to the prototype for the calibration of the single sensor, hoping for good linearity under every load condition. The out-of-plane effects resulted negligible, if a good project, preventing from axial loads on the model, is arranged. Three dynamometers have been built and tested to allow a statistical analysis on their behavior; finally, the most similar two have been chosen to build the set. Some preliminary tests proved that the best performances are achieved if the whole

sensor is made up of one piece only (friction and hysteresis are reduced to a minimum), though requiring a good skill when tooling the surroundings of the thin beams which could suffer of a plastic deformation. To simplify the tooling task, an aluminum alloy (Avional), has been adopted for the sensing elements. The built dynamometers have been fixed to a frame with links very similar to the real ones and the same frame was provided with devices capable of giving the desired loads for calibration. Loads normal to the sensing plane have been considered (Figure 14): these loads

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6. THE CALIBRATION PROCEDURES

6.1. STATIC CALIBRATION

Calibration has been performed trough certified weights: the main concerns faced at this stage were the sensitivity to the load application point and the cross sensitivity effect, that is the dynamometer response along one axis when a load is applied to the normal

direction: if it had a perfect behavior it should sense 0. This is not the real case,

Lift	Dyn 1	Dyn 2	Dyn 3
	[με/N]	[με/N]	[με/N]
Sensitivity	4,37 με/N	3,63 με/N	4,73 με/N
Linearity error	0.09%	0.20%	0.09%
Hysteresis	0.48%	0.16%	0.56%
Zero at unload	-0.62%	-0.62%	-0.65%
Strain at full scale	128,6 με	128,6 με	139,2 με
Full scale	29,42 N	29,42 N	29,42 N

Table 3: sensor main features: linearity error is given as the maximum distance, at a certain load, between the given measurements and the best fitting calibration line, scaled to the full scale load

in fact, due to small imperfections, there is always some cross sensitivity, giving no zero output where it is expected.

To improve reliability, a calibration matrix, instead of a simple curve, has been identified, to account for cross-sensitivity, which was the main expected problem (Figure 15).

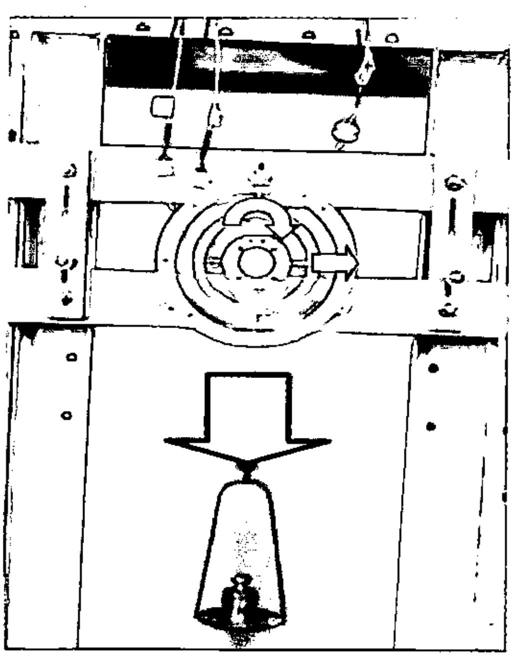


Figure 15: calibration set-up

The first calibration consisted in five cycles of load and unload from zero to 100 N, in different days, to check for sensitivity variations and also possible hysteresis. Tests have then been repeated with random loads. Calibration has been given in strain first, to check FEM calculation, and only in a second time it has been performed in force. Also a check on resolution has been done by applying a 1 kg mass and then a 1.02 kg mass, assuming this limit as the minimum resolution of interest. Table 3 shows the results obtained for the force components and the three sensors. The sensor alone shows good linearity and repeatability, with standard deviation lower than 0.05 N for force and 0.0035 N m for torque. These tests allowed a final comparison between the numerical predictions and the measured values. Table 2 shows this comparison. To justify the differences between the model and the prototype, a sensitivity analysis has been carried out on some possible error-sources, that is the strain gage position, and the uncertainty in the sensing beams thickness (neglecting notch effects at the ends). The main results were that 1 mm error in the overall positioning of the four strain gages leads to a global error of less than 4%, while 5/100 mm error in the beams thickness gives a rough 5% error. These analysis justified, at least from a qualitative point of view, the observed discrepancies. Also a check on cross sensitivity was executed, showing values lower than 0.5 % at full-scale load, corresponding to the uncertainty in the estimation of the load direction in the order of 0.5°. All the possible cross effects have been considered: the most relevant problems seem to arise when torque is considered, as this is very sensitive to even a small asymmetry in the geometry of the sensing element.

Due to these reasons, it has been stated, before applying the calibration curve, to use a calibration correction matrix; this matrix, multiplied by the measurement vector, gives the real corrected values:
written also as

$$\begin{bmatrix} \text{Lift}_{meas} \\ \text{Drag}_{meas} \\ \text{Pitch}_{meas} \end{bmatrix} = \begin{bmatrix} l_l & l_d & l_p \\ d_l & d_d & d_p \\ p_l & p_d & p_p \end{bmatrix} \begin{bmatrix} \text{Lift}_{applied} \\ \text{Drag}_{applied} \\ \text{Pitch}_{applied} \end{bmatrix}$$

$$\overline{F}_{meas} = [M]\overline{F}_{applied}\left(l_l, d_d, p_p = 1\right),\ [M]^{-1}\overline{F}_{meas} = \overline{F}_{applied}$$

with $[M]^{-1}$ = correction matrix.

Corrections are very small, less than 1%, well below the overall target uncertainty of 5%, so that in a first approximation they can be neglected.

A final experimental check concerned drift sensitivity: a constant load applied for several hours led to variations in the order of 1%. As drift is mainly related to temperature effects, this justifies the attention paid to thermal protection of the strain gages. The effects of out plane loads, *already examined by* numerical FEM simulations, were checked, confirming the need of spherical low friction links between the model and the sensors, in order to minimize the undesired hyperstatic effects.

6.2. DYNAMIC CALIBRATION

Only impulsive tests have been carried out to get the sensor natural frequencies. The experimental results confirmed the FEM predictions, showing the lowest natural frequency of interest for the sensor alone around 117 Hz. As during tests the model should be just an added mass, lowering the natural frequency, this effects has been checked for on the global frequency response function, giving 35 Hz with a 4 kg rigid model mass at each side. The final assessment is clearly dependent on the model stiffness and mass distribution.

6.3. ASSEMBLING

The assembling of the external dynamometer set was more critical. The two dynamometers are supported by an external frame, the section model is carried at its extremities by the inner rings of the two dynamometers (Figure 16 to Figure 18). A complete 360° rotation of the model is the functional request, together with allowance for automatic computer controlled execution of the wind tunnel tests, with high repeatability and resolution in positioning. Different solutions have been studied concerning the mechanics of the external rotating connection between the sensor and the frame. The selected scheme is shown in Figure 16 b)).

The links to the model are at the sensor inner ring, while the link to the frame is at the external ring, allowing the strain flux to pass from the first to

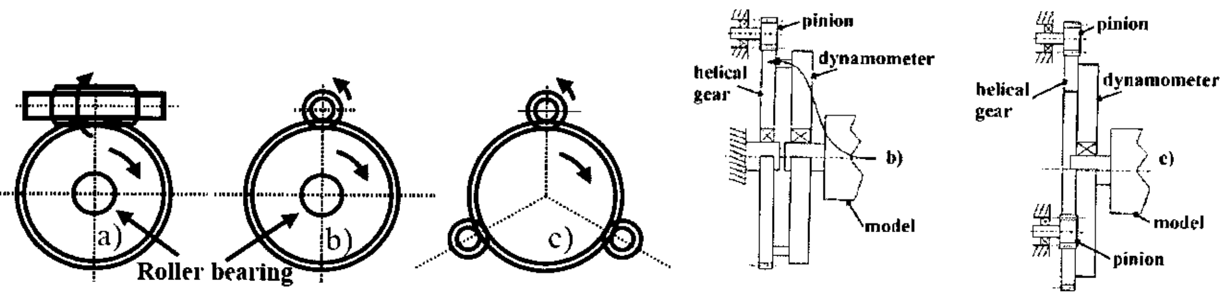


Figure 16: different solutions for holding and moving sensors

the latter through the thin dynamometric beams, avoiding any other contact, which would affect the measurements. The external ring of one of the two sensors has been tooled and coupled to a motorized gear wheel, allowing for full 360° model rotation.

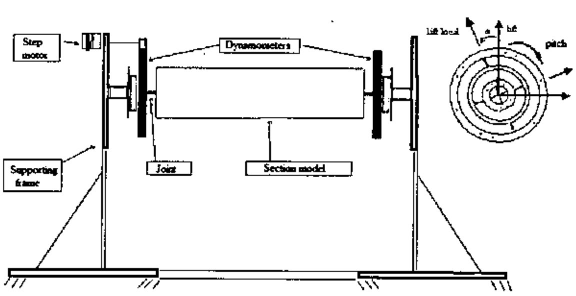


Figure 17: the whole dynamometer assembling

The advantages of a one sided motorized sensor are obvious (no torsional hyperstatic actions, no need of controlled synchronization of the two motors). The main problems are about the request for a high model torsional stiffness to avoid deformations due to the aerodynamic loads and to the uneven torsional load on the sensors, one of them virtually free to rotate. The

connections between the section model and the dynamometers play a fundamental role in the correct loading of the sensor. A special joint has been adopted (Figure 18); its equivalent cinematic behavior is the restraint of vertical, horizontal and torsional DOF, and allowance for all the other rotations and axial displacement. This virtual cinematic behavior is reached through a very low stiffness of the joint in the allowed DOF, compared with the corresponding sensor stiffness. No friction is involved, but just the stiffness of the joint metallic components, therefore producing no dissipation in case of

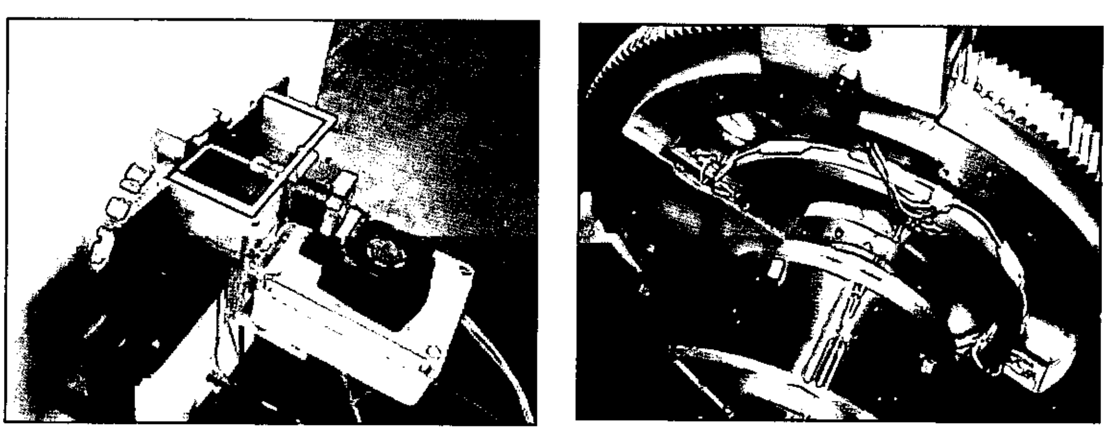


Figure - 18: details of the general assembly dynamic tests. The importance of the joints is mainly due to the attempt to avoid undesired loads on the sensors, bound to model deformation, error in positioning or in other words to any hyperstatic configuration.

The dynamometric set has been finally integrated in an automatic computer-controlled procedure allowing for the measurement of the aerodynamic coefficients of a section model at different pre-defined angular positions. As far as the driving unit is concerned, a micro-stepping actuator has been selected, having torque characteristics and electronic control specially designed for compatibility with the maximum loads allowed by the sensor and suited for the dynamic characteristics of the complete dynamometric set. Inertial loads *on the sensor due to the model inertia,* and resonance of the motor-sensor-model chain are the main problems, leading the step motor control unit design. The angular position measurement is given directly by the open loop step-motor control, with a resolution of 0.15° *corresponding to a single step.* Considering that the microstep control allows for 1/128 step resolution, it's clear that the positioning accuracy and repeatability relies essentially on the transmission mechanics. A parallel way of defining the model angular position is given by means of a MEMS accelerometer. This one, under quasi static conditions, measures the gravity acceleration component related to the device angular position according to a sine/cosine law. Figure 19 gives the results for this calibration. The angular position transducer, though having a lower accuracy, compared to the nominal resolution of the open loop step-motor control, gives a redundant information, checked just in case of loss of step of the drive unit.

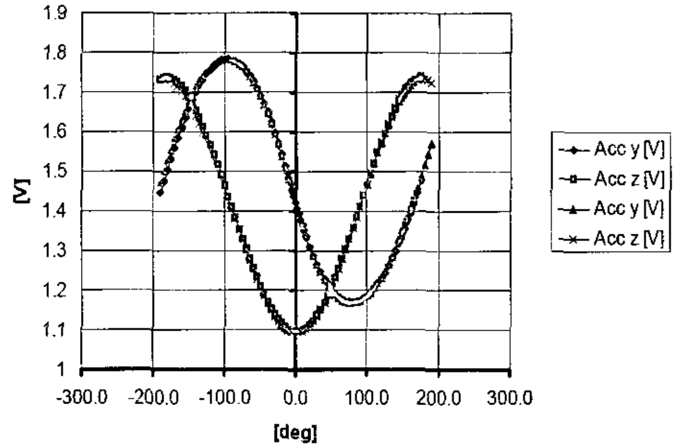


Figure 19: accelerometer calibration

6.4. WHOLE DYNAMOMETER CALIBRATION

The calibration of the whole dynamometer, followed by the uncertainty analysis, has been repeated, as the unavoidable alignment errors of the two sensors were expected to enlarge uncertainty. Known local drag, lift and pitch loads have been provided. No sensible uncertainty enlargement has been observed. A simulation of the worst case has been performed assuming a random combination of the uncertainties playing a role in defining the drag and lift forces in a global reference system. The most significant *results are the following:* the single sensor maximum uncertainty is about 0.05 N with 50 N full-scale load; in global coordinates the overall uncertainty is function of the accuracy of the rotation angle measurement: with reference again to 50 N full-scale load, the global force uncertainty is 0.5 N with potentiometric angle measurement uncertainty on rotation 0.4°), while it drops to 0.1 N with the step-motor open loop estimate (rotation uncertainty 0.1°).

6.5. WIND TUNNEL CALIBRATION

The wind tunnel procedure is performed in two steps: the first is aimed at checking that during transportation in the wind tunnel, no damage or any calibration change happens. Another test, seldom performed unless some problems are observed in measurements, uses tests on a NACA-0012 wing section model; this profile, having well known aerodynamic characteristics and already tested in the same wind tunnel using other kind of dynamometers, gives a good reference. This procedure is also used as a cross check, as results in terms of static coefficients need not only reliable force measurements, but also very good wind speed measurements. These are performed by means of a pitot tube and a precision micromenometer.

Figure 20, Figure 21, Figure 22 give the final calibration checks for the case of the Kobold blade.

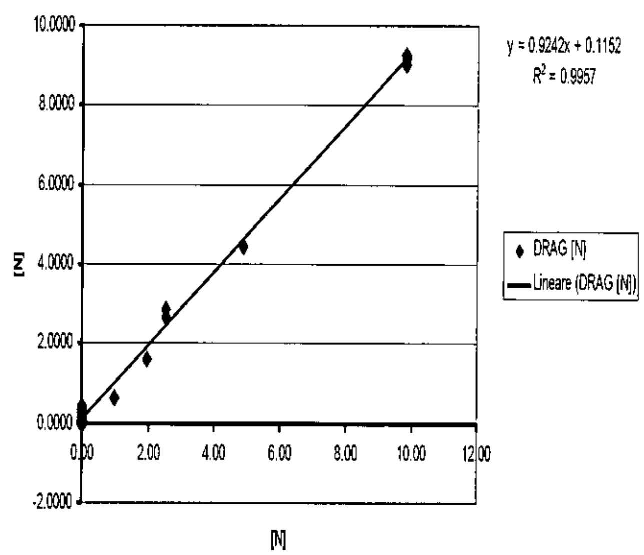


Figure 20: final drag verification

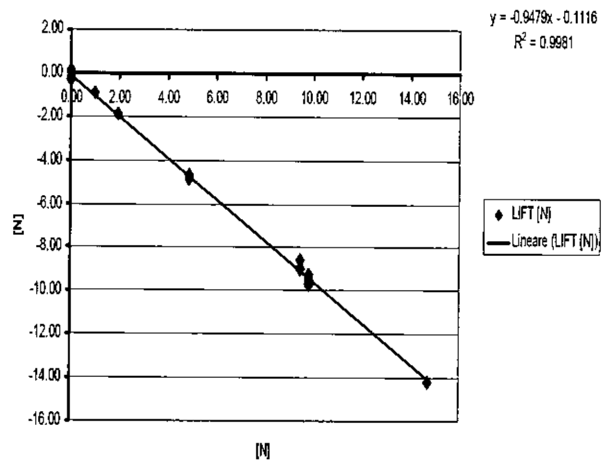


Figure 21: final lift verification

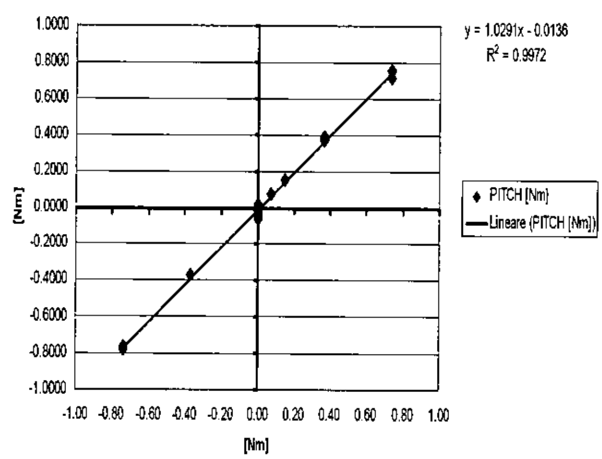


Figure 22: final pitch verification

7. RESULTS

Figure 23, Figure 24, Figure 25 show the results obtained with smooth surface. In the plots coefficients measured at different wind speeds (between 8 and 12 m/s) are shown together, as preliminary tests have proven that no difference is appreciable due to this parameter variation in the mentioned field. Measurements have been repeated, even in different days, to ensure repeatability, and very low data dispersion has been observed. Data obtained in the surrounding of +180° rotation and -180° rotation are also well superimposed each other, confirming the measurement set-up reliability.

The plots are given both in the full range -180° +180° as well as in the fundamental main working range of the wing -20° +20°. In the former, the global behaviour of the wing is studied in its full range, also including the angle of attack regions encountered just occasionally, under turbine rotation start up or strong wake conditions. In the -20° +20° range the effective wing operating conditions are studied in detail, allowing a clear understanding of its high lifting capabilities and of the corresponding low drag characteristics. As from design, quite high lift values are observed, in addition a number of points evidencing sudden flow separation/reattachment are also observed out of the operating conditions; the stall at +12° and a singular point in CM at -10° , again correlated to flow separation, are worthy being mentioned.

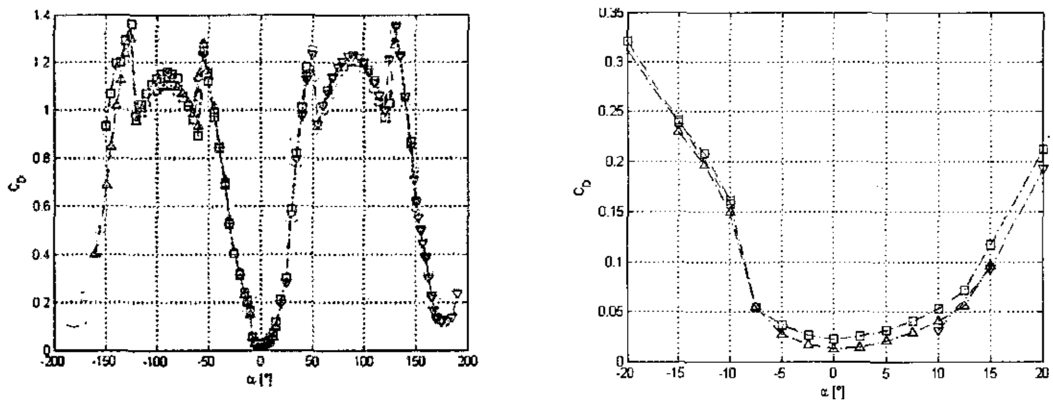


Figure 23: CD with smooth surface: -180° +180° (left) -20° +20° (right)

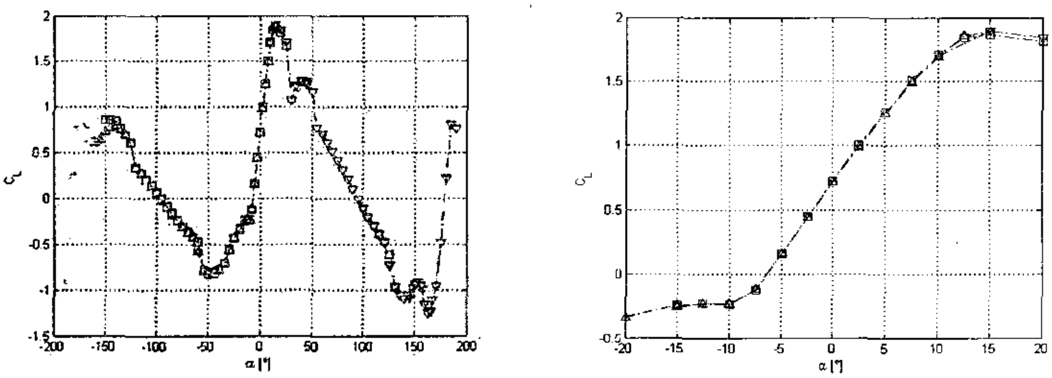


Figure 24: CL with smooth surface: -180° +180° (left) -20° +20° (right)

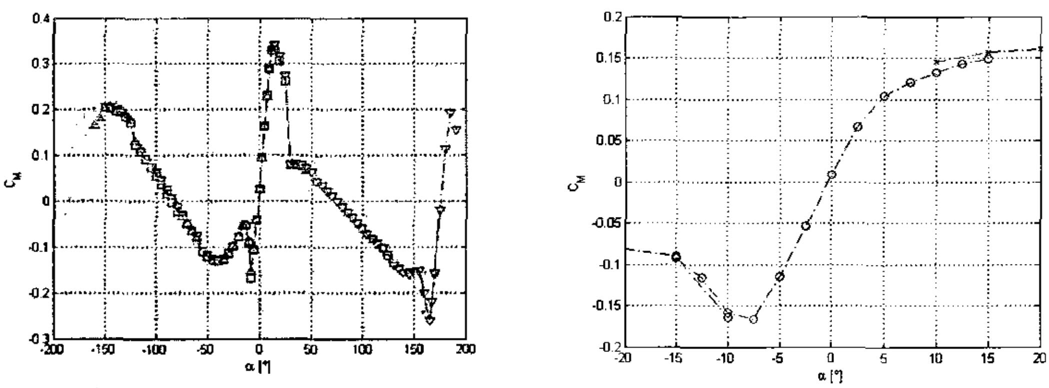


Figure 25: CM with smooth surface: -180° +180° (left) -20° +20° (right)

The second series of tests has been performed on the wing with increased roughness. Results are given in Figure 26, Figure 27, Figure 28 even if, for a better understanding of the roughness effects in the fundamental operating range of the wing, results from both test sessions have been then plotted together in Figure 29, Figure 30, Figure 31.

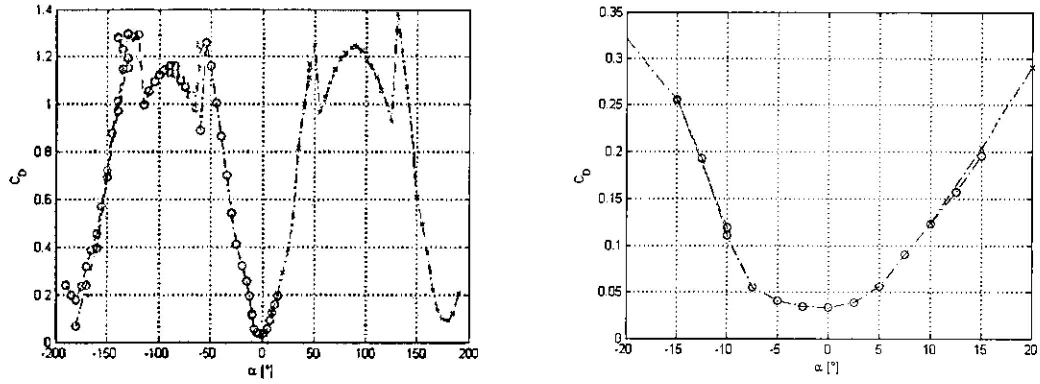


Figure 26: CD with rough surface: -180° +180° (left) -20° +20° (right)

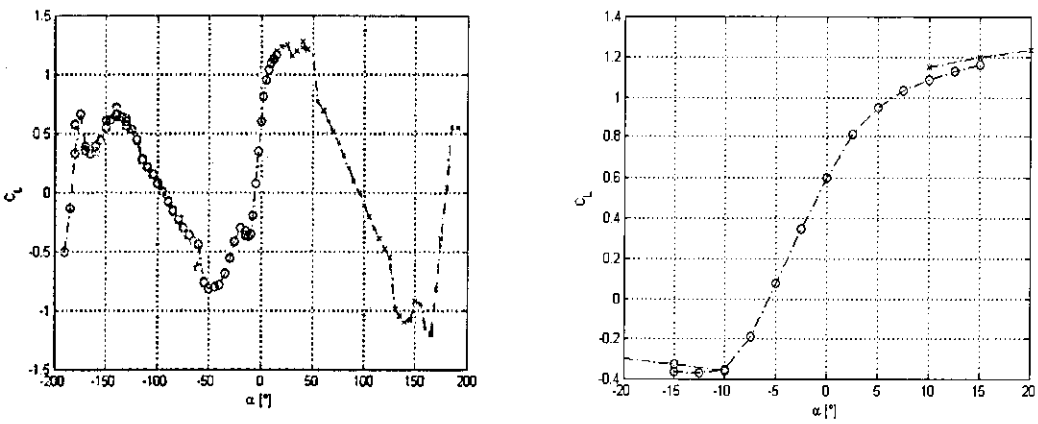


Figure 27: CL with rough surface: -180° +180° (left) -20° +20° (right)

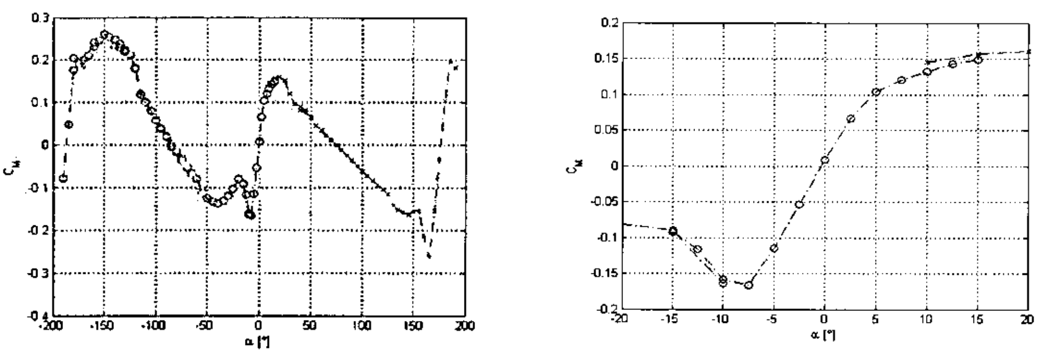


Figure 28: CM with rough surface: -180° +180° (left) -20° +20° (right)

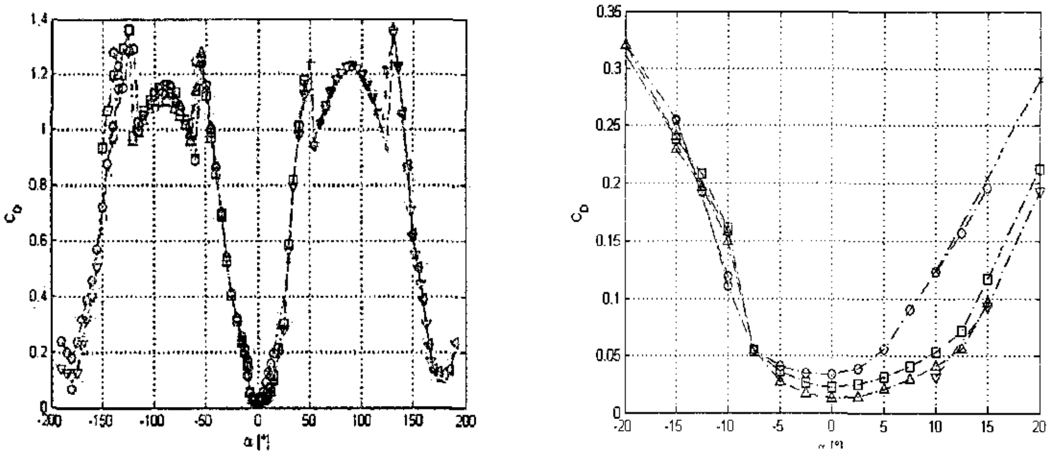


Figure 29: CD comparison smooth and rough surface: -180° +180° (left) -20° +20° (right)

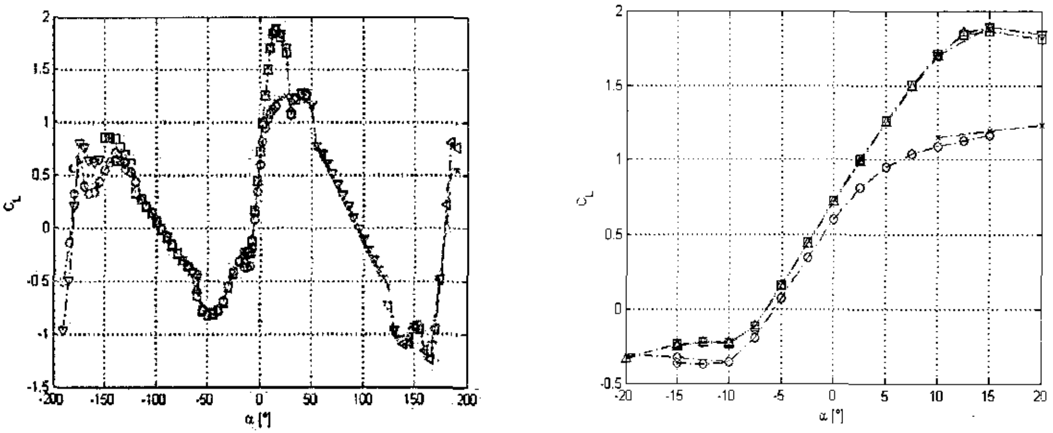


Figure 30: CL comparison smooth and rough surface: -180° +180° (left) -20° +20° (right)

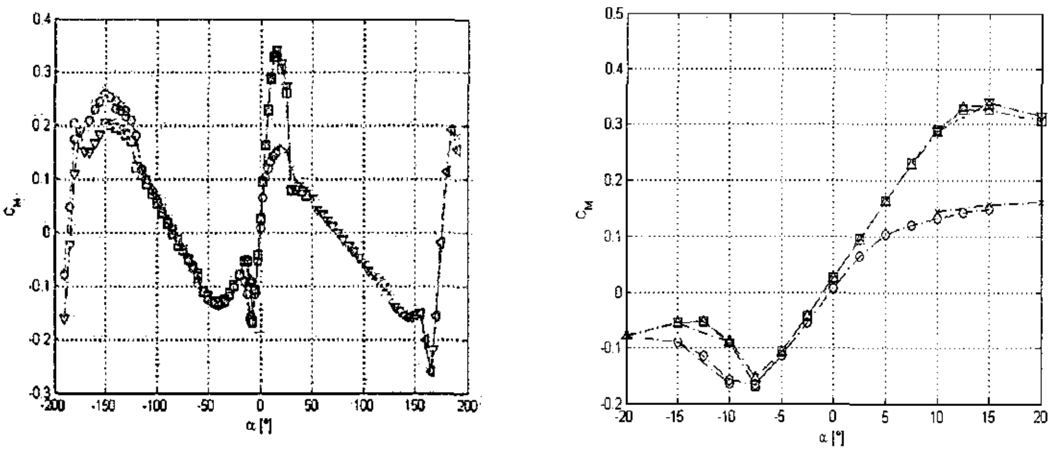


Figure 31: CM comparison smooth and rough surface: -180° +180° (left) -20° +20°(right)

Some facts are easily observed: as expected, due to the roughness effects, a larger drag is encountered around zero angle of attack and in the whole operating range. At the same time the large roughness anticipates separation at lower angle of attack, resulting in a quite relevant reduction of the maximum lifting capabilities of the wing. As already mentioned the Reynolds number range at which the tests were realized in the wind tunnel is somehow lower than that at full scale prototype conditions, so that it is expected that the tests are a bit conservative in the way that the full scale wing, even with the same surface roughness could show a lower reduction in the maximum lifting capabilities and a separation a bit delayed to higher angle of attack. A change is again observed when the wing offers its tail to the incoming flow, i.e. in the surrounding of - 150°, when the behaviour again is that of a wing profile. For high angles of incidence, when the wing works in stalling conditions, its behaviour is typical of a bluff-body section, being much less sensitive to the different Reynolds values, and therefore exhibiting aerostatic coefficients very close each other in the two test runs.

THE ENERMAR SYSTEM

Alberto Moroso, Helena Eriksson
Ponte di Archimede

1 - INTRODUCTION

Marine currents represent a large renewable energy resource and have the potential to give a significant contribution to fulfill the worldwide energy demand. The president of Ponte di Archimede S.p.A., Elio Matacena, came up with the idea of utilizing a vertical axis turbine to extract energy from the marine current in the 80's. He had then been inspired by how his ships, ro-ro ferries from Caronte S.p.A. shipping company, moved in the Strait of Messina, site famous since ancient times for its very strong currents, by the means of Voith Schneider vertical axis propellers, very particular devices - completely different from the normal screw propellers -used for those ships requiring a high maneuverability such as tugs and bidirectional ferries.

The main advantages of the vertical axis turbines, compared to horizontal axis ones, are the designing and building simplicity and that the turbine, no matter where the flow comes from, will always rotate in the same direction.

The ENERMAR system - with its core, the patented Kobold turbine - is successfully operating in the Strait of Messina since June 2001, In January 2005 it was drydocked for maintenance, the generator and the inverter have been changed to comply with the requirements for the Italian electricity grid. In October 2005 the Kobold prototype was connected to the grid. This is the first marine current turbine in the world to be producing electricity to a local electricity grid, see Figure 1.

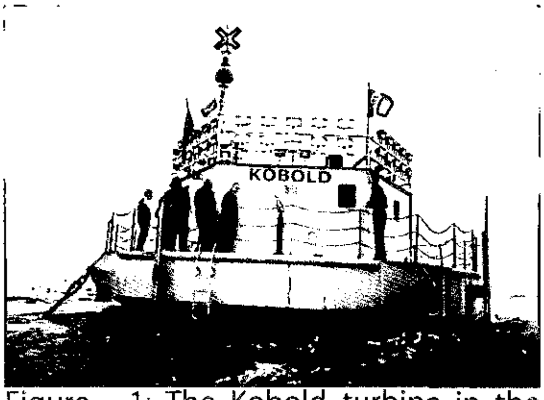


Figure - 1: The Kobold turbine in the Strait of Messina

The theoretical power of any fluid flow (air, water, etc.) is given by the following formula:

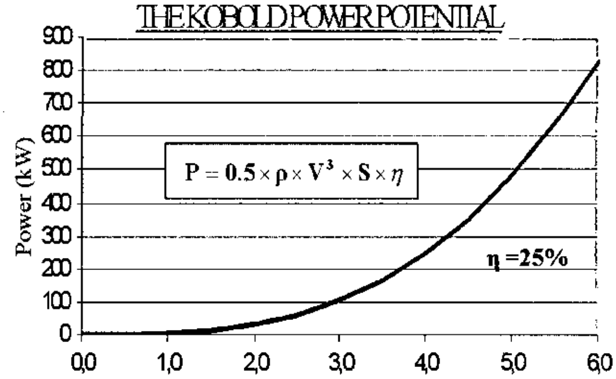
$$P = 1/2\, \rho\, S\, V^3$$

in which S is the projected area of the turbine, ρ is the fluid density and V is the current velocity. However, the maximum extractable power is known as the "Betz's Limit". This limit of 59.3% is due to the fact that it is not possible to extract all the kinetic energy form the flow, which would stop the flow, because a residual kinetic energy is needed by the current in order to flow away from the turbine and leave space to other incoming flow.

In the theoretical power formula the velocity is present to the power of 3, if the velocity doubles, the power gets 8 times bigger; to double the power is enough to increase the current velocity of the 25%, and so on.

Another basic point of the formula is represented by the fluid density: the water density is about 850 times bigger than the air, thus having plants of the same size, at the some velocity the water plant will produce 850 times the power of a wind plant; or also to have the same power of a water turbine in a current of 8 knots velocity (about 4 m/s), a normally strong current, the wind turbine will have to work in a wind of about 136 km/h (38 m/s) which is the typical speed in a strong storm. By this comparison it is evident that, at the same power output, the water plants are more affordable than the wind ones, smaller and implying minor building costs, and shorter payback times.

As seen below, the produced electrical power is the product of the global efficiency, the turbine diameter, the blade height ($S=30\ m^2$ in case of Kobold turbine), the water density (ρ) and the current speed (V). The actual efficiency - although it should more correct to call it power coefficient - of the Kobold turbine is about 25%. This efficiency will be increased further with an optimized mechanical and electrical system. For example the bearing of the turbine shaft was changed during the maintenance and this increased the efficiency of the system of about 3%. Furthermore it is worth a note that already the Kobold turbine has a efficiency comparable to wind ones, which have about forty years of development.



2 - THE DEVELOPMENT HISTORY - FROM AN IDEA TO THE KOBOLD PROTOYPE IN THE STRAIT OF MESSINA

The very early tests of a current device commissioned by Ponte di Archimede S.p.A. were carried out in the hydrodynamic tunnel of the Voith, in Germany, in 1986, when several models were tested. All those prototypes derived from the Voith Schneider vertical axis marine propeller.
In the Voith Schneider propellers any blade rotates cyclically of a certain angle around its vertical axis; the law of this angle variation is related to an internal point: all the blades, during a revolution must have the normals of the chords directed towards this point. By changing this angle, by moving this point, it is possible to change the thrust direction in all the 360°. In this way a ship propelled by a Voith Schneider is extremely maneuverable even with a single propeller and can sail without difficulty in any direction.
The Voith turbine worked exactly in the same way, having the blades moving cyclically during the revolution.
At the Voith hydraulic tunnel several models were tested having from 3 to 6 blades. The model which gave the best results was the 5 bladed one, showing the real possibility of Marine Current Energy, although there were some points which needed some improvement: the efficiency was not really high (around 15%), the turbines in some conditions were not self starting and the Voith propellers (and therefore the turbines) are devices with complicated mechanisms and moving parts to allow the blades motion, thus heavy, delicate and expensive.

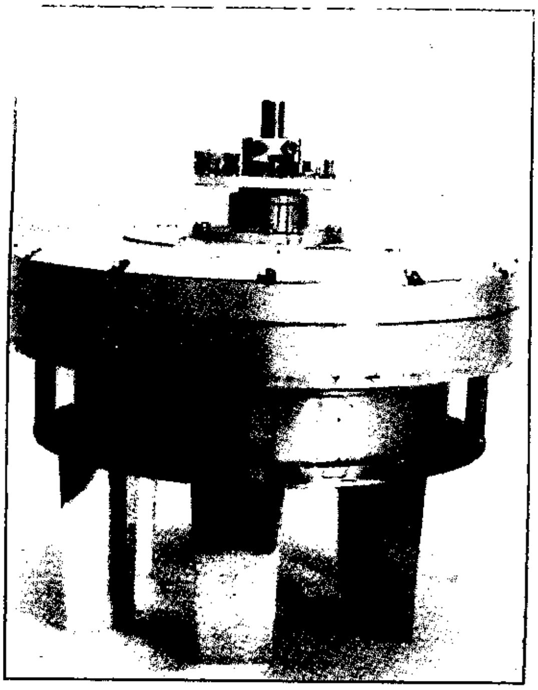
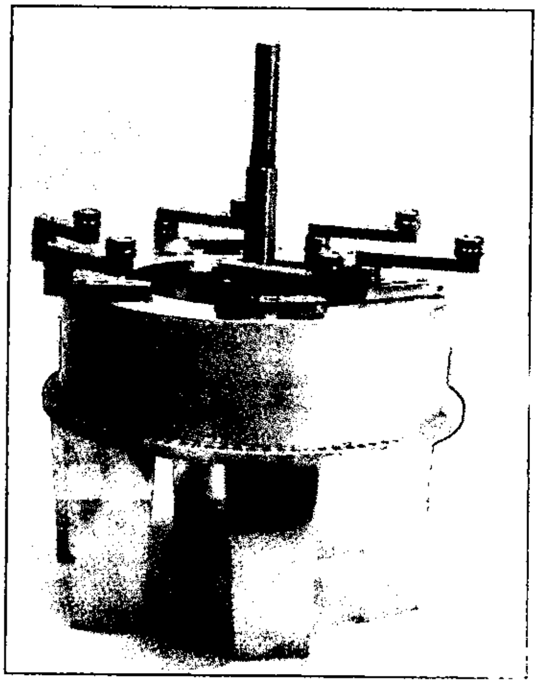


Figure - 3: Voith Schneider hydroturbine



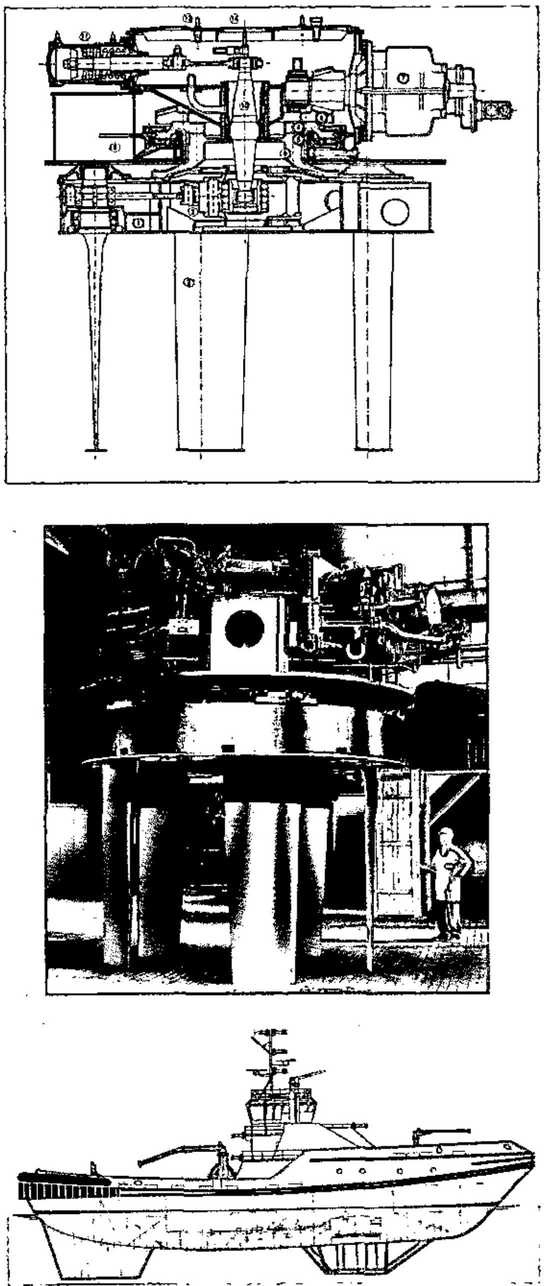


Figure - 4: Voith Schneider marine propeller

The Voith tests led Ponte di Archimede S.p.A. to start in 1995 the development of a new concept turbine which had to be as simple as possible, without any moving mechanism and, above all, self-starting in any condition.
The result of these studies was the concept of a new hydraulic turbine, the Kobold Turbine, having self-moving blades, thus without any mechanism to control the blade orientation, and having a high starting torque under any condition. Like any vertical axis mill, the Kobold turbine rotates in the same direction no matter the current direction.
The concept of a simple, cheap and reliable machine having characteristics of sturdiness and high efficiency was the target of the study of Ponte di Archimede Co. which, in 1998 patented the Kobold Turbine.

A first mathematical model was then set up by Ponte di Archimede in order to evaluate the feasibility of this new concept. In this first prototype the blades of the turbine were modeled as flat plates and they worked in all the possible angles of attack, before and after the stall, thus having both lift and drag to generate the motive forces and the torque. The blade is not active in all its revolution but it has an idle fraction of revolution in which the generated forces are resistant and not motive. The first model of the Kobold turbine was designed by Ponte di Archimede and tested in the towing tank of Naval Engineering Dept. of University of Naples "Federico II" at the end of 1996 The blades were free to oscillate up to 90 degrees (with respect to the radial direction).

Two different models were tested in the towing tank, a first with 3 blades and a second with 5 blades. For both of them the blade profile was a flat plate having a chord of 90 mm and a height of 230 mm. The turbine diameter was 800 mm and the two models were tested at the velocities of 1.0, 1.5 and 2.0 m/s.

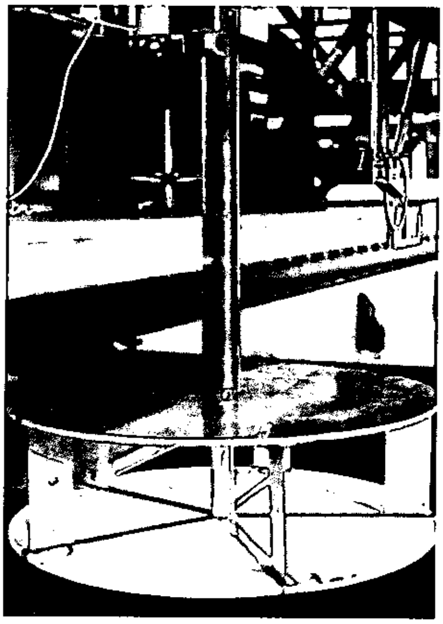
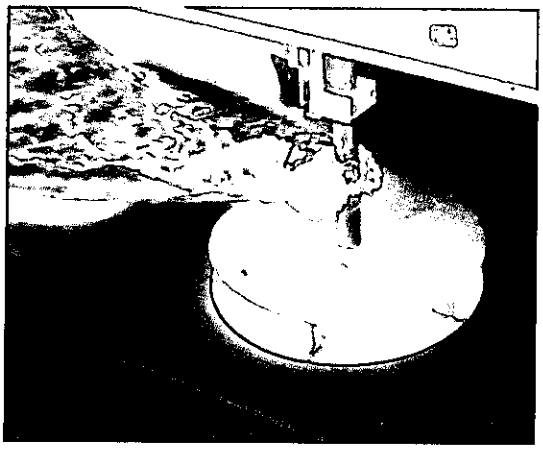


Figure - 5: Kobold turbine model (5 blades) tests in the towing tank of Dept. of Naval Engineering of University of Naples



The towing tank tests fully confirmed the theoretical calculations of the first mathematical model of the turbine behavior. After this first stage of tests the behavior and the working principles of the turbine were more clear, so further theoretical studies on the blade motion brought the Kobold to a first patented optimization. The turbine performances were remarkably improved changing the angle of blade motion, thus changing the lift - drag ratio, improving the working fraction and reducing the idle fraction of revolution in the working point of the turbine.

Further improvements led the Kobold turbine to the actual configuration again protected by a new patent. A second numerical code developed at Dept. of Aeronautical Engineering of University of Naples "Federico II" was used to predict the turbine behaviour and output power, taking into account the interference between the blades - now evident for the higher rotational speed of the blades in respect of the first model - , the passive resistance of other turbine components (for instance the arms) and other major aerodynamic parameters.

The optimization of the turbine led to change some parameters in the working point of the turbine, so this time the torque was mainly generated by the lift of the blades and the idle fraction of the blade revolution was drastically reduced.

To validate the correctness of this new and more sophisticated mathematical model, the numerical activity was coupled with extensive experimental activities consisting in wind-tunnel tests of a larger model of Kobold turbine. In fact a new model was built and tested in the wind tunnel of Dept. of Aeronautical Engineering, University of Naples (see Figure - 6).

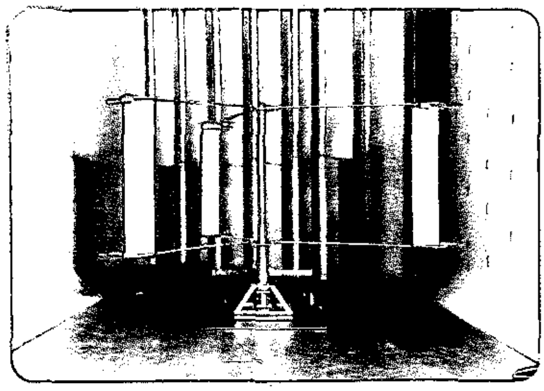
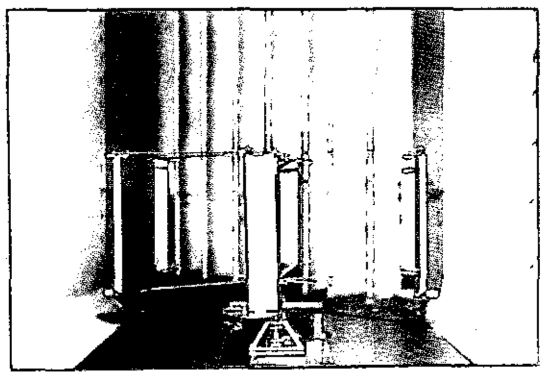


Figure - 6: Model of Kobold turbine in the wind-tunnel of the Department of Aeronautical Engineering of University of Naples (3 blades, up; 6 blades, down)



This model was designed to work in the wind tunnel, thus working at completely different current (in this case wind) and rotational speeds and was built in such a way to change as many parameters as possible in the turbine configuration.

The model had a diameter of 2.2 meters, blades height was of 0.8 meters and the blades chord was of 0.17 meters. It was tested with 2, 3, 4 and 6 blades. The blade airfoil was a NACA 0018 standard profile and due to the high number of possible parameters variation, hundreds of tests were performed.

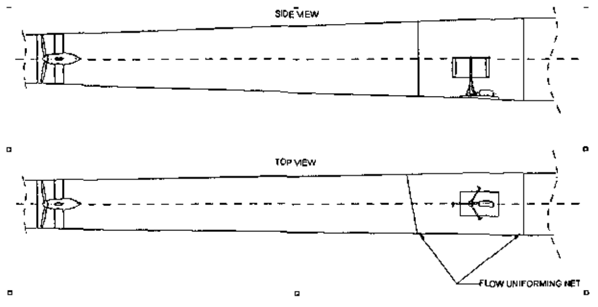


Figure - 7: Wind Tunnel tests arrangement

A particular care was given to the possibility to change the angle of blade *oscillation. The first Kobold turbine* model tested had the blade oscillating like the ones tested in the towing tank. To optimize the angles and to avoid the influence of inertial forces on the blade oscillation, on the blade was positioned a counterweight in order to have the blades fully statically balanced, so to have only aerodynamical forces acting on them. The oscillation angle was controlled trough two adjustable wooden blocks used as limit stops for the blade itself (see Figure - 8).

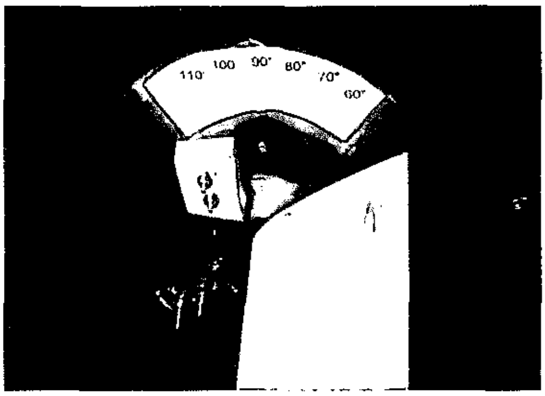
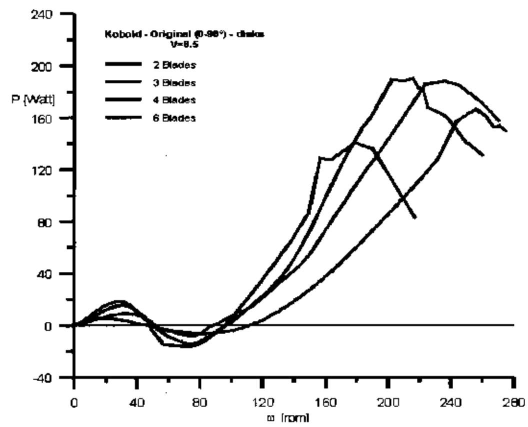


Figure - 8: Details of the blade tip with counterweight. Arrangements to optimize blade pitch angle

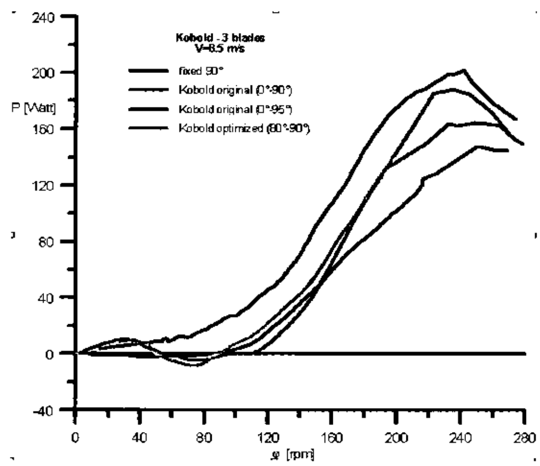
In the following graphs a significant summary of the experiments is reported in Graph - 1 it can also be seen the effect of blades number on produced rotor gross power. This graph clearly shows why a 3-blade configuration was chosen for the real prototype (in fact the maximum rotor gross power is the same of 4 blade arrangement, but with obvious less losses due to blade sustaining arms and reduced construction costs).



Graph - 1: Original Kobold turbine (blade articulation 0-90°). Gross rotor power for different blade number configuration (wind-tunnel tests)

Optimization of blade oscillation angle was then performed to solve the problem of negative power in the low rpm range. As shown in the first graph there is a small zone in the lower rpm region in which the turbine suffers of negative power output: to further accelerate and pass this zone the turbine needs some external power. Once this transition has passed, again the turbine speeds spontaneously up to the top speed

In the Graph - 2 the gross rotor power for different blade oscillation angle setting is shown. Confining the blade oscillation angle into a very small sector (10° from the tangential direction) several advantages were



Graph - 2: Kobold turbine optimization. Gross rotor power for different blade articulation settings (wind-tunnel tests)

gained: mainly it was eliminated the negative zone in the power curve, but also the total power output was improved and the starting torque was increased.
At high rotational velocities the behavior of the non improved model is almost the same of the improved one; the big influences of the way of the blade oscillation is evident in the turbine acceleration, in the way to arrive from the starting to the descending branch of the power curve, the usable branch for the normal applications.

The turbine was tested several times, modifying its characteristics according to the numerical and experimental test results. All the investigations led to the improvement both of the mathematical model and of the turbine characteristics, deeper investigating the kinematical and the dynamic behavior of the tested device.

The final result of these theoretical evaluations and model tests was the Kobold prototype in the Strait of Messina, see Figure - 9.

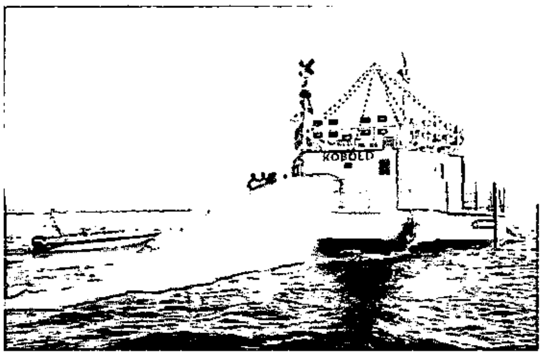


Figure - 9: The Kobold turbine in the Strait of Messina

3 -THE KOBOLD PLANT IN THE STRAIT OF MESSINA - THE ENERMAR SYSTEM

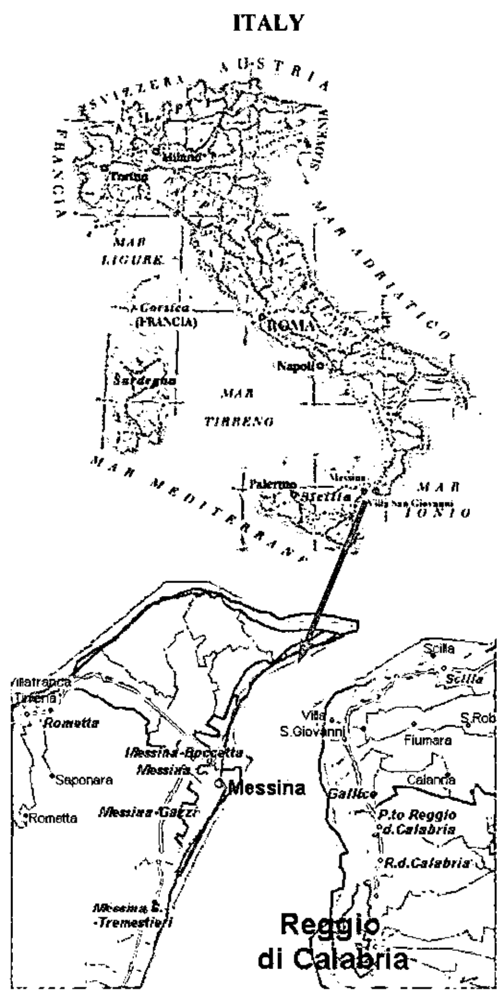


Figure - 10: The location of the Kobold prototype

The Kobold turbine has been designed to satisfy, at the highest possible level, the environment safeguard and efficiency needs, as well as the necessities of low construction and maintenance costs. The ENERMAR system has been designed so that minor causes cannot result in disproportionately heavy damage. The design has taken into account the practicability of carrying out inspections of relevant components.

The characteristics of the Kobold turbine are the following:

- *direction of rotation independent of marine current direction.*
- *a very high starting torque, that makes the turbine able to start spontaneously, also in loaded conditions, without the necessity of any starting devices.*

The airfoil used for the turbine blades is a new concept unsymmetrical profile, so called HILIFT 18, designed for this purpose by the Department. of Aeronautical Engineering of the University of Naples using numerical codes, taking into account both the maximization of the turbine performances and the risk of the cavitation which would quickly damage the blades.

It is the first time that was used an unsymmetrical profile for vertical axis turbine applications.
The blades structure, mainly for the hydrodynamic loads and for the weight, was studied using advanced FEM programs and was realized in carbon fiber and epoxy resin.

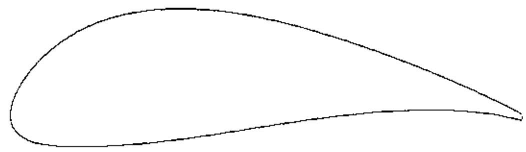


Figure - 11: HILIFT 18 profile

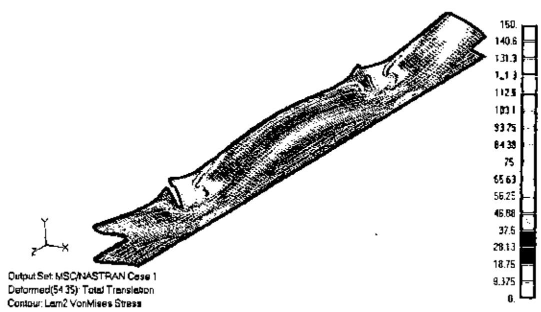


Figure - 12: Blade stresses

From the mechanical point of view, the Kobold turbine has been designed following simple and effective principles, so as to need for its whole useful life very limited maintenance interventions. The design has taken into account the practicability of carrying out inspections of relevant components.

The main turbine dimensions are the following:

Diameter	6 meters
Blade Span	5 meters
Chord	0.4 meters
N° of Blades	3

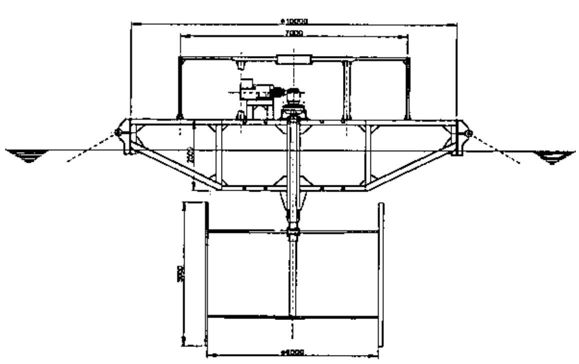


Figure - 13: The ENERMAR system

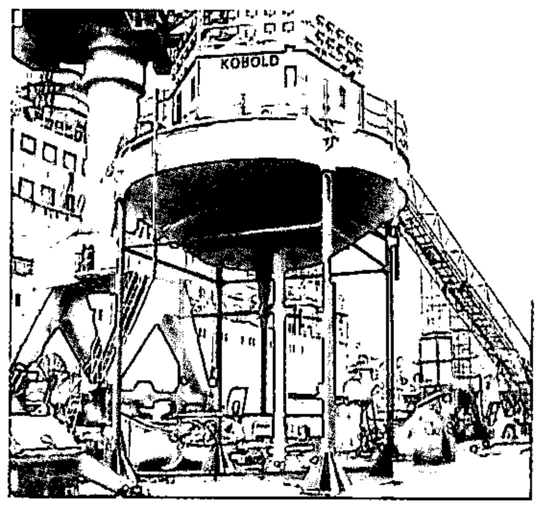


Figure - 14:- The ENERMAR system on the dock

The 3 -blades turbine rotor is mounted under a round shaped buoy of 10 m diameter.

The buoy was built in steel according to the Italia Shipping Register (RINA) regulations for the steel ships and certified by RINA.

The main characteristics of the floating platform are the following:

Diameter	*10.0 m*
Depth	*2.5 m*
Design Draft	*1.4 m*
Steel weight	*25.0 t*
Displacement	*35.0 t*
Metacentric height	*5.0 m*

This last parameter indicates the stability characteristics of the floating platform: the bigger is the metacentric height, the higher is the platform stability. If compared to a standard ship with the same displacement, the platform stability is about 6 times bigger.

In naval architecture the metacentric height is indicated with the term (r-a) in which "r" is related to the geometrical parameters of the floating platform (immersed volume and moment of inertia around the inclining

axis of the waterplane), while the term "a" is related to the floating platform mass properties and indicates the vertical position of the center of gravity. To have a big stability, thus, it is important to have the term (r-a) higher as possible, and it is normally achieved keeping the center of gravity lower as possible.
Another main point for the stability characteristics of the floating platform is represented by the displacement Δ (equal to the platform weight), in fact the stability moment is given by the following formula in which θ is the inclination angle:

$$\Delta \ (r\text{-}a) \ \sin \theta = \text{Moment of Stability}$$

Since the turbine, when working, produces a thrust having approximately the current direction, this thrust (which is around 10 - 15 t) generates with the mooring reaction a moment inclining the whole plant.
This trimming moment depends obviously on the thrust but also on the arm, i.e. the distance between the mid-span of the blades and the mooring point on the platform.
For reasons of both global plant efficiency and safety on board, it is important that this trimming angle is as small as possible. Actually, in normal working conditions, the trimming angle is around 5 degrees.

The platform is moored to the seabed by means of four mooring lines composed each of a chain (27 m) at the sea bottom and of a textile rope going up to the platform. The anchoring devices are 4 mooring blocks made of concrete having the weight of 35 t each.

The site where the plant is positioned

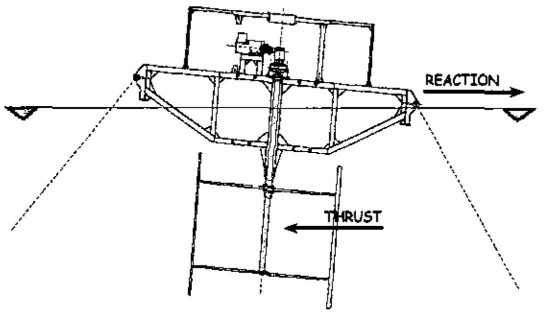


Figure - 15: Trimming moment in working conditions

is very closed to Ganzirri, in the Strait of Messina, by the Sicilian coast, distant from the shore about 150 - 200 m.
The depth goes from 15 to 35 m and the maximum current speed is around 2.0 m/s although there are places, in the Strait of Messina, where the current speed can be more than 3.0 m/s.

The moorings, due to the weight of the lines, work like non linear springs but exponential, following the law of the catenary. This implies that if the displacement of any line it is a little more than the others, the force of this line will be very much higher than the others, thus the mooring lines work only one per time, and this is truer the tighter is the lines, i.e. the higher thrust of the turbine is.

The mechanical energy produced by the turbine is turned into electrical by means of a synchronous brushless 380 V three-phase, four poles electric generator. Since the turbine rotates very slow (18 - 20 r.p.m.) while the generator, to have an output at 380 V and 50 hz, needs to rotate at 1500 r.p.m., the turbine is connected to the electric generator through an epicycloidal gearbox with ratio 90:1 increasing thus the rotational speed at the generator shaft.

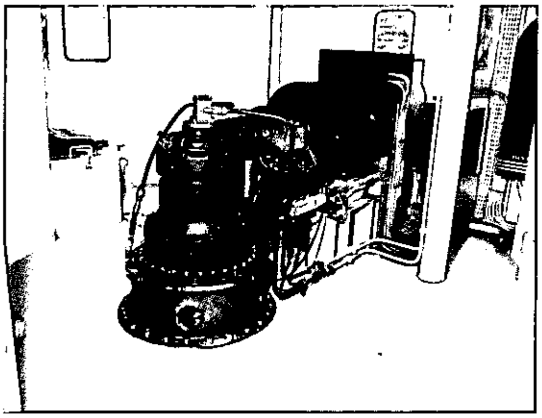


Figure - 16: Machinery room - Generator and gearbox

The global efficiency of the system, also and more correctly called *power coefficient,* is defined as the ratio between the produced electrical power and the theoretical power available in the current relative to the intercepted area:

$$\eta = \frac{Pelectrical}{.5\ \rho\ V^3\ S}$$

where S = *Diameter* Blade Height* (*S=30 m2* in case of Kobold turbine), ρ is water density and *V* is the current speed. The measured global efficiency was (before 2005) around 23%, which is comparable to the long time well developed wind turbines and so this first results can be considered excellent even because on-going improvements in the mechanical transmission system will certainly rise the global efficiency very soon.

The power produced was calculated measuring the current in every phase and the tension between the phases, therefore the power measurements were net and didn't take into account the several losses in the various devices.

The main losses that are present in the system are mainly of three typologies: mechanic, electric and hydrodynamic. There are mechanical losses in the bearings and in the gearbox, there are electrical losses (the so called losses in the "cupper") and ventilation losses (for cooling) in the generator and there are hydrodynamic losses in the bracing of the turbine. These last ones are "physiological", they can hardly be reduced and this can be done only changing some design parameters.

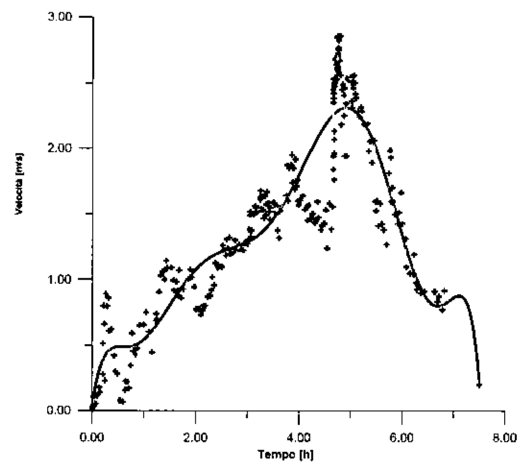


Figure - 17: Current velocity in the Strait of Messina

There are some "added" hydrodynamic losses which take origin from the blade braces when the whole plant is inclined during the normal working. For this inclination the brace fairings don't work any more at zero angle of attack but with an angle equal to the inclination angle, so they generate a lift and thus an added drag which represent a passive resistance for the whole system, to be kept as low as possible.

Although the plant design power is about 80 kW, the maximum power output was around 25 kW due to the installation site, which is not the best,

for this purpose, in the Strait of Messina, site famous among the sailormen since ancient times for its strong and dangerous currents. In fact the currents are generated by the phase opposition of the tides in the Ionian and in the Tyrrhenian seas, therefore every 6 - 7 hours there is an inversion in the current direction. The two currents are known as discendente (descending, Tyrrhenian - Ionian direction) and montante (rising, Ionian - Tyrrhenian direction).
Although in some points of the Strait the current can reach more than 3 m/s, in the place where the plant is moored the current velocity is hardly more than 2 m/s and the plant is sheltered from the descending, thus it is active only during the phases of the rising current.

Up until January 2005 the electricity produced by the turbine was used on board only for experimental purposes, by turning on 20 floodlights each of them absorbing 1 kW of power (total produced power 20 kW) with a current speed of about 1.8 m/s and driving the electro-pump (25 kW) with a current speed of about 2.0 m/s. In this way, except the pump, the electrical load was only resistive, purely homic, so it was possible to calculate the power multiplying the current in the phases by the tension between the phases.

In a later stage a computerized system was installed on board to continuous monitor several parameters of the system, a torque meter was added to the generator shaft to calculate the power before the generator, thus non including the losses in the generator in the power output of the system.

As reported in the introduction, the

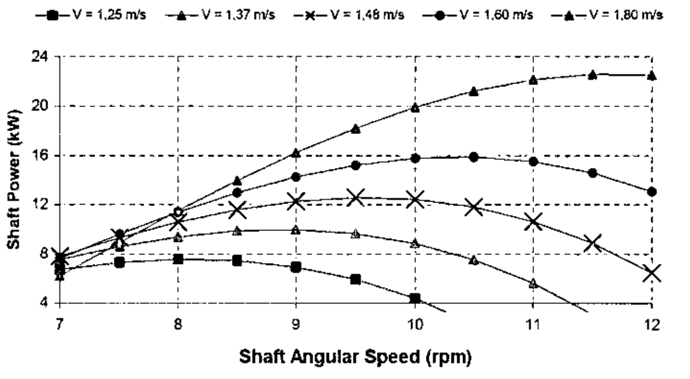


Figure - 18: Kobold power output

plant has just been permanently connected to the Italian electric grid. This is the first marine current energy plant to be permanently connected to a national grid.

Since the turbine rotates at any speed, depending only on the current velocity, the electricity is produced at any frequency and tension. This gives no problems when the electric power is used on board for experimental purposes, but when giving electricity to the national grid, the requirements are very strict in terms of frequency, tension and phase.

The energy is produced by the system at any angular velocity and, since there is no any blade-pitch control, the turbine rotates at any velocity, depending only to the current speed. The only way to control the r.p.m. is to change the load of the turbine by keeping it at the maximum power output for that current speed. Since the electrical current produced is directly dependant, in terms of tension and frequency, on the angular speed of the generator (and thus of the whole system), it is necessary to regulate these parameters before sending the energy into the national grid.
To meet the grid requirements a static

rectifier-inverter was installed on board in order to have, no matter the turbine speed, always the same electrical output in terms of tension and frequency, and always in phase with the national grid.

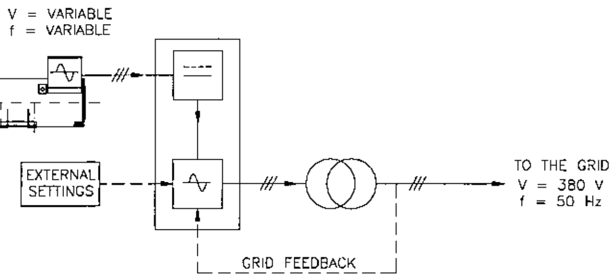


Figure - 19: Main scheme of the electric part

4 -THE ENVIRONMENT

The environmental impact of the Kobold turbine has been evaluated particularly from the point of view of the compatibility with the sea, flora and fauna. The environmental impact and compatibility study, carried out by the University of Messina (ITALY), has reached the following conclusions:

- *the environmental impact is negligible.*
- *the Kobold units are compatible with the Italian rules for the installation and removal of sea structures.*

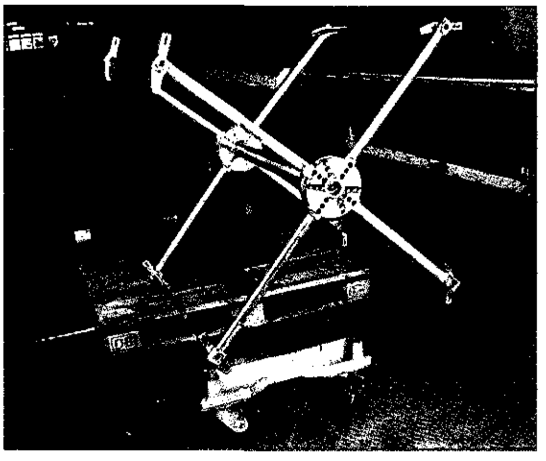
The visual impact of the plant is very low and, in case of plant removal, the works for the site reclamation are of a small amount: there are no permanent structures on the seabed and the bigger components, the mooring blocks, are easily removable using a normal crane.

5 - RESEARCH

With the experience from a full scaled system in the water for 4 years of time Ponte di Archimede S.p.A has all the necessary information to develop an optimized mechanical system and is further on developing a design tool together with INSEAN in Rome and Politecnico di Milano.

Since the transfer air - water is not so immediate, the contribution of INSEAN, with its experience in naval architecture, both numerical and experimental (INSEAN has one of the biggest towing tanks in the world), and of Politecnico di Milano, with its experience in aerodynamics and wind tunnel tests, will be precious to fully understand the differences in the turbine behavior in air and water. This comparison will be very important to decide which studies can be carried out in the wind tunnel - wind tunnel tests are cheaper and easier to manage in case of multiple configuration models - and which ones have to be necessarily done in the towing tank or in the hydrodynamic tunnels. It is important to note that the tests carried out in the wind tunnel are in a completely different range of speeds - just to make a comparison the Kobold at sea rotates at less than 20 r.p.m., the model tested in the wind tunnel at University of Napoli had an angular speed of more than 300 r.p.m. - and this can cause significant differences between the model tests and the full scale realizations because of the influence of other phenomenon.

At present both INSEAN and Politecnico di Milano are working on the project, with Politecnico di Milano having already tested the complete polars of the airfoil used for the blades of the Kobold, and INSEAN ready to test a Kobold model in different configurations using its towing tank facilities.



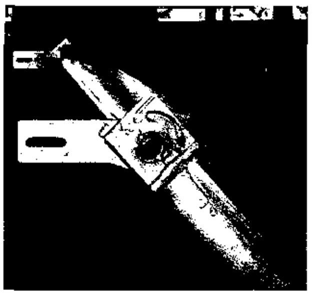


Figure - 20: Kobold model at INSEAN

Another important point that will be tested in the towing tank is the influence of the turbine itself on the undisturbed flow: it was noted, during the past tests carried out on board, that the current velocity measurements are influenced by the turbine. If we measure the current velocity too far away from the turbine we measure another current which could be significantly different from the one interesting the turbine. If we measure the velocity too near, there is the turbine influence, thus the measured current is slower than the real. It is important to investigate this phenomenon otherwise the efficiency calculations could be not effectively real.

In the towing tank tests a couple of Pitot pipes will be positioned in different places to investigate the influence of the distance from turbine on the measured velocity, since it is exactly known the flow velocity which is the carriage velocity.

Furthermore, using the most advanced techniques in computational fluodynamics (CFD), a new sophisticated mathematical model is near to be ready in order to have a more powerful tool to estimate different design conditions without carrying out expensive model testing. This will be very helpful for future projects where the turbine will have to be optimized for specific site conditions. The computer model and the optimized mechanical and electrical system are to be finished in 2005.

Vertical-axis Turbines for Marine Currents Exploitation: Research on the Kobold Turbine Concept

F. Salvatore, L. Greco, G. Calcagno
INSEAN - Italian Ship Model Basin - Rome (Italy)

A. Moroso, H. Eriksson
Ponte di Archimede S.p.A. - Messina (Italy)

ABSTRACT

Research on vertical-axis turbines to produce energy from marine currents is addressed. In particular, an ongoing research project by INSEAN, the Italian Ship Model Basin in collaboration with Ponte di Archimede S.p.A. is described. Scope of the project is to investigate the hydrodynamics of vertical-axis turbines of the 'Kobold' type. The aim is to improve knowledge on mechanisms of conversion of water current energy into mechanical energy and to develop reliable design tools. The activity includes both experimental work and theoretical/computational modelling. Project activities and main results achieved so far are presented and discussed.

1 - INTRODUCTION

Global energy demand and its dramatic rate of growth related to the increasing impact of developing countries is rapidly becoming worldwide a social issue of primary importance. The increasing cost and unreliability of traditional energy sources and the necessity to limit the impact of economic development on environment contribute to consider renewable energy as a necessary option.

Among renewable energies, marine currents and tides represent a relatively new and almost unexploited source, with a worldwide diffusion of potentially highly-productive sites. Marine currents are typically originated by two major mechanisms. Permanent currents are caused by differences in water temperature and/or density between adjacent seas. This type of currents are typically stable in both intensity and direction. A second type of sea currents is originated by tides and is characterized by a cyclic variation of both intensity and direction. In most cases, marine currents are the result of a complex composition of the two mechanisms above.

The exploitation of marine currents and tides to produce energy is achieved through special-purpose turbines. Current projects address both horizontal-axis as well as vertical-axis turbines. Horizontal-axis turbines operate similarly to wind turbines. Typical designs of horizontal-axis hydroturbines present rotors that are fully submerged and sustained by pylons based in the sea bed. Problems like rotor orientation with respect to the direction of the current, and positioning of the electrical generator require a careful design. Preliminary results from ongoing activity on some prototypes show that this concept can be economically convenient if very large plants are operated.

A different layout characterize vertical-axis turbines. Torque is generated by blades that are connected to a vertical turbine shaft through streamlined arms. The electrical generator is top mounted on the turbine shaft and housed in a room that can be located outside water on board of the floating platform sustaining the turbine itself. In view of their relative simplicity, vertical-axis turbines represent a promising technology to exploit marine currents by means of small plants with reduced installation and maintenance costs. Thus, these turbines are suitable for deployment in remote areas to serve small communities.

The present paper focuses on vertical-axis turbines. Specifically, an ongoing research program on vertical-axis turbine by INSEAN, the Italian Ship Model Basin is described. The activity is performed in the framework of a cooperative agreement with Ponte di Archimede S.p.A, an Italian company developing a particular concept of vertical-axis turbine known as 'Kobold'. Scope of the project is to study Kobold turbine hydrodynamics that means to investigate the mechanisms of conversion of marine current energy into mechanical energy. To improve existing knowledge on this aspect is fundamental to understand how to design plants with high performance in terms of delivered power.

The research on turbine hydrodynamics described here combines both experimental as well as theoretical and computational work. Project activities and main results achieved so far are presented and discussed in the following sections.

2 - VERTICAL-AXIS TURBINES FOR MARINE CURRENTS: THE KOBOLD CONCEPT

The term Kobold turbine denotes a vertical-axis multi-bladed rotor that is fully submerged and subject to an incoming flow caused by a marine current. Each blade has a straight rectangular, high-span planform and is connected to the rotor shaft by one or more arms. The blades is free to rotate about a spanwise hinge axis between two fixed positions (blade pitch degree of freedom). A sketch of a typical three-bladed turbine layout is shown in Fig. 1.

Conversion of streaming water energy into mechanical and electrical energy is based on a simple mechanism. The hydrodynamic force acted by the incoming flow on the blades generates a torque that force blades, and hence the turbine, to rotate about its shaft.

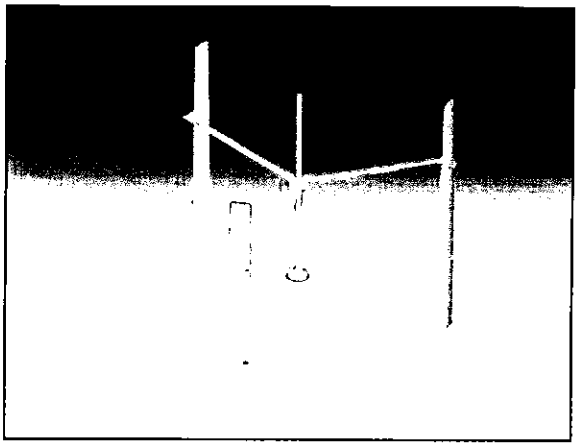


Figure 1: Basic components of a typical three-bladed turbine.

Using an electric generator, mechanical shaft power can be converted into electric power.
An important aspect is that a multi-bladed turbine of this type can produce power regardless of the direction of the onset flow. In addition to this, a distinguishing feature is that the Kobold turbine is able to start rotating from rest without any external device to force rotation. This is made possible by the fact the blades are free to adjust to the local flow through flow-induced pitch rotations about the hinge axis.

From the above description it is apparent that production of power from water currents is primarily related to the hydrodynamic forces that are acted on blades. Nonetheless, the global performance of the turbine results from an interplay of several components. Specifically, the design of the floating platform where the turbine is attached and the platform mooring system are fundamental to preserve stable positioning of the submerged rotor in a hydrodynamically optimal trim. Not less important is the identification of the electric generator characteristics that allow to convert mechanical shaft power into electrical power with minimum losses. Thus, a successful turbine design can derive only from a multi-disciplinary work, in which turbine hydrodynamics represent the first necessary step.

Maximing the turbine power output can be achieved only if the mechanism of generation of the hydrodynamic force on the blades is clearly identified and tools to design high-performance rotors are developed. In view of the complexity of physical aspects affecting the turbine performance, the most appropriate approach is to combine experimental activity and theoretical studies. This is largely reflected in the research program described here, in which three distinct investigation phases are considered:

- understanding the physics involved through experiments on small-scale turbine models
- developing theoretical models and computational tools to predict turbine performance
- assess computational tools through validation based on experimental knowledge

3 - EXPERIMENTAL ACTIVITY ON TURBINE HYDRODYNAMICS

Basic experimental knowledge on vertical-axis turbines of Kobold type comes from observations and measurements on a full-scale prototype that is operating since 2001 in Messina strait, Italy. A review on this experimental activity is presented by Moroso (2005).

In order to improve existing knowledge and provide quantitative measurements of principal performance figures under different operating conditions, experimental activity on turbine models in confined testing facilities represents a major contribution.

To this purpose, the research program here described includes an experimental activity on a Kobold turbine model that is performed in a towing tank at INSEAN facilities. Due to the large dimensions of the tank (220 m. long, 9 m. wide, 3.5 m. deep), relatively large models can be tested. For the present activity, a 1:5 scale model of the turbine prototype operating in Messina strait is being used. Model diameter is D = 120 cm, blade chord and span are, respectively, 8 and 80 cm. This is the largest vertical-axis turbine model ever tested in water.

Figure 2: Model of Kobold turbine realized for testing at the INSEAN towing tank.

The advantage to use large models for testing is related to the fact that flow similitude between model scale and full scale is established and measurements on the model can be accurately extrapolated to real prototype scale.
Model testing of the turbine is performed according to typical procedures used to test ship and submarine models. The model is attached to a carriage and towed at given speed along the tank. In this way, the operating condition of a moored turbine plant subject to an incoming water current of given speed is simulated.

The water current intensity is simulated through the carriage speed that can be varied between 0 and more than 10 m/s and is controlled with very high precision. A complete set of operating conditions and measurements have been considered.

Operating conditions include:

- three-bladed and four-bladed turbine configurations
- different configurations of blade pitch
- operation at constant speed
- start from rest

For all these different conditions, turbine delivered torque and power as well as turbine rotational speed are measured whereas carriage speed is recorded. Measurements also include the evaluation of passive torque due to blade arms. A sketch of the measurement set-up is shown in Fig. 3.

Resulting data from this experimental work allow to determine turbine performance over a complete range of operating conditions.
This activity is under progress and results will be presented by the end of 2006.

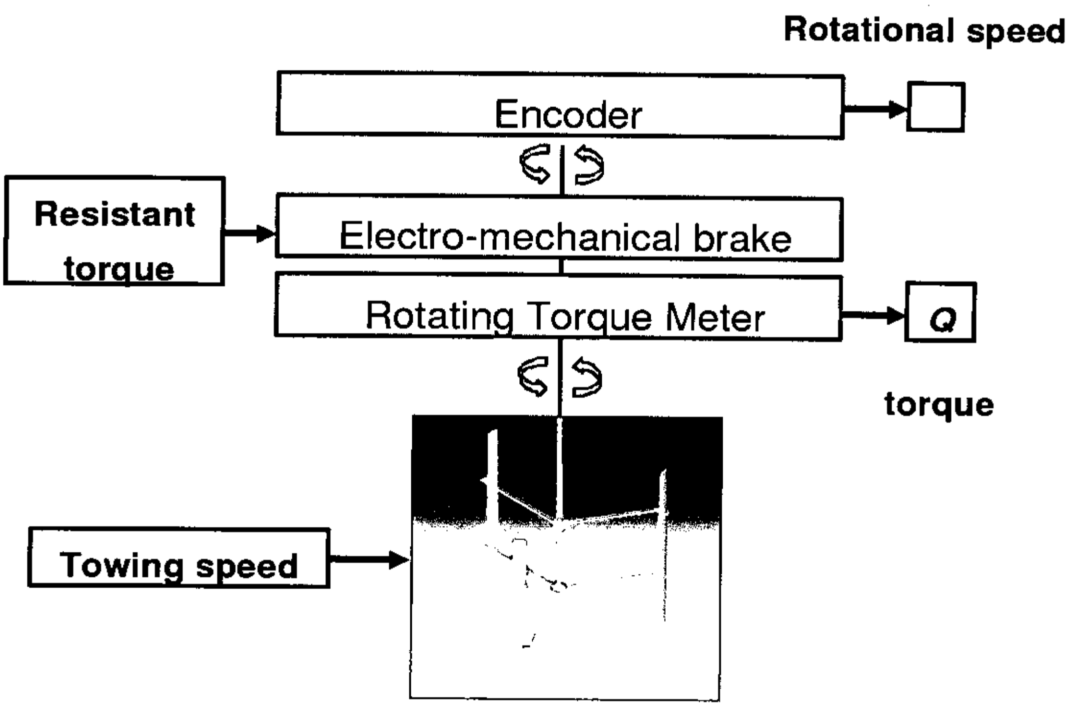


Figure 3: Schematization of the experimental set-up used for Kobold turbine model testing at the INSEAN towing tank.

4 - THEORETICAL AND COMPUTATIONAL MODELLING

Theoretical activity is finalised to develop mathematical models in order to describe the physics involved in the process of conversion of marine current energy into mechanical energy through the turbine. Through mathematical modeling turbine operation under different conditions can be simulated. Mathematical models are then implemented into computational codes that are integrated into software tools to design high-performing turbines.

In the previous pages, it has been mentioned how the extraction of power from water is primarily related to the hydrodynamic forces that are acted on the turbine blades.

The approach followed in the present research program consists in distinguishing two phases in the development of theoretical models:

- o isolated blade hydrodynamics
- o multi-bladed assembly operation

Let us consider first an isolated blade. During rotation about turbine shaft, the blade undergoes cyclic variations of flow conditions as sketched in Fig. 4.

Assuming onset flow characteristics are given, blade performance quantities F, Q and P are determined through the hydrodynamic coefficients CL and CD. Such coefficients characterize blades of different shape. In particular, blade span and blade sectional profiles are major geometrical aspects affecting the hydrodynamic coefficients CL and CD. Blade geometry considered in the present work is related to an early design of Kobold turbine blades. Specifically,

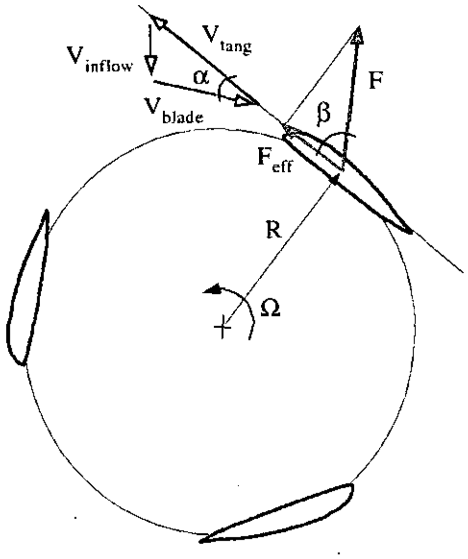


Figure 4: Sketch of a Three-bladed turbine section in a horizontal plane; definition of main parameters and physical quantities.

blade span to chord ratio is about 10 and blade sectional profile of aeronautical type (i.e., similar to airplane wing *sectional profiles) are used. A sketch of* Kobold turbine blade profile is given in Fig. 5.

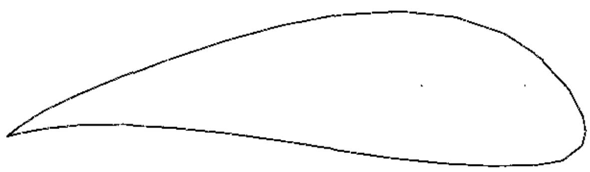


Figure 5: Kobold turbine blade profile.

Figures 6 and 7 depict Kobold blade profile coefficients CL and CD from measurements in wind tunnel. Coefficients are plotted as a function of blade angle of attack. At very low angle of attack (i.e., between -10 and 10 degrees), blade efficiency, i.e., ratio between CL and CD is maximum, and this operating condition is optimal in that best performance of the turbine is expected.

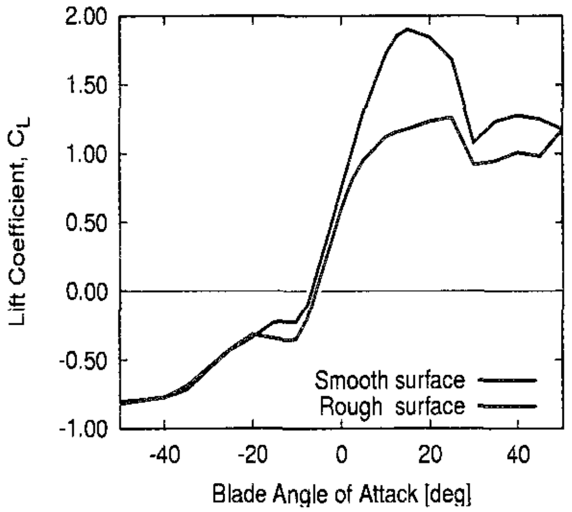


Figure 6: Kobold turbine blade profile coefficients CL from wind tunnel measurements.

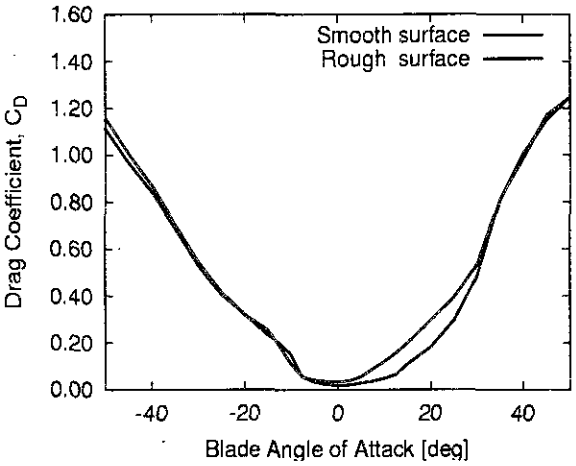


Figure 7: Kobold turbine blade profile coefficients CD from wind tunnel measurements.

A careful analysis of turbine blade angle of attack variations during a revolution about the turbine shaft is then necessary.

Recalling Fig. 4, blade angle of attack is determined as a combination of turbine rotational speed (or tangential velocity VT) and onset water current V0). A typical chart of blade angle of attack variations during a revolution is plotted in Fig. 8.

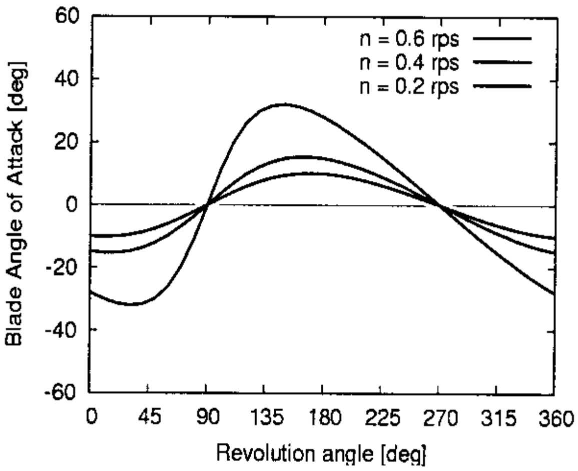


Figure 8: Blade angle of attack variations during a revolution. Onset water current speed V0 = 2.0 m/s. Effect of variation of turbine rotational speed (rps).

The theoretical model used here to predict hydrodynamic coefficients CL and CD is based on a formulation that is valid for bodies of arbitrary three-dimensional shape immersed in a non-uniform flow. The methodology is known as Boundary Element Method (BEM) and is widely recognized as a powerful mean to study the performance of rotorcraft systems as well as seacraft and aircraft.
A description of the methodology is beyond the scope of the present paper; details may be found in Morino et al. (1975), whereas recent applications to marine rotor hydrodynamics are illustrated by Salvatore, Testa and Greco (2003), Pereira, Salvatore, Di Felice, F. (2004), Salvatore, Greco and Calcagni (2005).

This methodology is specifically oriented to evaluate the hydrodynamic forces generated on solid bodies immersed into moving fluids. Hydrodynamic forces acting on the turbine blades are intimately associated with vortices that are generated on the blade and are convected downstream. These vortices describe a persisting path downstream the blade that is referred to as the blade trailing wake.

In order to provide accurate predictions of the forces generated by the blade it is then necessary to describe vorticity generation and convection process. To this purpose, a trailing wake model has been developed that is valid for blades in arbitrary unsteady motion. An example is given in Fig. 9 which depicts numerical predictions of the shape of trailing wake downstream a blade undergoing an oscillatory translating motion. Due to oscillations, blade angle of attack cyclically varies similarly to what happens for a vertical-axis turbine blade during a revolution.

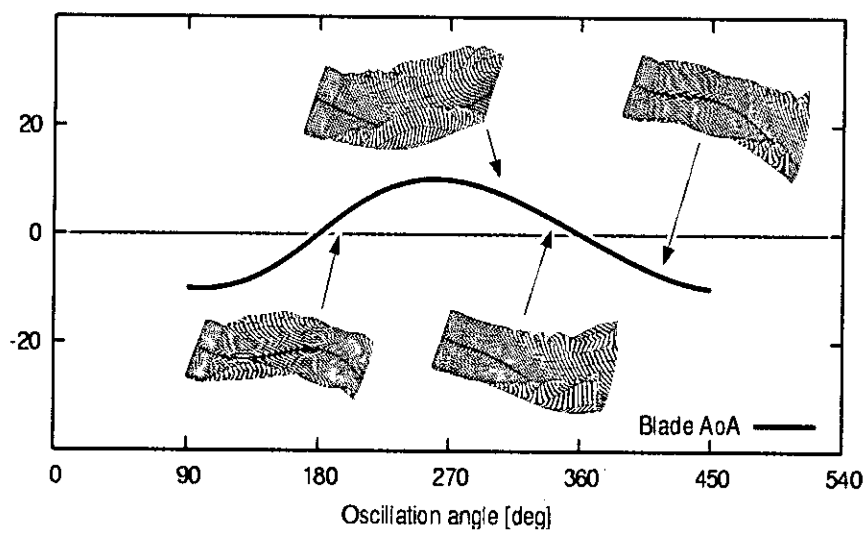


Figure 9: Blade in oscillatory translating motion: variation of blade angle of attack and calculated trailing vorticity path at four representative time steps.

Considering Fig. 9, it is apparent that the trailing wake is largely affected by blade unsteady motion, and blade hydrodynamic forces fluctuate accordingly.

Once isolated blade hydrodynamics modelling is completed, the proposed methodology is extended to consider a complete multi-bladed configuration. From a simple analysis of turbine operation based on the single-blade case described above, it might appear that the higher the number of blades, the larger the amount of energy that can be delivered by the turbine. Unfortunately, this simple extrapolation is not correct. In a multi-blade assembly, each blade interferes with flowfield perturbed by other blades. Moreover, blades can impact on the vortical wake released by other blades. The impact determines a temporary loss of performance of the impacting blade. The above aspects are to be carefully analysed in order to determine reliable predictions of multi-bladed turbine performance.

The development of a theoretical and computational methodology to study multi-bladed turbines including interactional effects is the primary aim of the present modelling work. To the authors' knowledge this is the first attempt to derive a hydrodynamic model based on a BEM for three-dimensional arbitrarily unsteady flows to study vertical-axis turbine performance.
A sketch of a geometrical model for a three-bladed assembly with vortical wakes emanating from blade trailing edges is given in Fig. 10.

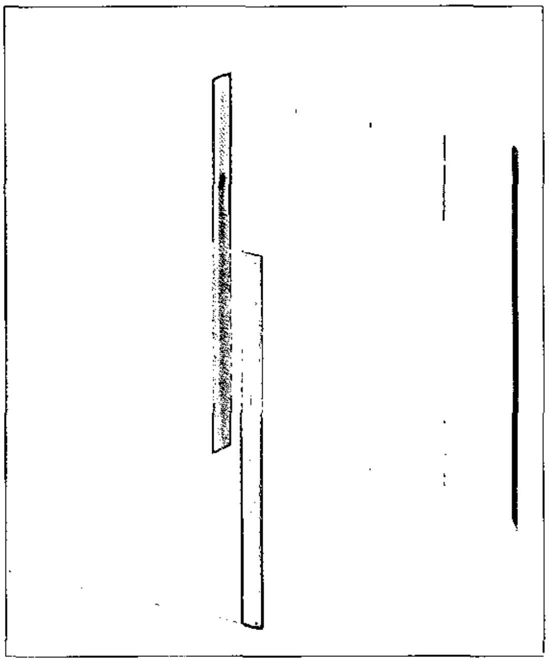


Figure 10: Numerical model of a three-bladed turbine for computational predictions using a Boundary Element Methodology: blade pressure distribution and trailing wakes.

Equations by the mathematical model used to describe the flowfield around the turbine are numerically solved to determine the distribution of flow quantities on each portion of blade and wake surfaces. In particular, the local force (pressure coefficient) that is exerted by water on the blades is determined. Finally, by integrating the pressure and friction coefficients over the surface of all blades, turbine torque and power follows.

Pressure distribution on the blades is dramatically affected by the impact of wake vortices released by other blades. A suitable model to take into account these effects is considered here. The model is derived by an original approach proposed by Salvatore et al. (2005) to study the interaction between the wake released by a ship propeller and a rudder placed in the propeller slipstream. From the viewpoint of wake-vorticity/solid surface interaction, a propeller-rudder configuration is fully equivalent to blade-to-blade interaction occurring in vertical-axis turbines. The practical importance of modelling wake-vorticity/solid surface interactions will be clarified in the next section, where results from the present theoretical model will be compared to experimental measurements.

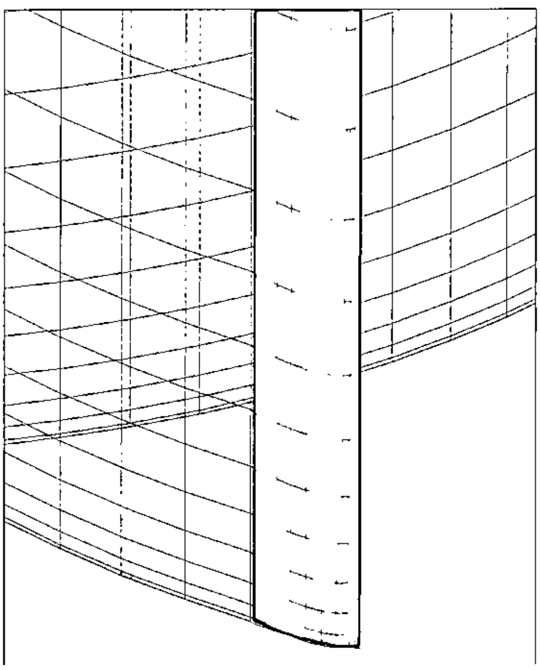


Figure 11: Detail of blade with distribution of pressure coefficient evaluated using the Boundary Element Methodology.

5 - ASSESSMENT OF COMPUTATIONAL TOOLS

Experimental and theoretical activities described above are complementary tasks that are combined to provide a thorough knowledge of turbine hydrodynamics. Such knowledge can be exploited to develop tools that are fundamental to assist designers to define layout and operating conditions of high-performing plants.

This phylosophy inspires the research activity that INSEAN is conducting on vertical-axis turbine hydrodynamics. An important part of this activity is represented by validation of theoretical and computational tools. Specifically, numerical codes derived by theoretical models are used to simulate given turbine operating conditions; performance predictions are then compared to existing measurements taken from experimental activity either on small-scale models or full scale plants.
As stated above, experimental activity performed at INSEAN on the Kobold turbine model is still underway, and results suitable for validation of numerical prediction codes will be available in the next months. Here, a preliminary validation based on experimental data published in the open literature is presented.

The test case that has been chosen is described in Strickland (1979). Specifically, a straight one-bladed vertical axis turbine with a NACA 0015 airfoil is considered. The blade pitch is fixed and the blade hinge is at mid chord. The experiment was performed in a towing tank with a depth of 1.22 meters, a width of 5 meters and a lenght of 10 meters. The airfoil chord is 0.1524 meters, the rotor diameter is 1.22 meters. The rotor blades work partially submerged in the water and partially in air: specifically the submerged part of the blades has a length of 1.1 meters and the blades extended to within 15 centimeters of the tank bottom. The towing speed considered for the comparison is of 0.091 m/s, thus giving an advance ratio of 0.625.

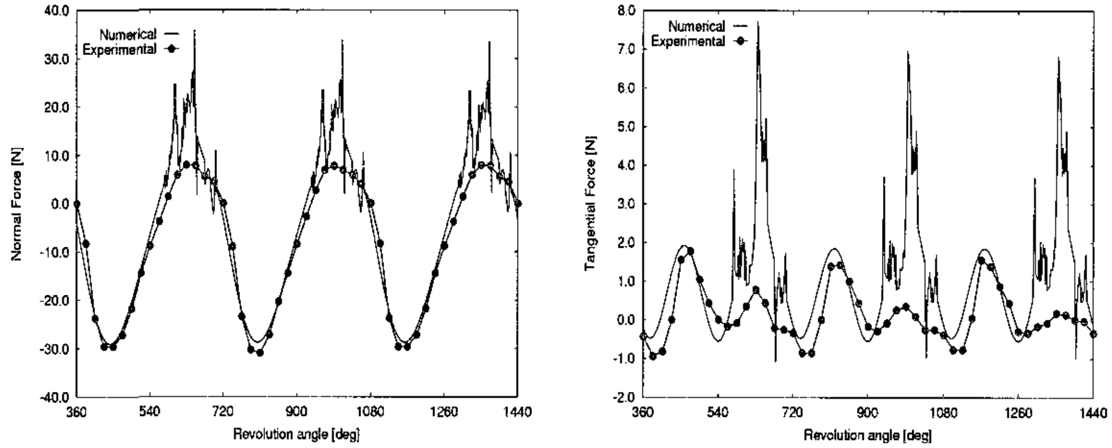


Figure 12: Normal and tangential forces on blades during a revolution. Notional vertical-axis turbine. Numerical predictions compared to experimental data from Strickland et al. (1979).

Figure 12 shows the time history of the normal force (FN) and of the tangential force (FT) along the rotor revolution angle. Experimental data obtained through strain gages are compared to numerical results. The agreement seems to be satisfactory (except for values of the revolution angle corresponding to blade-wake interaction) thus giving a preliminary confirmation of the ability of the numerical code to correctly predict forces acting on the blades.
It should be pointed out that in the numerical calculation only the submerged fraction of the blade has been considered.

6 - CONCLUSIONS

Among renewable energies, marine currents represent a relatively new and almost unexploited source. Recently, some interesting research and technological development programs have been started to assess promising concepts as possible solutions to build large-size plants to produce energy from marine currents and tides.

One of those programs is the research project by INSEAN (Italian Ship Model Basin) described in this paper. The activity, focusing on vertical-axis turbines, is performed in the framework of a cooperative agreement with Ponte di Archimede S.p.A, the Italian company developing the Kobold vertical-axis turbine.

Aim of the project is to improve knowledge on the mechanisms of conversion of marine current energy into mechanical energy through a vertical-axis turbine. Research activity includes both experimental work and development of theoretical/computational models.
Experimental activity is performed at INSEAN facilities on a large-size model to investigate basic turbine performance parameters over a wide range of operational conditions. Theoretical models and computational codes developed within the project demonstrate their capacity to provide important information on turbine hydrodynamics. Delivered torque and power can be predicted with satisfactory agreement with results from model test measurements.

Preliminary results show that both experimental knowledge and theoretical/computational tools can be used as powerful means to assist designers to develop power production plants.

The activity described here represents the first phase of a mid-term program in which several aspects of turbine operation will be considered. Future research will address towing tank simulations of turbine operation in rough sea, station-keeping of turbine platform, evaluation of mooring forces. Also, some information on the environmental impact of turbines will be achieved through measurements of underwater noise produced and of the turbulence levels in water after the interaction with turbine blades.

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Some Aspects of EDF Modelling and Testing Activities, within its Marine Current Energy Research and Development Project

ABONNEL C , ACHARD J.L , ARCHER A , BUVAT C , GUITTET L , LENES A , MAITRE T, MANIATI M , PEYRARD C , RENAUD T , VIOLEAU D

ABSTRACT

This paper discusses some aspects of the modelling and testing activities deployed by the Research and Development Division of EDF (EDF R&D) and one of its French academic partner, the LEGI laboratory, to contribute to the development of a novel technique for power generation using the kinetic energy of tidal streams, still called Marine Current Energy (MCE). Through numerical modelling, experimental measurements at sea and tank testing, EDF improves its knowledge of the French potential tidal sites and also its capacity to evaluate the various technologies and concepts some of which could become industrial tomorrow.

1 - INTRODUCTION

Electricité **D**e **F**rance, the major French utility, has been producing tidal power for several decades now, as the La Rance power plant - 240 MW installed, was launched in 1966, near Saint Malo in Brittany. While this plant goes on producing electricity today, EDF got engaged at the end of the 90's in new research and activities on complementary means of production, aiming at diversifying its sources of clean renewable energy. Among such sources : the ocean or marine ones. Indeed, France is well endowed with both wave energy and marine current energy (MCE)[1] : according to the EC sponsored study "Marine Currents Energy Extraction: Resource Assessment" (CENEX, 1996), France has got 20% of the global European marine current resource - estimated around 48 TWh for an installed capacity of 12500 MW, a little more than the 10th of the world resource estimated around 450 TWh, following certain pre-defined characteristics to make them suitable for energy exploitation. Between wave and marine current sources, the choice was made to focus on MCE, as it presents several interests : potential contributor to the base load, predictable, dense and regular, it is also less exposed to severe 'storms than other marine renewables.

Thus, EDF launched its R&D MCE project " Hydroliennes en mer " in January 2004, aiming at : (i) evaluating the maturity of technologies being developed within this emerging tidal market, (ii) identifying and characterising the tidal sites in the French territorial waters, in order to prepare the decision of the EDF Group to invest (or not) in a first industrial demonstration site in the French territorial waters by some years. One may have noticed that EDF, as an industrial utility willing to become an end-user of MCE, focuses its R&D activities on improving both its knowledge of the potential French tidal sites and its capacity to evaluate the various technologies and concepts being developed. Thus, while other entities, as the ones presenting in this first CA-OE workshop, deal with the development of devices themselves, EDF chooses a complementary approach, by itself or in partnership, to "pull" this emerging market of ocean energies. To do so, several tools are used according to the issue. Some examples are provided in this paper : numerical modelling and measurements at sea to deal with the resource, numerical modelling and tank testing with the LEGI Laboratory to evaluate various concepts. **One should notice that the KOBOLD turbine of Ponte di Archimede is not considered at this stage, but it could be in the future.**

Thus, in this paper we will present three different scales, from the "large" picture of the whole Close Atlantic Channel and North Sea area to the converter vicinity, going through the farm area, each time dealing with both numerical and experimental data. Similarly, to evaluate the developing technologies, we will present the collaboration with the LEGI, based on both experimental and numerical approaches.

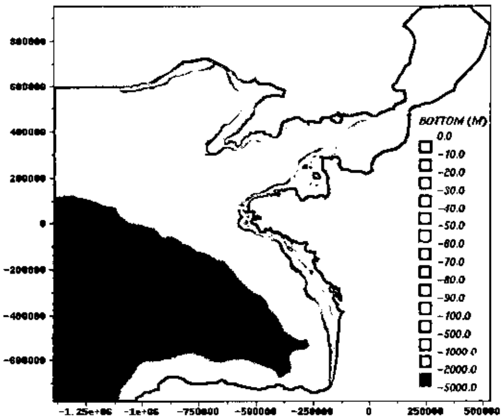
2 - FRENCH "MARINE CURRENT ENERGY RESOURCES" ANALISYS

Although the MCE resource is potentially enormous, in most sea areas the velocities, and hence the energy densities, are too low for economic exploitation. Therefore the resource of interest has to be verified and refined as there are only few places that should be usefully exploited : places where the seabed topography and the effect on concentrating the flow caused by coastlines, such as in straits and around headlands, cause fast currents to occur regularly.

2.1 - The "large" picture : modelling and measuring tidal currents

2.1.1 - Numerical modelling with the TELEMAC system

In order to make a first evaluation of the marine current kinetic energy on the French coasts, to compare with the results of the European study (CENEX, 1996), a pre-existing numerical 2D-hydrodynamic model was used at EDF, based on the 2-D shallow-water equations (or Saint-Venant equations) which are known to be suitable for modelling tides in coastal areas. The model, constructed with the Telemac-2d code, developed in a finite element formalism at EDF R&D for tidal and river applications (Hervouet, 2003), lies from the North Sea to the Spanish coasts including the Channel and a part of the Atlantic Ocean (Figure 1). The mesh is composed of 15,350 nodes and 29,229 triangle type cells. The input conditions at liquid boundaries are tide signals which are generated in the Atlantic Ocean, move over the European continental plateau and penetrate into the Channel.



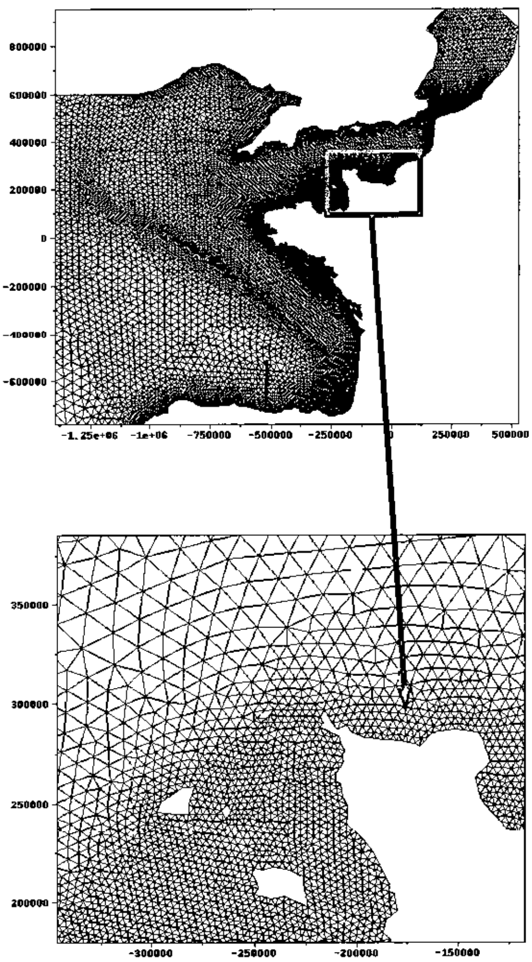


Figure 1 - Bathymetry (top right) and mesh of the North Sea, Channel and Atlantic Ocean "*Large TELEMAC Model*" (up)

The model was validated with tidal data from several harbours along the French coasts. Pretty good results were obtained in terms of water levels and velocities, provided a sufficient distance from the simplified coastline is respected. Such results were coherent with the European study.

To make a realistic assessment of the energetic potential of the coastal areas, tides of a whole year were simulated. It was assumed that one year was sufficient to mask the inter-annual tide coefficient variability, and therefore give representative results. The output variables were velocity and kinetic instant power (Figure 2). Annual extractible energy was obtained by integrating the instant power over the year. Theoretical extractible energy was considered. It is given by the Betz law which corresponds to an ideal turbine in an infinite medium :

$$E_{extractible} = \frac{16}{27}\frac{1}{2}\rho \int_{0}^{1year} V^{3}.dt \quad (1)$$

With:

$E_{extractible}$= extractible kinetic energy (J/m^3)
ρ= sea water density (kg/m^3)
V = velocity (m/s)
t = time (s)

This gross energy will then have to be converted into effective extractible energy by considering the selected turbine technology and the corresponding efficiency. Other effects as turbine wake in farms will also have to be taken into account, as detailed in § 2.2.

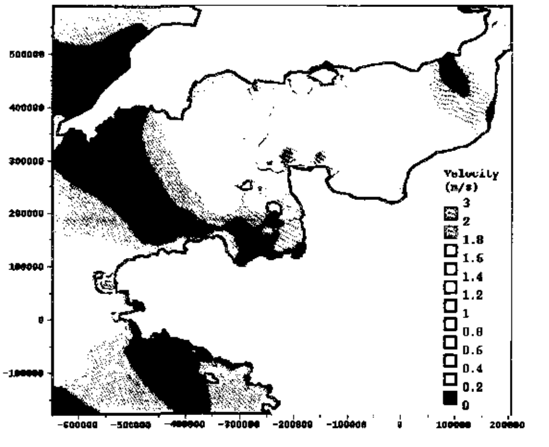


Figure 2 - Instantaneous velocity along the French coast, obtained with the Telemac-2d large model.

Once the energetic 'crude' information is available, the second step towards a site identification consisted in crossing all these calculation results with environmental and regulation data. A Geographic Information System (GIS), based on the ARCVIEW software, was used. Once the data were georeferenced, the GIS system permitted not only to superimpose the different data layers, but also to make surface and mean calculations. The cross-analysis of all the defined constraints, such as energetic potential, distance from the shore, bathymetry, military or civil regulated zones, marine activities etc, leads to the identification of roughly ten potential zones along the French coasts.

These zones were sorted according to their energetic potential, their technical feasibility and their environmental constraints. From this list, the more interesting sites were selected as potential project sites where a turbine prototype could be installed. Thus, the GIS system constitutes an achieving tool that can be used and updated with the detailed studies engaged from there : experimental measurements at sea (see § 2.1.2), smaller scale numerical models to go further with complex currents circulations and therefore allow "tidal farm" design (see § 2.2).
The boundary conditions of such local models are supplied by the "large" telemac-2d model results.

2.1.2 - Experimental measurements at sea

Numerical models previously presented reproduce only tidal currents, depth-averaged and without any waves at the free-surface. Real marine currents are actually complex flows on which free-surface effects have a significant influence. The vertical shear for a current turbine is typically larger than for a wind turbine, inducing cyclical loading. The addition of waves further complicates the flow, with its influence being more than just an adding-turbulence effect.

As few data actually exist for the water column itself in such zones of strong currents, we decided to have experimental measurements at sea for several reasons :

- o *to confirm the local validity of our numerical results obtained with our large model in the most interesting zones : this is discussed straightforward*

- *to gather data to help understand how the waves can influence the velocity in the water column. First elements discussed in § 2.3.2*

- *indirectly to "open" the discus sion and consultation with other sea-users and authorities about the development of MCE, as acceptability will be one the key-factors of a successful deployment.*

The first campaign was achieved in January 2005, in the so-called "Raz de Barfleur", in the North-East part of the Basse-Normandie department (Figure - 3a).

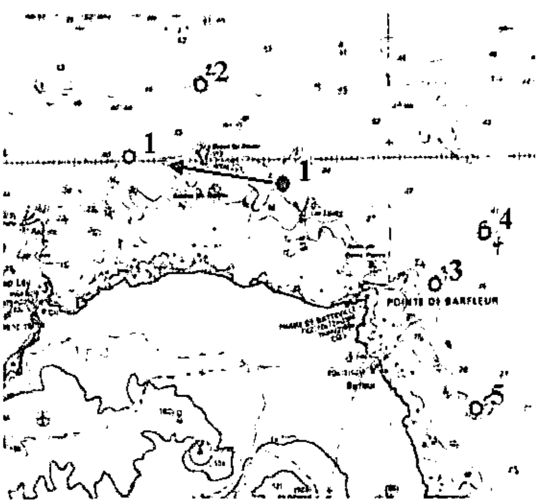


Figure - 3 a: Location of the devices during the Normandy measurements in January 2005. The modification of the point 1 illustrates the "consultation process" with local fishermen.

The measurement devices remained averagely 15 days (a whole tidal cycle) in the water, between 7th January and 5th February for the last one.
Figure - 3 b shows the positions of devices, which were organized as described in Table - 1.

Point n°	Type of device(s)	Measured parameters	Immersion depth
1	AWAC	Wave and current	20 m
2	ADP 500 kHz	Current	50 m
3	ADP 500 kHz	Current	20 m
4	Aquadopp profiler 600 kHz	Current	41 m
	Datawell wavebuoy	Wave	surface
5	AWAC	Wave and current	20 m

Table - 1: Position and type of measurement devices used during the January campaign in Normandy. Except for the Datawell buoy, all the other devices are designed by the Nortek company[2].

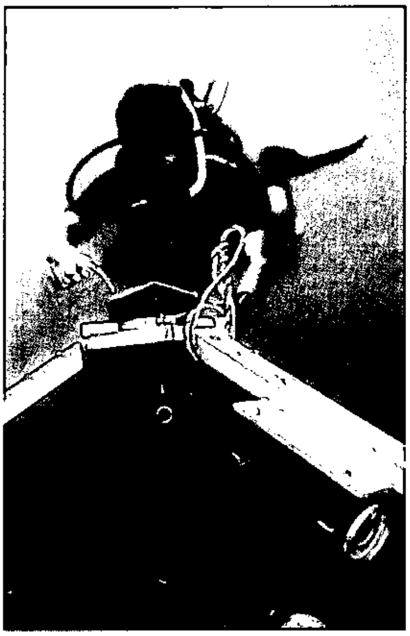


Figure - 3 b: Example of device installation/removal on the sea bottom.

All these devices are based on the Doppler principle[3] . Programmed at the beginning, they are fully autonomous for measurements and storage of data in an internal datalogger. ADP and AWAC measured velocities every meter in the water column, averaged 1 or 1.5 minutes every 10 minutes ; the Aquadopp in point 4 measured velocities every 2 m, averaged 1s every 3s.
With the measurements of average values of current and waves, we were able to confirm the calibration of the numerical models, in particular in terms of

mean depth-averaged velocity. Depending on the point, the velocities were not as strong during the ebb flow and the tide flow.
A second series of measurements have been also performed in April in the Brittany waters, in the area of "Les Héaux-de-Bréhat", according to the same protocol, but only in two points.

2.2 - The "*farm-size*" picture : modelling current-structure interactions

The design of a complete marine current converters farm requires the capability of predicting the main interactions that can occur between converters and tidal currents. Indeed, not only the turbines work through currents, but they have also an influence on them in their vicinity. Effects of shear stress and diffusion can be responsible for a dramatic decrease of momentum in the converter's wake. These phenomena can be quite complex in a real situation since tidal currents are unsteady and affected by bottom levels. As a consequence, a correct prediction and optimisation of the power which can be extracted from a turbine farm should be obtained through numerical modelling.
We go on using the 2-D shallow-water equations (or Saint-Venant equations) which are suitable for modelling tides in coastal areas. In this context, one problem is the numerical modelling of a converter: a local mesh refinement would require a high computational effort and would not allow to model the effect of turbines. Alternatively, one may consider that a structure acts on the flow as a strong shear area (Hervouet, 2003). In the depth-integrated momentum equation, the effect of such a shear stress will be taken into account through an additional sink term in the r-h-s:

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}\cdot\nabla\mathbf{U} = -g\nabla\eta + \frac{1}{h}\nabla(h\mathbf{D}) + \gamma\mathbf{k}\times\mathbf{U} + \frac{\mathbf{F}}{h} + \frac{\mathbf{S}}{h} - \frac{D_s}{2A_s}C_D|\mathbf{U}|\mathbf{U} \quad (2)$$

In equation (2), U, h and h are respectively velocity vector, water depth and surface elevation, while D is a diffusion-dispersion tensor, g a Coriolis parameter and F and S bottom and wind friction. The last term represents the effect of a converter on currents, Ds, As and CD being an equivalent diameter, an equivalent horizontal surface and a drag coefficient, respectively. Practically, instead of using a mesh like those presented in Figure - 4.a, the proposed method works on the kind of mesh showed in Figure - 4.b.

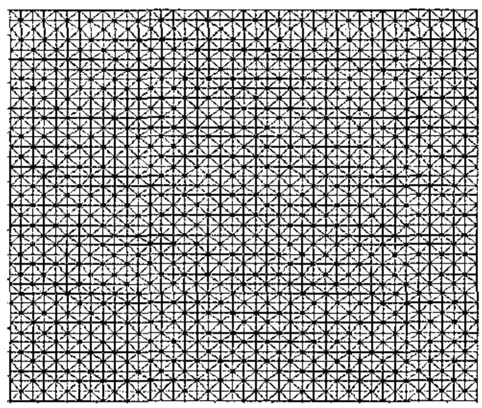
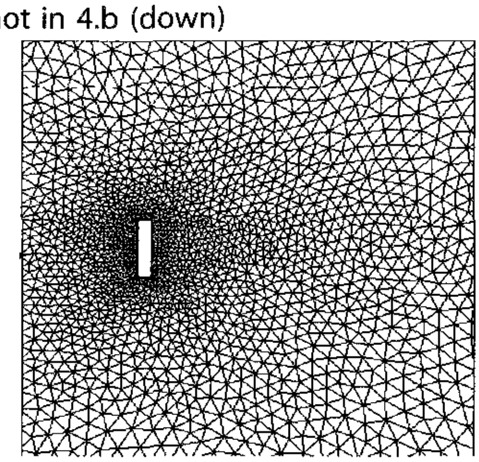


Figure - 4: Two finite elements meshes used to computed the velocity field in the vicinity of a square structure. In 4.a (up), the structure is meshed, while it is not in 4.b (down)



In this case, As will be the surface of 8 triangles covering the bottom area occupied by the converter, and the drag term appearing at the end of equation (2) must be considered in this only area. The drag coefficient CD can be estimated from experiments or theoretical investigations; for an accurate modelling, one should mention the fact that CD must depend on the velocity direction, e.g. on the tidal stage.

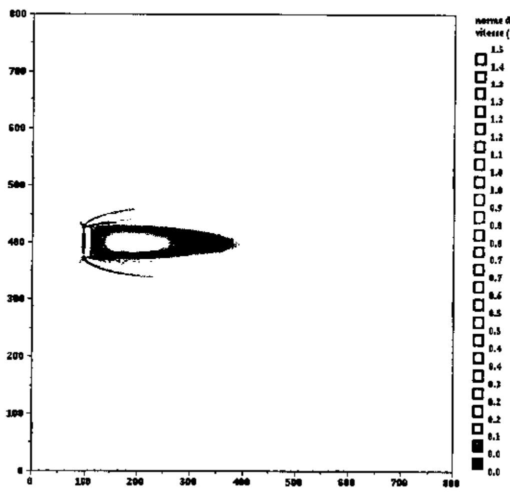
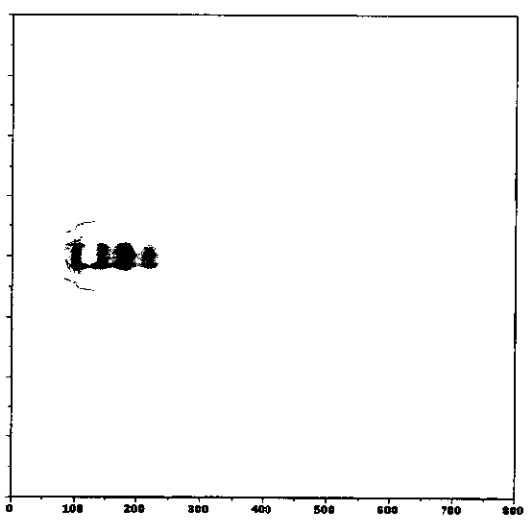


Figure - 5: Finite elements computation of depth-averaged velocities behind a square structure, using both meshes presented in figure 1. Comparison between the case of a meshed structure (5.a, up) and the method consisting of the additional shear term appearing in equation (1) (5.b, down).



The abovementioned model was first tested in the telemac-2d code. The wake behind a square structure was modelled using both methods: Figure 5 gives the distribution of velocity magnitude with (a) a structure included into the mesh and (b) the additional shear term in equation (2), showing that the present approach provides fairly good results. More precisely, Figure 6 shows three velocity profiles computed with both methods.

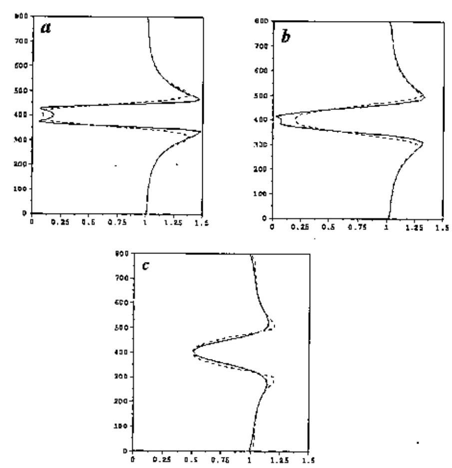


Figure - 6: Velocity profiles obtained from the 2-D computation presented in figures 1 and 2, at 150 m (a), 300 m (b) and 600 m (c) downstream. Comparison between the case with a meshed structure (solid lines) and the case with an additional shear force (dotted lines).

Starting from these promising results, the telemac-2d code is now used to compute the behaviour of velocities during a complete tidal cycle in the area of a converters farm. Figure 7 shows the wake effect due to 35 converters in a hypothetical area with complex bottom levels. Extensive works will provide recommendations to optimise the design of such a configuration, particularly the distance between converters.

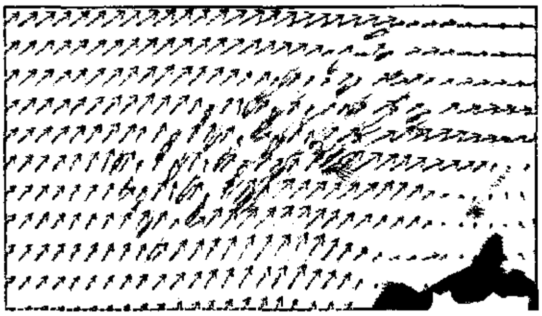


Figure - 7: Depth-averaged velocity field during flood in a potential area for marine current turbines, simulated with the telemac-2d code. The wake effects are considered through equation (1).

2.3 - The "device-size" picture : modelling wave-current interactions

To be able to understand better and optimise the instantaneous productibility of a converter, it appears interesting to refine the approach once again and reach the converter scale. Indeed, as reminded in §2.1.2, the real structure of the water column is not that well known.

In particular, how can the waves influence the velocity in the water column and then can lead to a fluctuation of the output power (with a short period) as well as a fluctuation of the mechanical loads on the turbines - this last point means dynamic phenomena and fatigue troubles for the different components of the turbines ? To estimate the amplitude of these fluctuations, the approach is twofold : numerical modelling and experimental measurements at sea.

2.3.1 - Numerical modelling

This study considers 2D vertical flows with waves decomposed in 2 parts:

- *A static part characterised by a steady re-circulation of water, leading to a modified time-averaged vertical profile of current (Figure 8).*
- *A dynamic part that considered the superposition of the oscillatory motion of water particles to the steady undisturbed conditions.*

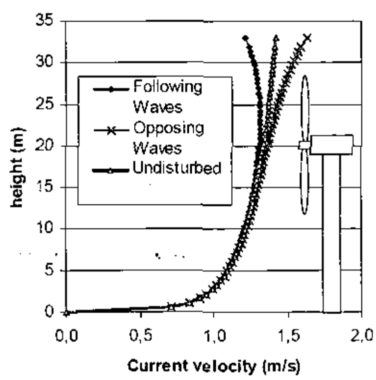


Figure - 8 : simplified modeling of the velocity vertical profile

The static part is shown to have a significant influence on the power output. Following waves tend to decrease it, while opposing waves tend to increase it.

The dynamic part of the wave causes large oscillations in power and thrust. This influences the "quality" of the power (flicker) and causes fatigue to the drive train and to the support struc*ture. The detailed study shows that* fluctuations are due to variations of the angle of attack under influence of wave oscillatory motion.

Though the wave influence is clearly illustrated, the models used in this study are not sufficient for a complete representation of the effect of waves and of the turbine behaviour. Phenomena such as the modification of the mean current are still not well known. The empirical description of the mean current profile under the influence of waves, used in this study, is inaccurate and subsequent results should be considered carefully. This is the reason why experimental data are useful.

2.3.2 - Experimental measurements at sea

As presented in § 2.1.2, experimental measurements were performed in January 2005 in Nord-Cotentin in north of France. While average values of current and waves measurements were performed to calibrate and to verify the numerical models (see § 2.1.2), some instantaneous values of current and free surface were measured too. This will allow us to check the influence of the waves on the water column : this section presents very preliminary results for these recent measurements.

The position of the free surface was measured every 3 seconds. At the same time, the horizontal speed was measured along the water column every 1 meter from the seabed to the free surface. These measurements allow to plot the velocity for several wave positions. In a first time we are going to see what are the characteristics of waves near Barfleur and we will deal with interaction between waves and stream in a second time. The measurements are based on the spectral density of energy in the waves because it is possible to deduce the height and frequency of waves with such data.
As expected the height of waves increase with the distance to coast, but the measurements also gives other general information about waves in different ways. For example in the East of Barfleur (point 4 - Figure 3a) the waves come from the North and North-West and have a lower frequency than the Eastern waves. The waves' period times vary commonly between 2 and 9 seconds, with differences linked to the directions of waves.

Measurements also show that the stream direction has an influence on the characteristics of waves: when waves and stream have the same direction, the height and the period-time of waves generally decrease; they increase when stream direction is opposite to waves direction and the waves energy is concentrated in low frequencies.

Moreover we get some information about the influence of surface waves on the vertical speed profile: in Barfleur, according to our measurements, the wave height has very little effect on the stream velocity profile. But it has some influence on the fluctuations (amplitudes and periods) of the tide stream : such an influence can be observed down to a depth of several meters.

The exploitation of such data related to the influence of wave on stream is also a important issue because the fluctuation of stream due to waves can lead to perturbations on output power. We will also focus on period times of the waves and compare the most common of them with the natural frequencies of current turbines. The global data about waves will have also to be used to make a fatigue troubles' study.

3 - VERTICAL-AXIS TURBINES EVALUATION : AN EDF-LEGI COLLABORATION

To harvest marine current energy, two

major kinds of water turbines exist : horizontal-axis water turbines, and vertical-axis water turbines or transversal-axis water turbines. Any potential end-user in the domain of MCE has to strengthen its own point of view on the various concepts and designs being developed before deciding to invest in any.

To illustrate which kind of work is done by EDF to get prepared and anticipate, the development of suitable tools (experimental and numerical) ongoing on vertical-axis water turbines in the LEGI, a French laboratory specialist in hydraulics and turbo machinery. The work described in this paper is co-financed by EDF and the French Government agency ADEME. Indeed, different technologies of transversal-axis water turbines are developed in different places around the world, and EDF estimates tools are required to compare such different technologies, between themselves and with horizontal-axis water turbines. The tools being developed at the LEGI are both experimental and numerical, complementary.

3.1 - The experiment

3.1.1 - Description of the experiment

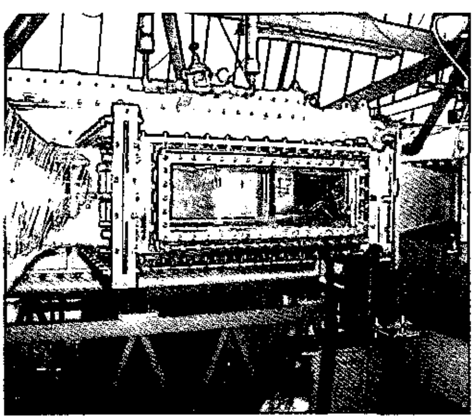


Figure - 9 : Photo of the tunnel

The hydrodynamic tunnel of LEGI (Figure - 9) has been modified to set up an experiment to be able to test and compare different technologies of the vertical axis water turbine.

The turbines are to be tested in a hydrodynamic tunnel which has been modified to accept one vertical axis water turbine. The turbine is placed in a rectangular tunnel; three sides of the tunnel are in plexiglas, so that we are able to observe the turbine on three sides: on the lateral sides and the bottom side of the tunnel. All the sensors for the experiment are mounted on the top of the tunnel.
The tunnel shape was chosen to be able to study the turbine slipstream.

Different types of turbine are to be tested in this tunnel. In a first step, it is planned to test one Darrieus turbine (Darrieus, 1926), one Gorlov turbine (Gorlov, 1997) and one Achard turbine (Figure - 10). **Thus, the Kobold turbine was not considered in this work, but the principles of analysis could apply the same way.**

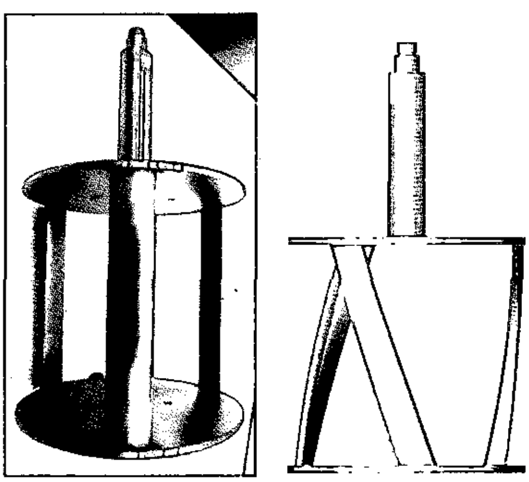
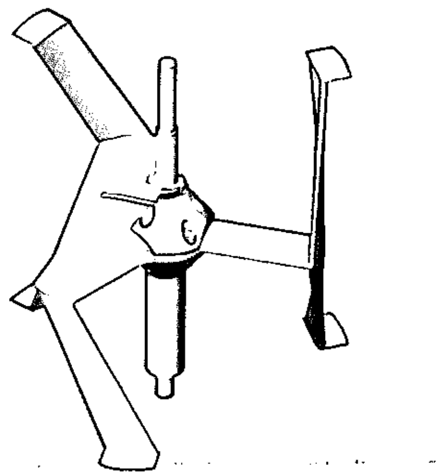


Figure - 10 : Photo of Darrieus turbine (left) and drawings of Gorlov (right) and

Achard[4] (down) turbines which will be tested in the tunnel of the LEGI (source Milé Kusulja) (manufacturer SERAS, a department of CNRS).



3.1.2 - Measurements

To be able to determine the turbine performances, of course, we will measure the rotation speed of the machine and the torque it produces. Moreover, we will measure forces applying on the turbine. Forces are measured thanks to a system made in LEGI. The directions of the measured forces are:

- *the one parallel to the flow*
- *the one parallel to the rotation axis*
- *and the one perpendicular to the 2 other measured force directions.*

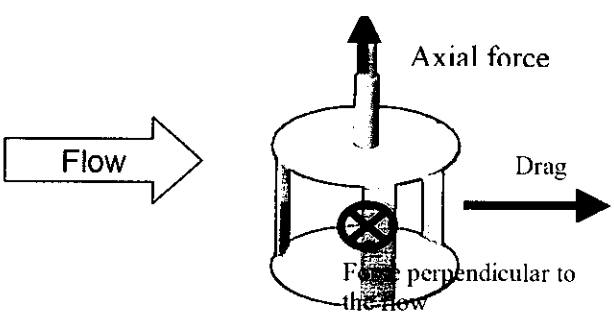


Figure - 10: Schema of the measured forces

This measuring system includes rails which support the system in the measured force directions. So, the system is able to move slightly in order to make the force sensors react. Some parameters of the flow like pressure and discharge are also measured.

3.2 - Aims

The experiment is a good source of information about the performances of different types of turbines. From the measurements, we will deduce the extracted power. We will also determine the characteristic curve, valid for all the turbines in similarity with the tested turbine.

According to previous numerical studies in LEGI and to experimental studies in other laboratories, we should find a power coefficient maximal for a tip speed ratio, λ , between 1 and 3. The tip speed ratio which characterised the rotational speed of the turbine with regards to the flow speed, is defined by the following equation :

$$\lambda = \frac{R\omega}{V} \qquad (3)$$

with R turbine radius ; λ rotational speed of the turbine ; V flow speed in the upper waters far away from the turbine.

In our experiment, there is also a will to learn about the forces applied to the whole turbine. The knowledge of the forces will be precious information to calculate the size of water turbine farm structure and of farm anchorage. For these calculations, it is good to have the average values but also the peak values.

We also expect to measure the variability of torque and forces on one revolution. Indeed, because of the rotational

movement and dynamic phenomena like dynamic stall, the forces on blades are varying a lot during one turbine revolution. As there are a small number of blades, the variations are not totally averaged for the whole turbine. The forces on the turbine are difficult to calculate: the experiment is useful to study these forces. The knowledge of the forces variation will be useful to study the fatigue of the turbine and axes material.
Some comparisons between turbine technologies can be made thanks to the characteristic curves and all the force measurements. So, this experiment is a good tool to compare the different turbine types on the performances but also on the forces applied to material and anchoring problems.

3.3 - The numerical aspects

The experiment will give information only for few turbines. To be able to estimate performances of a wider range of turbines, a little code is developed. The code results will be compared to the experiment results to estimate the code efficiency and then to improve it. The code is based on the numerical model used for vertical-axis wind turbines. Two different kinds of models were studied :

- *Models based on the momentum theory*
- *Models based on vortex theories*

LEGI has studied models based on the momentum theory. All these models are inspired by Glauert work on propeller. To estimate the global performances of the turbines, vortex models do not give better results than models based on the momentum theory. However, they predict more precisely efforts but need more calculating time.

For the models based on the momentum theory, three types can be distinguished :

- *Single streamtube model : the whole turbine is inside a single streamtube. It is modelled by one receptor disk.*
- *Multiple streamtubes model : the flow going through the turbine is split into several streamtubes. The turbine is modelled by one receptor disk.*
- *Double-multiple streamtubes model : the flow going through the turbine is split into several stream tubes. The turbine is modelled by two receptor disks : the flow passing through them successively.*

These models, and some improvements, have been studied notably by Sandia laboratories (Strickland, 1975) and Ion PARASCHIVOIU (Paraschivoiu, 2002). At present, LEGI work on these three models.

To improve these numerical models, one must consider dynamic stall, downstream blades going through upstream blade wake, streamline divergence, relative flow streamlines curvature...These improvements must be important to adapt these models to vertical-axis water turbines.

4 - CONCLUSION AND PERSPECTIVES

This paper presented various activities, mostly ongoing and preliminary - dedicated to "fluid" modelling and testing, at EDF R&D and its partner LEGI, to improve the knowledge related to

Marine Current Energy in France.

Enough has been done to highlight the complementarities of numerical and experimental approaches, both on the currents' studies and the harnessing devices' analysis. From the desk to the sea, going through the laboratory, and vice-versa...

A lot remains to be done in the years to come for the first devices to produce first kWh, in structural mechanics, electrotechnics, electronics... We hope that studies like the ones presented in this paper will contribute to achieve such an ambitious target, even if, due to the recent start of these studies, most results are still to come. They will be shared on time.

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GLOSSARY

[1] 'Tidal stream energy' is synonymous of and alternatively used for 'marine current energy (MCE)' in this paper.

[2] AWAC = "Acoustic Wave And Current" ; ADP and Aquadopp = Acoustic Doppler Profilers, by Nortek.

[3] Doppler principle : change of frequency due to the velocity of a source or receptor

[4] Jean-Luc Achard, Professor, CNRS, LEGI. LEGI has actually its own MCE project, named "HARVEST" ans aiming at the development of this ACHARD device (Maitre & Achard, 2003) (Achard & Maitre, 2004).

Fuel Cell Microcars for Small Sicilian Islands

V. Antonucci, F.V. Matera, L. Andaloro,
G. Dispenza, M. Ferraro

ABSTRACT

CNR-ITAE is developing hydrogen fuel cell microcars for small Sicilian islands. These vehicles are lightweight and zero-emission. Regenerative braking and advanced power electronics make these vehicles very efficient. Moreover, to achieve a very easy-to-use technology, a very simple interface between driver and the system is under development, including fault-recovery strategies and GPS positioning for car-rental fleets. The project includes a hydrogen refuelling station powered by renewable energy, in order to make the overall system self-sufficient, as well as to test the technology and increase public awareness toward clean energy sources.

Keyword: fleet, fuel cell, powertrain, regenerative braking, ZEV (zero emission vehicle)

1 - INTRODUCTION

The forecast growth in fuel consumption by road transport has been identified as a major policy challenge in the European Union (EU). This can be explained by concerns about fuel consumption-related emissions of greenhouses gases (GHG), and the increasing dependence on imported oil.

In this context, it is generally agreed that actions need to be taken to curb GHG emissions. Thus, strong interest has arisen in the last decade for fuel cell-powered vehicles.

Polymer electrolyte membrane fuel cells (PEMFC) are the most promising power sources in the near future for residential, mobile and automobile applications. They offer the potential of compactness, lightweight, high power density, easy system management and low temperature operation. They are actually also considered the best solution for automotive applications. This is due to criteria related to large flexibility, fast start-up, small dimensions, high efficiency and low working temperature; this latter characteristic is important for safety aspects. PEMFCs use highly conducting electrodes made of graphite, which form the terminal of each cell and separate adjacent cells in the stack. The electrodes are grooved to allow easy passage of the gases to the 'surface of action' while also maintaining electrical contact with the electrolyte-catalyst-gas interface. At the anode, hydrogen is catalytically dissociated to leave hydrogen ions. An external circuit conducts electrons while the positive ions (protons) migrate through the electrolytic membrane to the cathode. There they combine, again under action of a catalyst, with oxygen and electrons returning from the external circuit to form water. The state-of-the-art catalysts for both electrodes are based on carbon-supported platinum; the electrolyte is an ion-conducting perfluorosulfonic membrane. Stacks are obtained by connecting a number of cells in series while gas distributors (bipolar plates) accomplish the function of feeding the fuel to the anode side and air (or oxygen) to the cathode.

2 - THE SICILIAN ISLANDS

In recent years small islands have attracted major attention, with several European and national programs addressed to the development and protection of these areas. Small Sicilian islands, recently declared as mankind heritage, include large portions of protected areas; thus, they represent a good opportunity for sustainable development solutions.
The 14 Sicilian islands (Figure - 1), organized in 8 municipalities, extend from 3 to 38 sq.km, with a significant height above sea level (Table - 1, right).

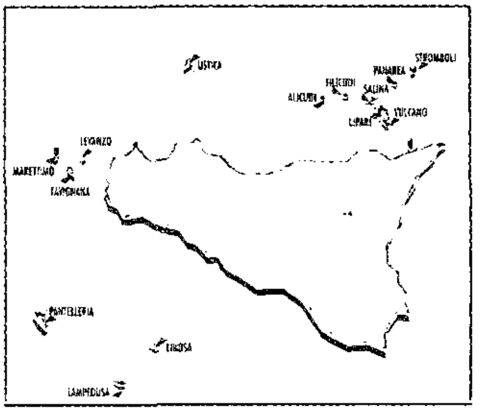

Figure - 1: Sicilian islands layout

Often, during wintertime, they remain isolated due to atmospheric and sea conditions. Main supplies, such as potable water and fuel, are provided by bulk carriers from the mainland, excepting some islands where drinking water is produced by desalination of sea water. Power is locally produced by diesel generators connected to the local grid.
The main human activities are agriculture, with valuable typical products, fishing and tourism. Although tourism infrastructures are not always very well developed and organized, population grows roughly 5 times during summer holidays.

Vehicles are generally not allowed during summer for non residents; however, the most used means of transport are gasoline cars or smoky and noisy two/four strokes vehicles.

Island	Municipality	District	Area,sq.km	Height asl (min-max), m
Lampedusa	Lampedusa e Linosa	AG	20.2	0-193
Linosa and Lampione			5.3 and 1.2	0-195
Lipari	Lipari	ME	37.6	0-924
Vulcano			21	0-500
Strmboli and Strombolicchio			12.6	0-926
Filicudi			9.5	0-775
Alicudi			5.2	0-675
Panarea and surrounding rocks			3.0	0-421
Salima	S. MArina di Salina	ME	27	0-963
	Malfa			0-860
	Leni			0-962
Ustica	Ustica	PA	8.65	0-248
Favignana	Favignana	TP	19	0-686
Marettimo			12	0-984
Levanzo			10	0-278
Pantelleria	Pantelleria	TP	83	0-836

Table - 1: Area and height above sea level of small Sicilian islands.

3 - FUEL CELL VS. BATTERY

In small islands, typical use of vehicles mainly include rent car for tourists, taxi and shuttle service, with no special requirements in terms of speed. These vehicles must also be able to overcome steep slopes even at full load, and should be noiseless and smokeless.
The electric traction, today based on conventional batteries, is currently preferred from an environmental point of view, but it has strong limitations due to short operating range and long recharging time. A disadvantage of current Electric Veichle technologies is that the energy supply required to power the vehicle needs to be stored as electricity on board the vehicle. The batteries that are needed for this purpose are expensive, have a short recharging cycle, and have a limited storage capacity. The range of an electric vehicle is therefore much smaller than for vehicles fueled with gaseous or liquid energy carriers. Batteries currently have a recharging time of approxi-

mately 6 to 8 hours, which makes these cars less suitable for intensive use. Replacing empty batteries with charged batteries is at present not considered a serious option, mainly because the batteries are too heavy.

Although several models of battery-powered light vehicles are commercially available, most of them are not suitable for these applications. Very steep slopes require an high torque motor (or a motor coupled with a reduction gearbox) and a large amount of energy stored on board. In the case of battery-powered vehicles, this would require a large number of batteries installed onboard with strong limitations in terms of weight and volume.

The increased weight would dramatically reduce acceleration performance of the vehicle and increase the need of an oversized braking system. Also goods or luggage on-board storage capacity would be sacrificed. Moreover, battery disposal would rapidly become a problem without an adequate and efficient policy of waste battery management.

Recharge is another critical issue for battery powered vehicles. The long recharge time, requires an adequate vehicles fleet management. Although some alternative solutions have been proposed, such as battery-pack turnover or on-board power generation with small reciprocating (gasoline or diesel) engines, none of these seems to really meet the need of a clean and efficient vehicles fleet; moreover, the problem of battery disposal would remain to be solved.

4 - MICOROCAR DESIGN

At present, the automotive market is investing in microcars. Microcars in Europe are about 250,000 (more than 30,000 in Italy) and, in 2003, 10,000 microcars have been sold vs. 8.500 in 2002 (18% increase). They are an alternative model of mobility thanks to their characteristics (small size, limited speed, reduced consumption, easy driving).

Microcars can be advantageously used in areas where land morphology (narrow roads, steep slopes) or other restrictions (limited traffic areas) could cause transportation problems. Hence, small islands and natural parks can represent a real laboratory for testing and development of these vehicles. CNR-ITAE is developing this new generation of electric vehicles, in collaboration with industrial partners involved in fuel cell microcars production. The goal is to realize a transportation system able to solve the problems connected to individual mobility in protected areas with efficient, noiseless and non polluting vehicles, as well as to introduce an easy-to-use technology oriented to tourism and car rental.

The vehicles under development include a hydrogen fuel cells generator, a storage system for energy recovery and lightweight compressed hydrogen tank. An advanced interface between the fuel cell system and the electric motor allows regenerative braking and energy management, with consequent high overall efficiency. A further advantage, with respect to battery-powered vehicles, consists in the fast refuelling of the fuel cell system (few minutes vs. up to eight hours). Moreover, exhaust

battery management would not more be an issue.
The vehicles are provided with GPS positioning and diagnostic system; this, in case of fault, reports the vehicle status, the type of fault (as indicated by sensors) and the vehicle position to a remote unit which is able to interact with the driver for assistance.

Powertrain configuration

The vehicles are designed to meet the Italian regulation on "light quadricycles". The principal requirements are a maximum power of 4 kW, speed limited to 45 km/h and maximum weight of 350 kg for the whole vehicle excluding battery pack. Figure - 2 depicts a general scheme of the power train.

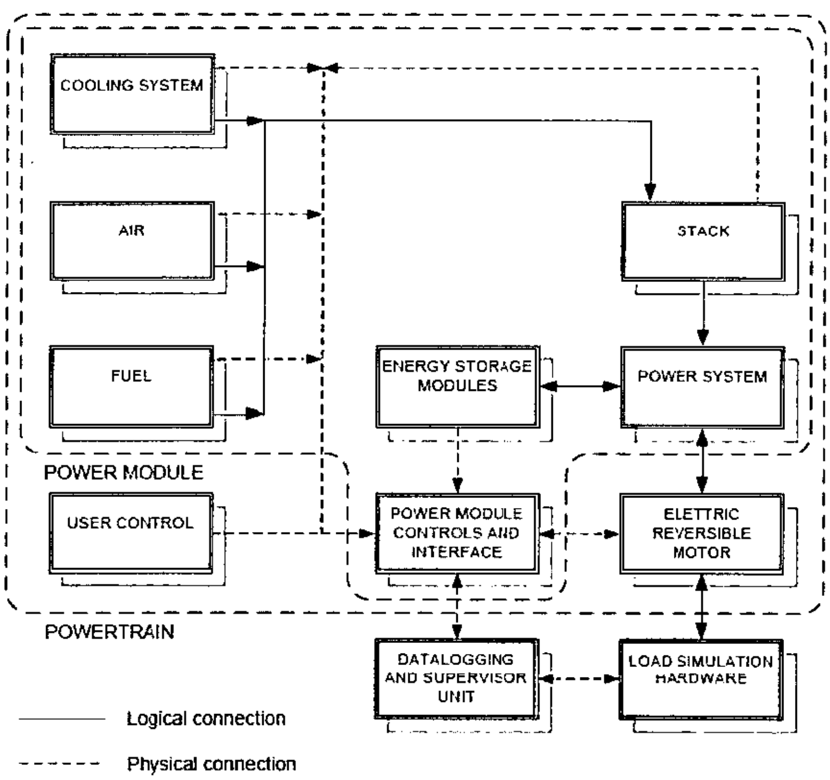

Figure - 2 : General scheme of the powertrain

The powertrain is designed with a two speed gearbox to face steep slopes at full load. Three models are being designed, having two or four seats and different volume for storage tanks and luggage compartment, in order to meet various requirements (hotel shuttle, car rental, goods transport).

The power requirements of the vehicle can significantly differ, depending on specific needs (weight to be transported, driving cycles, etc.). Thus, some degree of hybridization is needed.

Two powertrain configurations (parallel and series) are depicted in Figure - 3 and Figure - 4 (next page)

In the parallel hybrid powertrain (Figure - 3) most of the power for the electric motor is produced by the fuel cell. Moreover, the fuel cell provides to recharge batteries when required. In this case, batteries can assist the fuel cell when peak power is necessary (acceleration, climb, etc.) The battery pack acts also as power storage in the regenerative braking. In the series configuration (Figure - 4), power is provided by the battery. The fuel cell works only as a for the battery charger; this system is particularly suitable for urban driving cycle.

Where steep slopes are present, a large amount of energy can be recovered during downhill driving (regenerative braking). This recovered energy is one of the most important factors that increase the overall efficiency of the vehicle, as it affects the primary energy consumed (hydrogen) per km (i.e. J/km).

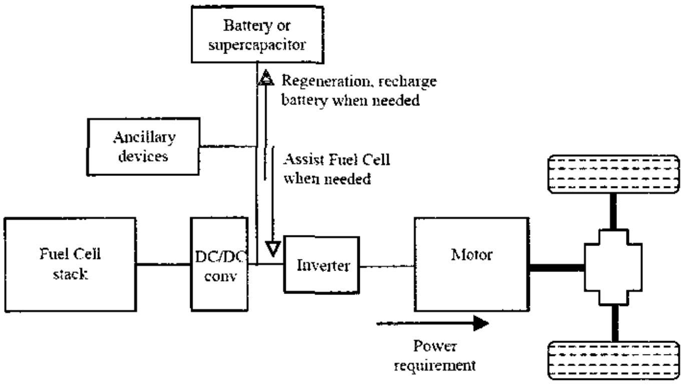

Figure - 3: Fuel cell parallel hybrid power train configuration

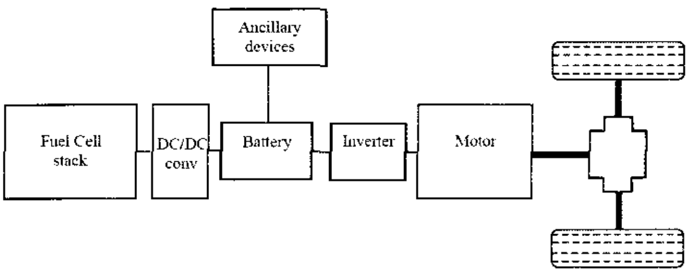

Figure - 4: Fuel cell series hybrid power train configuration

5 - HYDROGEN FOR SMALL ISLANDS

In recent years, several projects for the exploitation of renewable energy have been set to assess the potentiality and flexibility of such sources in these islands. In such places, the cost of electrical energy is typically very high and often the surplus cost is paid by public administration. Production of hydrogen can represent a possible solution to store the excess energy via renewable sources (solar, wind, etc.). Since methane reforming is not a viable solution in isolated localities, due to the lack of distribution infrastructure, water electrolysis can be an interesting option.

Nowadays, current fuel cell vehicles make use of centralized refuelling stations. Buses and microcar fleets are particularly attractive as an entry market for fuel cell vehicles, as they are centrally *garaged, refuelled and maintained.* Near term demonstration projects will help to disclose most stringent technical issues for different types of fuel cell vehicles.

Figure - 5 depicts a general view of the envisaged system.

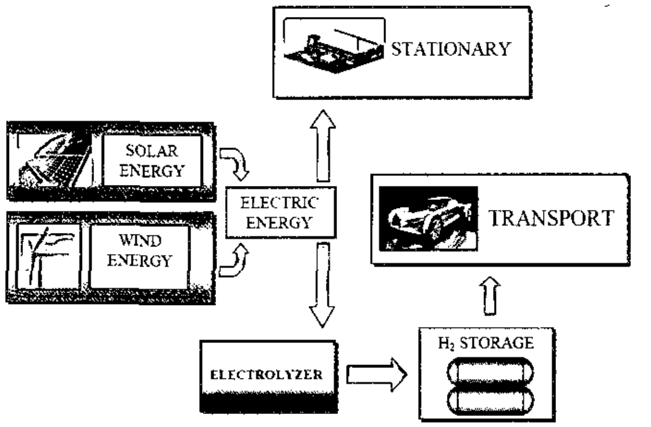

Figure - 5: General scheme of the envisaged system

The energy produced by photovoltaic panels and wind generators can be partially used for residential purposes; the excess could be transformed, by electrolysis, in hydrogen which is stored and then used for the fuel cell-powered vehicles.

6 - CONCLUSIONS

Main goal of this project is to design and test a small fleet of fuel-cell hybrid electric vehicles under the cited environmental and background limitations. The protection of environment in places such as Sicilian Minor Islands is a priority. In this view, the proposed application justifies the actual higher cost of fuel cell vehicles. Moreover, the close integration between hydrogen production by renewable energy sources and zero emission vehicles gives today the opportunity to test, under favourable circumstances, a energy technology that is considered one of the most promising in the long term.

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AUTHORS

Vincenzo ANTONUCCI, Dr. ,
Fuel Cell Research Manager , CNR - ITAE, Salita S. Lucia sopra Contesse n° 5, +39-090-624.234, fax:+39-090-624.247,
antonucci@itae.cnr.it

Fabio MATERA, Dr. ,
Automotive Fuel Cell Systems Dep. - Researcher, CNR - ITAE, Salita S. Lucia sopra Contesse n° 5, +39-090-624.236, fax: +39-090-624.247,
fabio.matera@itae.cnr.it

Laura ANDALORO, Dr.,
Automotive Fuel Cell Systems Dep. - Researcher, CNR - ITAE, Salita S. Lucia sopra Contesse n° 5, +39-090-624.235, fax: +39-090-624.247,
laura.andaloro@itae.cnr.it

Giorgio DISPENZA, Dr.,
Automotive Fuel Cell Systems Dep. - Researcher, CNR - ITAE, Salita S. Lucia sopra Contesse n° 5, +39-090-624.235, fax:+39-090-624.247,
dispenza@itae.cnr.it

Marco FERRARO, Dr.,
Stationary Fuel Cell Systems Dep. - Researcher, CNR - ITAE, Salita S. Lucia sopra Contesse n° 5,
+39-090-624.231,
fax: +39090624247,
ferraro@itae.cnr.it

The European Commission's activities in support of Renewable Energies, in particular Ocean Energy

Komninos DIAMANTARAS

Despite attempts to decouple economic growth from energy consumption (in progress to some extent in industrialised countries), energy is currently an important component of growth. As events have recently demonstrated, an increase in the cost of energy immediately translates into a decrease of GNP growth and in the well being of European citizens. Energy price volatility of the kind currently being experienced also has a determining effect on economic growth and investment decisions. Europe therefore requires a stable, secure and affordable energy supply.

Growth of energy consumption at world level is due to increase sharply in the years to come especially with the somewhat unforeseen economic boom of demographic giants such as China and India (conservative figures indicate a progression from 10 000 Mtoe in 2001 to 16 300 Mtoe in 2030, with the share of OECD countries going down from more than 50% to about 44%).

Energy is therefore at the core of global concerns, as exemplified by the Climate Change Convention and Kyoto Protocol aiming to reduce greenhouse gas emissions through cleaner and more efficient use of traditional energies, and introducing Renewable Energy Sources (RES) as alternatives to fossil fuels, and the Johannesburg Renewable Energy Coalition Joint Declaration "The Way Forward on Renewable Energy", and in a more general context the Göteborg and Lisbon Strategies on Sustainable Development.

I will therefore present the major energy research policies in place and will refer to the research activities in the field of renewable energies with emphasis on the sector of ocean energy, a short summary of which follows.

Over the last twenty years, the European Union financed ocean, wave and tidal energy research and developers. In total, twenty-nine projects have been awarded to research and development in the three main areas, of which four projects under FP5, one under FP6, while one is still under negotiation. In FP5 the EC contribution was 4.54 M , and in FP6 so far 4.8 M , while 2.5 M are still in the contract preparation phase. The cumulated EC contribution during the last fifteen years sums to about 23 M with a total eligible cost of the order of 48 M .

Increasing R&D funding is critical to advancing the development of ocean energy systems. Ocean energy technologies must solve two major problems concurrently: proving the energy conversion potential and overcoming a very high technical risk from a harsh environment. No other energy technology has had to face such demands. When deploying their prototype, device developers are confronted with the possibility of losing five years of development and investment in few hours time. Furthermore, the majority of the developers are SMEs for whom such a loss can be overwhelming. Additional R&D funding would help to mitigate the substantial technical risk faced by device developers daring to harness the energy of the marine environment.

Ocean energy systems cover a wide range of applications that can be deployed on the shoreline and offshore. Technology is emerging to allow large scale demonstration projects. At present, very few demonstration prototypes exist and they are mainly in Europe. The research activities cover the areas of shoreline and offshore wave energy devices, of tidal current turbines and of salinity gradient systems. Salinity gradient systems are a recent development and could be deployed in many European river estuaries.

The flagship prototypes developed with EU financial support are:

- Shoreline Wave Energy: two demostrators of 400kW$_e$ each, one on the island of Pico, Azores, and one on the island of Islay, Scotland (FP4 projects)
- Tidal current turbine: one prototype of 300kW$_e$ (FP4 project)
- Kobold marine current turbine: one prototype of 12 kW (FP4 project), and
- Offshore Wave Energy: one 1:4 prototype of 20kW$_e$ - known as Wave Dragon (FP5 project)

The following projects under FP6 have started recently and are at the implementation phase:

- The Coordinated Action on Ocean Energy systems, CA-OE with ~ 1,5 M C funding
- The SEEWEC project (point absorbers, offshore) with ~ 2,3 M EC funding
- The WAVESSG project (overtopping type, suitable for breakwaters) with ~ 1,0 M EC funding, and
- The WAVE DRAGON 4MW (4MW floating overtopping type, offshore) with total cost of ~ 14,7

M out of which ~ 2,47 M EC funding..

According to the IEA's the Renewables Information report, during 2003 more than 572 GWh of electricity were generated from wave, tide and ocean motion. The bulk of the electricity produced was generated in France through the 240 MW installed capacity project. Canada was the second highest electricity producer with about ~ 33 GWh.

It is also worth noting that since October 2001 the European Commission participates and follows through the Implementing Agreement on Ocean Energy Systems the latest developments at international level while promoting the research, development, information exchange and demonstration of Ocean Energy Technologies.

For additional information the reader can also refer to the following websites:

a) related to Ocean Energy:

European Wave Energy Atlas:
http://www.ineti.pt/proj/weratlas/

Coordinated Action on Ocean Energy:
http://www.ca-oe.net

Wave-Net:
http://www.wave-energy.net/index3 .htm

Wave Energy Centre (P):
http://www.wave-energy-centre.org/

WAVE DRAGON :
http://www.wavedragon.net/

LIMPET (Islay, Scotland):
http://www.wavegen.co.uk/what_we_offer_limpet_islay.htm

International Energy Agency:
http://www.iea-oceans.org/index1.htm

WAVETRAIN (Marie Curie Actions, FP6):
http://www.wavetrain.info/

b) related to the European Commission's activities and events :

EUROPA:
http://europa.eu.int/comm/dgs/research/index_en.html

http://europa.eu.int/comm/research/energy/index_en.html

http://europa.eu.int/comm/energy/index_en.html

INCO and Marie Curie:
http://www.cordis.lu/inco/home.html

http://europa.eu.int/comm/research/fp6/mariecurie-actions/indexhtm_en.html

CORDIS:
http://www.cordis.lu/fp6/

RENEWS newsletter :
http://europa.eu.int/comm/research/energy/pdf/renews3.pdf

Information days and similar events, conferences :
http://europa.eu.int/comm/research/energy/gp/gp_events/action/article_2790_en.htm

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Telephone: (+43-1) 26026-0, Fax: (+43-1) 26926-69
E-mail: unido@unido.org, Internet: http://www.unido.org