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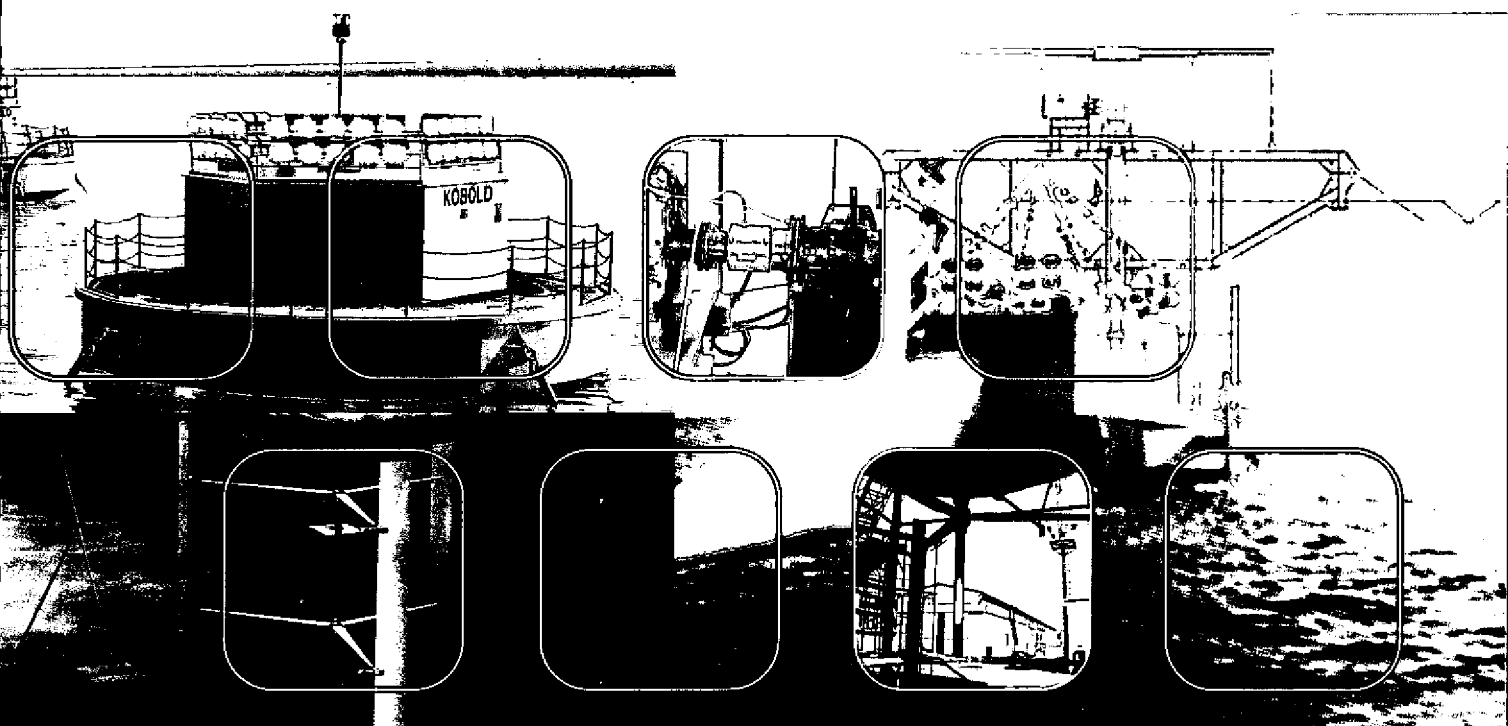
Messina Conference
15-16 September 2005



Kobold technology promotion and transfer for marine current exploitation in South East Asia

Papers and presentations

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CONTENTS

TECHNICAL PAPERS

The Politecnico di Milano role in the research "Current for current"

Alfredo Cigada, Alberto Zasso

1 - INTRODUCTION

There is no doubt that the interest towards renewable energies is going to grow in future years: the continuously growing trend in the petroleum cost will make this process faster and faster. Of course, according to each country particular situation, this interest is addressed towards different techniques, some of them related to sea current resources: under this point of view Italy, surrounded by seas, shares with many other countries the aim to try exploiting this potential richness to its full extent.

That's why Politecnico di Milano decided to pick up this new challenge and started working in the topic of marine current energy. The decision is rather recent, anyway the state-of-the-art research on this subject is still young, no commercial products exist today, so the moment has been considered as extremely favourable for a start.

Due to the just mentioned facts, at this stage, literature mainly deals with general evaluations concerning the economic convenience to start operating "*water mill*" plants: the matter is to get the highest possible power levels, the best efficiency, to make comparisons against other energy sources, also to find the best sites to build the new plants. Of course also some sceptical approaches are encountered, but the authors remember similar facts when "*wind farms*", for power generation from the wind, first came out, then spreading all over Europe. It's an important occasion for both research and technology growth and it can't be missed: staying behind now may mean not to be able to fill the gap, with those believing now in the project. This is the reason why the national and international funding for research programs puts special emphasis on the renewable energy systems, confirming the general interest on the topic: according to the preliminary documents, the EU VII Framework Program has a special budget devoted to this topic and also the national research program has recently opened a new call on the same theme. In addition it is remembered as the Italian Association for Wind Engineering is part in the organization of the conference OWEMES 2006, next year, in which Wind Turbines and Water Turbines are considered together in the work program. In 2004 the UK's Department of Trade and Industry has announced an investment in wave and tidal power technologies of **75 million euro**. At the launch of the funding, UK Secretary of State for Trade and Industry, Patricia Hewitt said: "*The UK's wave and tidal flows are the greatest in Europe and I want to ensure we harness these immense natural resources to generate power for the UK. Renewable energy - through wind, wave and other sources - plays a vital part in our fight against climate change, and we are committed to further developing renewable energy to play an increasing role in the UK's energy mix. This announcement reflects that vision and puts us firmly on the path to becoming the world leader in renewable energy*" she added. The same statements can be applied to Italy, or more generally speaking, to all Europe.

The particular situation of Politecnico di Milano, having a lot of international links on a number of research projects, and some important agreements with institutions from all over the world, has offered the chance to get in close contact with some research groups from several countries, also in the far east, which have expressed a strong interest towards marine current exploitation. These countries are China, the Philippines, Indonesia, all of them having special sites with strong tidal currents and in some cases, like for Indonesia, having a country broken in a number of small islands. For these situations marine current energy extraction looks very attractive, having a few if not at all competitors, as power has to be given to small communities (not so high rates) in places where cables for power transmission are hard to be brought. These countries have resolute will to get deep in this research, thanks to institutions like UNIDO, strongly believing in the project, or the network linking ASEAN and Europe.

In this scenario also the co-operation between Politecnico and Ponte di Archimede is worthy being mentioned, as both have shared common research interests in the past and still nowadays, having a common factor, which is water and water exploitation. Remaining in the marine current harvesting, a patented device from Ponte di Archimede, the Kobold turbine, has been taken by UNIDO as a prioritary project to be brought to Far East countries, and its improvement is the object of the present research carried out by Politecnico di Milano.

This short summary traces the framework in which Politecnico di Milano research on marine current energy moves its first steps.

As mentioned earlier, while literature concerning a general economic evaluation on this new energy source is rather rich, the number of papers concerning both research and technological aspects is still poor, partly due to the young science, partly probably due to an attempt to preserve the intellectual property on the achieved results.

At this stage, Politecnico di Milano research has just started, so this presentation is more a project plan, rather than a summary of results.

This plan has been organized at two levels:

a) A first level concerning blade optimization, aimed at considering the Kobold prototype turbine, designed and built by Ponte di Archimede, already operating in the Messina Straits. Assuming this solution as a state of the art, any possible improvement under the fluid dynamic point of view is sought for, to make power generation more efficient.

b) A more general and wide level, at which, according to the future availability of reasonable budget on this research, the whole problem of marine current energy will be faced, relying on the different and high level skills that Politecnico di Milano can offer within its Departments. At this stage the fluid dynamic optimization will be considered at a back-to-basic level: the vertical against the horizontal axis solution can be deeply re-considered, as well as the best kind of action to be exerted on the vanes, drag or lift. Also many other aspects will be re-considered, like the power conversion and transmission, the layout of the whole plan, as well as maintenance problems or the identification of suitable sites for exploitation. Also full scale tests on the existing prototype could be planned to get deeper into the problem.

However, the adopted strategy is to focus on the first phase, limiting risks and becoming familiar with the examined technology on the basis of a real working plant.

Efficiency improvement by proper turbine design can take advantage of the well established experience gained by the research group operating since decades on the fluid elastic problems and now operating in the new large Politecnico di Milano wind tunnel.

The use of a wind tunnel for a water turbine optimization could be considered rather odd at a first glance, however the past experience of the research group has proven that once the main similitude scaling is accounted for, then the first stage improvements are easier to be performed in air rather than in water, as instrumentation works in an easier and cleaner environment. On the other hand the hydraulic similitude approach is rigorous no matter air or water is the flow up to air flows speed at which compressibility effects are negligible. A similar approach was used with good results in testing flood effects on bridge decks and on hull performances where only the final stage was performed in water channel on an already roughly optimized model studied in wind tunnel.

It is worthy writing just a few lines on this facility and the group working in it.

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 Bridge Wind Engineering, as well as general Aerodynamics, 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 flow-structure interaction, is 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 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.

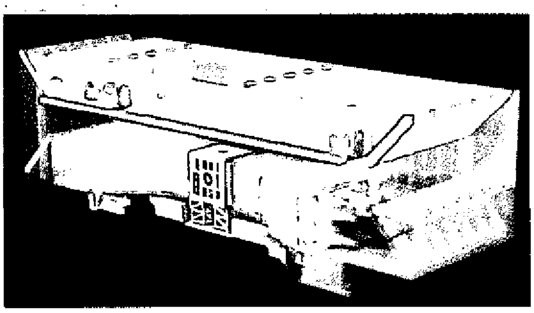


Figure - 1: Politecnico di Milano Wind Tunnel

The overall wind tunnel characteristics are summarized in Table -1;

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	< ±3	< 1.5
Low Turbulence	4×4	55	< ±0.2	< 0.15

Table - 1: Overall wind tunnel characteristics

the vertical arrangement and flow circuit are sketched in the vertical section of Figure - 2 and Figure - 3.

Figure - 2: Wind Tunnel section

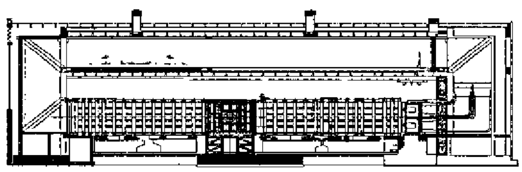


Figure - 3: Wind Tunnel section

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, 56m^2) allows for very low blockage effects even if large topographic 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 100.000 N). 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).

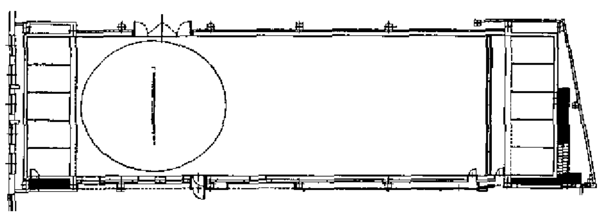


Figure - 4: Wind Tunnel top view

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 toThe 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}=55m/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, 56m^2) allows for very low blockage effects even if large topographic 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 100.000 N). 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). 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 to reach Reynolds numbers in the order of . 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 - WIND ACTION ON STRUCTURE

The research activity in the wind-structure interaction field has been first focused on the dynamics of overhead power lines vibrating under the effect of vortex shedding, moving then to long span bridge aeroelasticity, still now one of the core subjects of the research. The large expertise gained both in the experimental approach as well as in the numerical one, resulted in the availability of reliable simulation models for flow-structure interaction in very different application fields. On that subject, the new Wind Tunnel facility allowed to set up measurement techniques and correlated numerical simulation models among the most innovative and advanced in the international contest. Figure - 5 shows the Messina Bridge section model being tested in the Wind Tunnel. The Research Group is responsible for an International Benchmark focused on the comparison of the methods proposed by a worldwide network made up by the most active and renowned research groups for the numerical simulation of long span bridge dynamic response to turbulent wind.

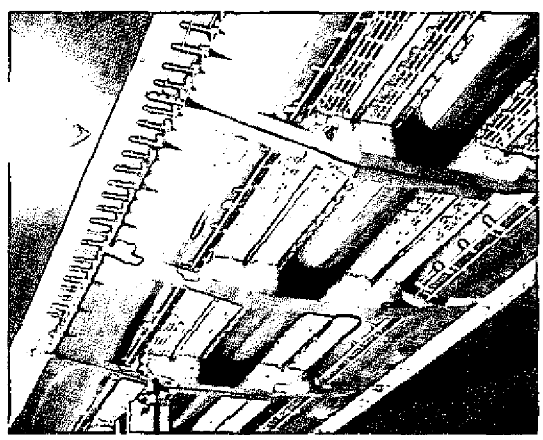


Figure - 5: Messina-Bridge model

The traditional up going research on train dynamics, in the railway field, has been recently extended to the new experimental data offered by the Wind Tunnel facility, allowing a deep understanding of the vehicle aerodynamics and mainly of the cross-wind effects. This subject is of crucial importance for very high speed trains: taking advantage of the large sized low-speed section, experimental campaigns on quite large scale models have been set-up with a correct reproduction of different boundary conditions related to the various arrangements of the rail tracks both in fixed and moving train configurations. The experience gained in the aerodynamic aspects, allowed, as a consequence, to enhance the Politecnico di Milano expertise in the railway field resulting in a more comprehensive and refined implementation of the numerical models simulating the train dynamics.

Figure - 6 shows an example of the instrumented and travelling train model in the Wind Tunnel. A research subject deeply integrated between base research and applications is about the dynamics of cylinders in the flow stream.

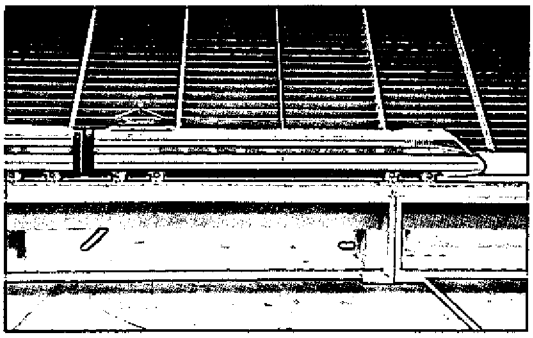


Figure - 6: Raikway vehicle ETR-480

Tensioned cables for very different applications, from overhead power lines to strands of suspended bridges to submerged oil risers, are just some possible examples. Figure - 7 shows two tensioned cylinders in tandem arrangement in the Wind Tunnel Another relevant research subject is about sailing yachts.

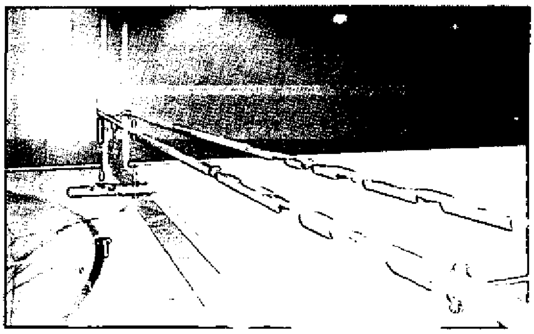


Figure - 7: Tensioned twin cylinders

Figure - 8 shows the scale model of an America's Cup boat fully instrumented with 6 components force balance and 4 channels sails remote control. Another research field is related to high rise buildings and large flexible roofs.

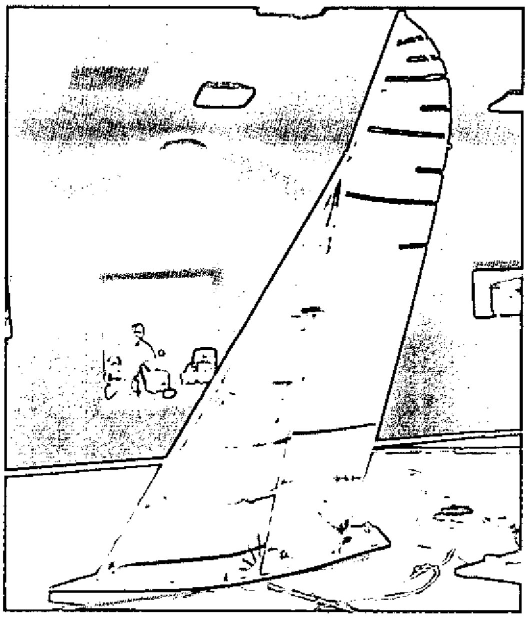


Figure - 8: America's cup yacht

Figure - 9 shows the scale model of a high rise building fixed to a 6 components balance and instrumented with 150 pressure taps, allowing for an understanding of the forces and pressure distribution due to the wind action.

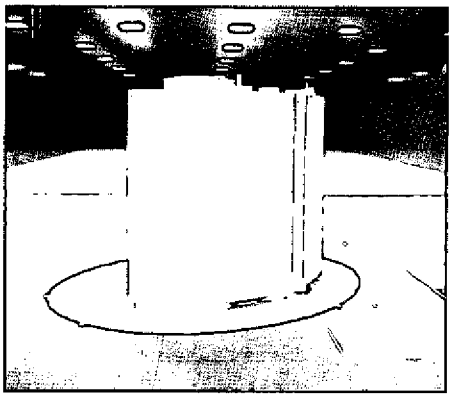


Figure - 9: High rise building

Figure - 12 and Figure - 13, on the other hand, show examples of very large and flexible roofs reproduced by aeroelastic scale models allowing to study the response of structures to turbulent wind.

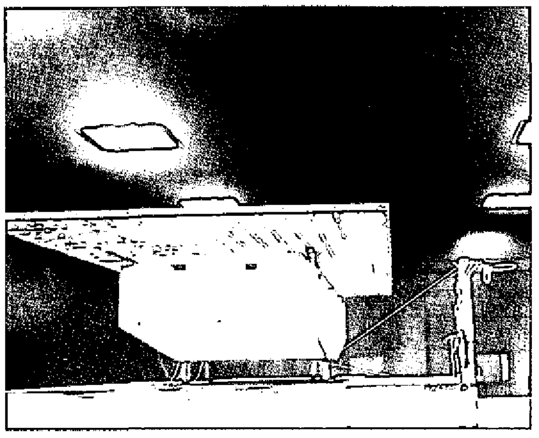


Figure - 12: Flexible roof aeroelastic model

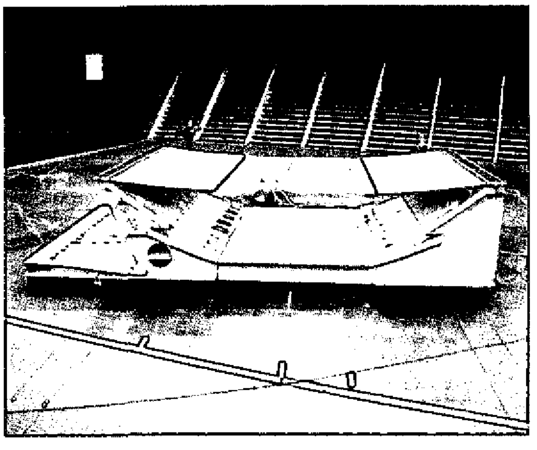


Figure - 13: Stadium roof aeroelastic model

Experimentation needs a computational support, often needed to go from wind tunnel models to the full scale prototype behaviour. Figrue - 10 and Figure - 11 show two relevant examples of full scale campaigns managed by Politecnico di Milano, the first on the free standing Store-Baelt tower at the construction stage, measuring the vortex shedding excitation, the second on the Humber Bridge, measuring the response due to the turbulent wind.

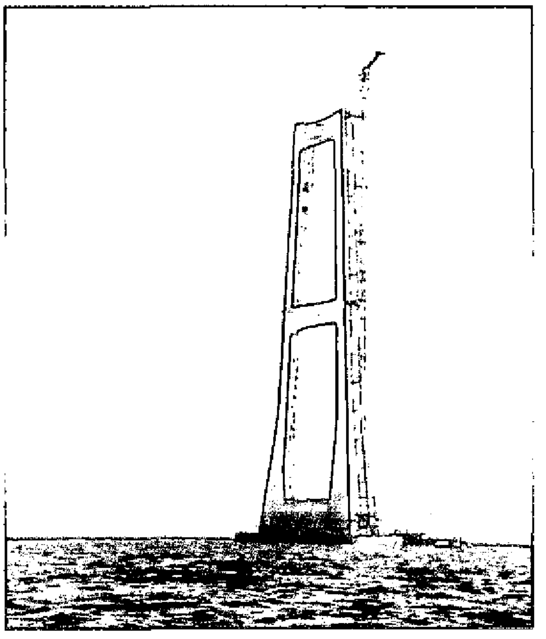
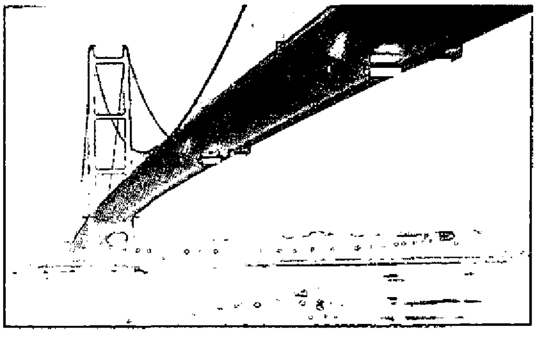


Figure - 10: Store-Baelt full scale monitoring



Figrue - 11: Humber Bridge full scale monitoring

A CFD approach to fully understand the over mentioned subjects is now an available tool, thanks to the increasing performances of computational resources. Figure - 14 and Figure - 15 show results of simulations performed on bridges and trains.

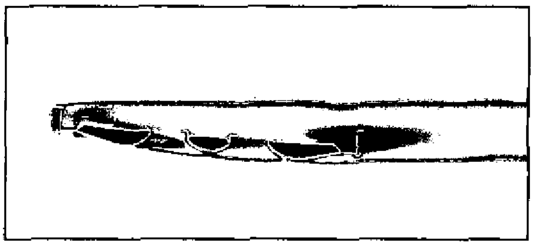


Figure - 14: Multiple-box girder CFD simulation

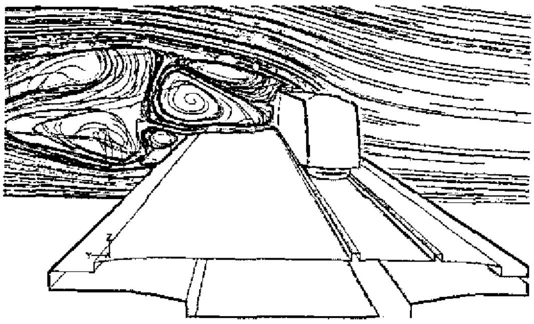


Figure - 15: ETR-480 train CFD simulation

Experimental data are fundamental for the validation of the very promising CFD techniques, considering future developments of numerical methods and computer science.

All these expertises are going to be put in the new project of the Kobold turbine.

4 - THE KOBOLD VANE

Prior to starting a wide range activity, a research plan has to be outlined. As already stated, 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:

- *Assessment of the present technological development*
- *Mathematical modelling*
- *Experimental tests on the complete turbine*
- *Optimisation*

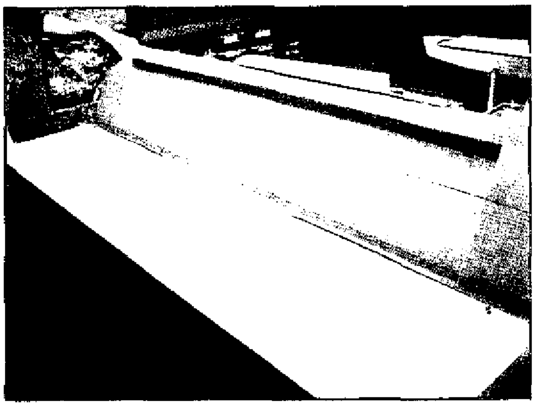
The first phase , that is the evaluation of the existing situation, may be split into different tasks:

- *Setting up of a single vane model to be tested in the wind tunnel*
- *Setting up of a suitable dynamometric balance to measure the aerodynamic characteristics*
- *Wind tunnel measurements*
- *Data analysis*

The aim of the initial phase is to deal with the wind tunnel tests on a single vane. The key activities involve a detailed wind tunnel evaluation of the turbine wing profile, measuring both the flow field in the surrounding of a vane and the global forces given by the stream. The allowance of a very large wind tunnel section enabled to make experiments on a large scale model (2/3 real to model scale ratio) with very low blockage level.

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 consisted in setting up a vane model, for the wind tunnel testing operation. 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 - 16);



Figrue - 16: building the vane model

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".

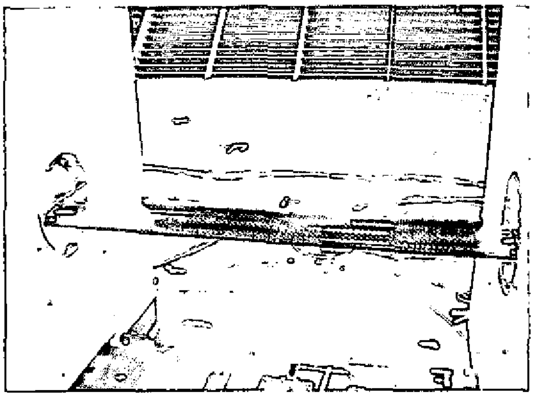


Figure - 17: the vane in the wind tunnel

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

$\mu_{AIR} = 1.83 \ 10^{-5}$
$\mu_{Water} = 0.0010$
$\rho_{Air} = 1.23$
$\rho_{Water} = 1.0 \ 10^{3}$

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 $Re_P / Re_M = 22.3\ V_{water} / V_{Air}$. Being the typical current speed in the order of $V_{current} = 1 / 2$ m/s , but with a relative speed under steady-state conditions around 2 times the current speed, then it has been assumed $V_{water} = 2 / 4$ m/s, and being the tests performed at a wind speed $V_{air} \sim 12$ m/s the typical Re ratio will be in the order of $Re_P / Re_M \sim 7.5$ 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 - 18).

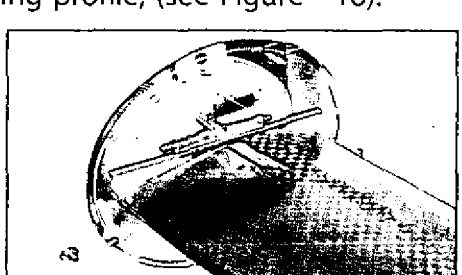
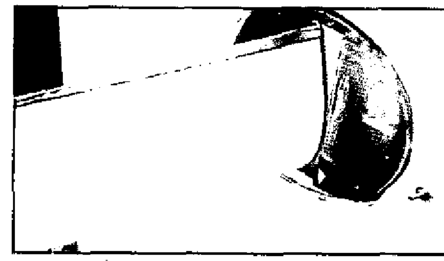


Figure - 18 The smooth and the rough wing coating



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. According to the model scaling, internal or external load cells are usually adopted. The long lasting experience gained by the research group has allowed to fit a balance concept, developed through years, to the special case of the "high lift 18 profile". The balance consists of a couple of external sensing elements, suitably designed to measure even very small forces, having almost no hysteretic or friction effects, therefore producing highly repeatable measurements.

Part of the balance design is its calibration, allowing to define measurement uncertainty, also accounting for cross effects of the various force components, by defining a calibration matrix, instead of a simple calibration curve. Tests have been repeated for three wind speeds, all the same it has been observed that this parameter has no effect on the static coefficient identification.

Another aspect worthy being mentioned is the fact that the balance is part of a rotating device, in guise of a "spit", therefore allowing a complete measurement on a 360° turn. The possibility of having data on the 360° rotation is an important fact, as the vane is expected to work at whichever relative angle between the incoming flow and the vane axis: even if it is true that the *turbine steady-state speed is 3 times* the marine current speed, then making the current-to-wing relative angle confined in a relatively low range, *all* the same when the turbine starts its rotation this does not apply, and the 360° data will offer a deeper insight in the start-up mechanism.

Data analysis, at the present step, has consisted in getting the static coefficients. The adopted references are shown in Figure - 19.

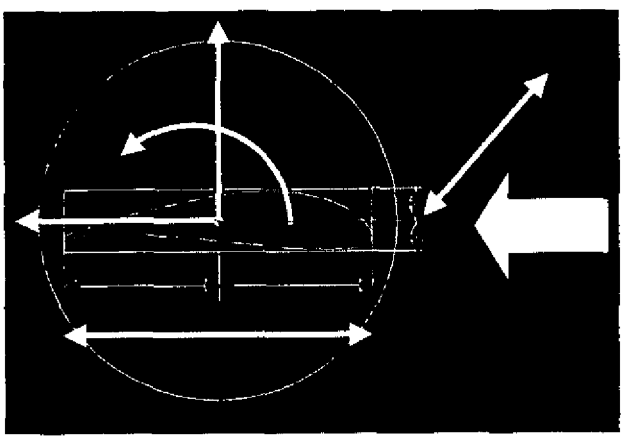


Figure - 19 Measure sign conventions

The non-dimensional static coefficients CD, CL and CM are defined on the basis of the following formulae, considering that the aerodynamic forces are functions of the wind pressure and of a reference wing surface, conventionally assumed equal to the projected surface.

The over defined coefficients are also

$$F_D = \frac{1}{2}\rho V^2 CW\, C_D(Re,\alpha)$$

$$F_L = \frac{1}{2}\rho V^2 CW\, C_L(Re,\alpha)$$

$$F_M = \frac{1}{2}\rho V^2 C^2 W\, C_M(Re,\alpha)$$

functions of both the relative angle between *the wind and the model and* are expected to exhibit some dependence upon the Reynolds number too. It *is hoped that no strong variation with* Reynolds number is observed, and at the same time the effects of a change *in the surface roughness is investigated.* Concerning the pitch coefficient CM, its value varies upon the position in the profile section to which force reduction is applied. In the present approach it has been stated to consider a point at half chord, even if the usual choice in the aeronautical field is ¼ chord: simple calculations allow to switch from one position to the other. The wind speed has been measured by means of a pitot tube connected to a precision micro-manometer, directly giving the dynamic pressure term, while the rotation angle of the whole "spit" has been provided in two ways: through the stepped motor moving the rotating device and 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 cosine law. Finally, after an on-site calibration verification, tests have been carried out for the two roughness levels of the wing surface.

Figrue - 20 to figure - 22 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.

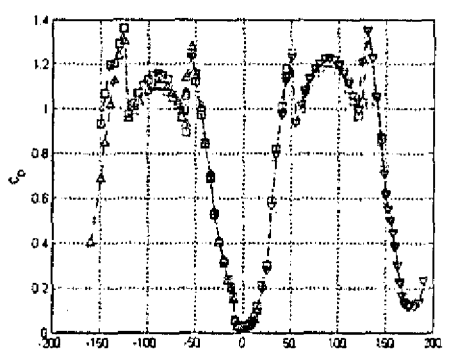
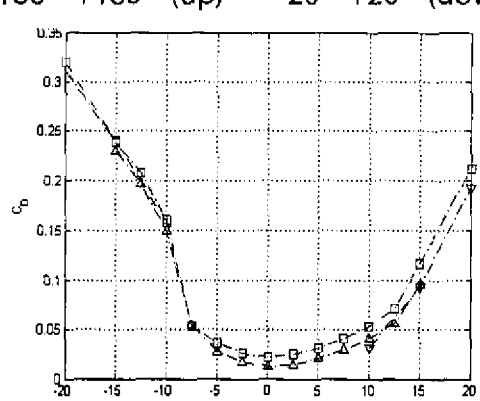


Figure - 20: CD with smooth surface: -180° +180° (up) -20° +20° (down)



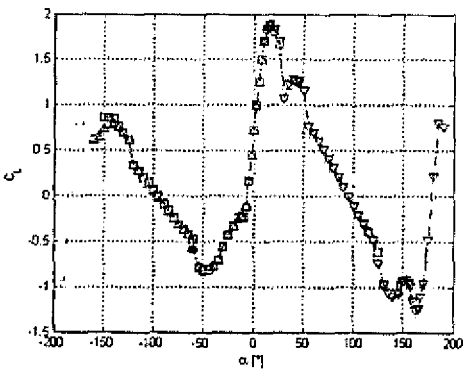
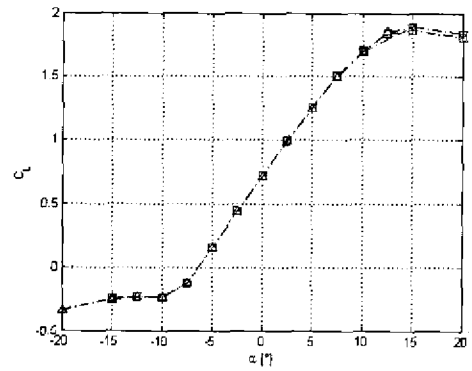
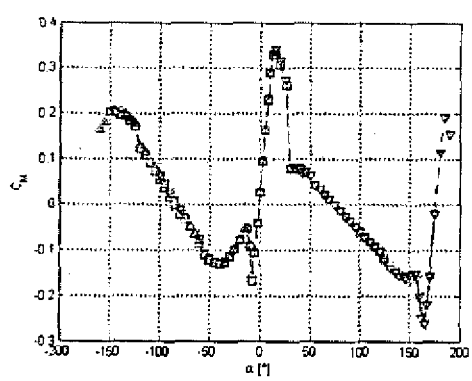
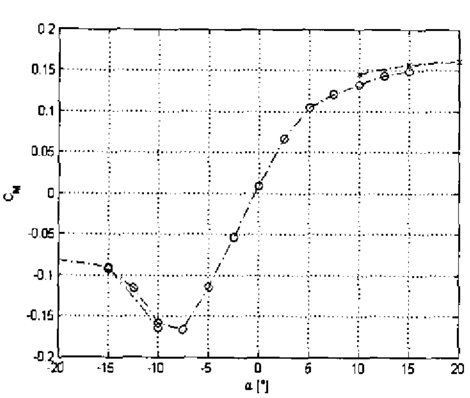


Figure - 21: CL with smooth surface: -180° +180° (up) -20° +20° (down)





Figrue - 22: CM with smooth surface: -180° +180° (up) -20° +20° (down)



The second series of tests has been performed on the wing with increased roughness. Results are given in Figure - 23 to Figure - 25, 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 - 26 to Figure - 28.

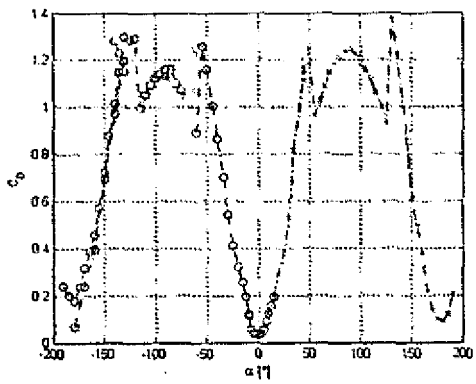
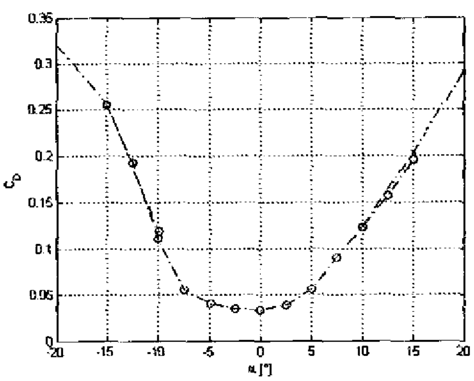


Figure - 23: CD with rough surface: -180° +180° (up) -20° +20° (down)



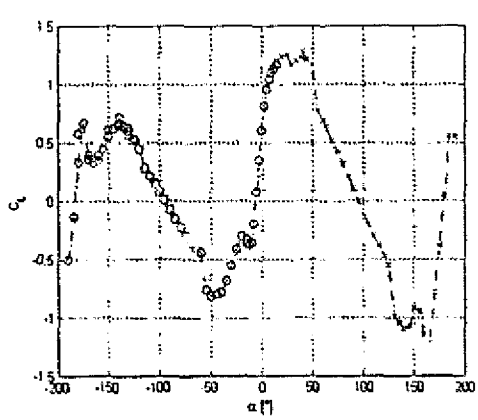
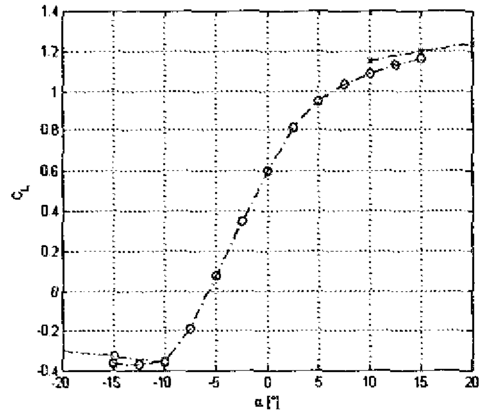


Figure - 24: CL with rough surface: -180° +180° (down left) -20° +20° (down)



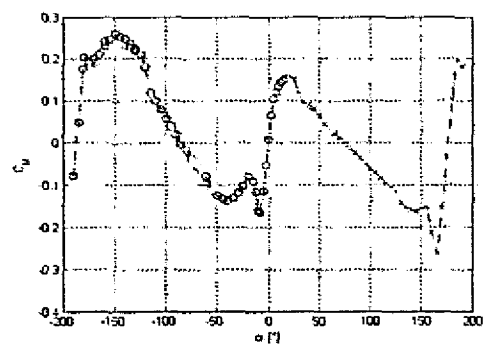
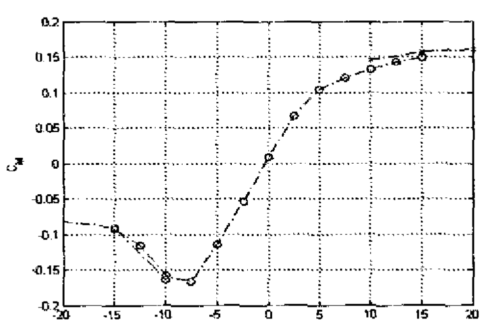


Figure - 25: CM with rough surface: -180° +180° (up) -20° +20° (down)



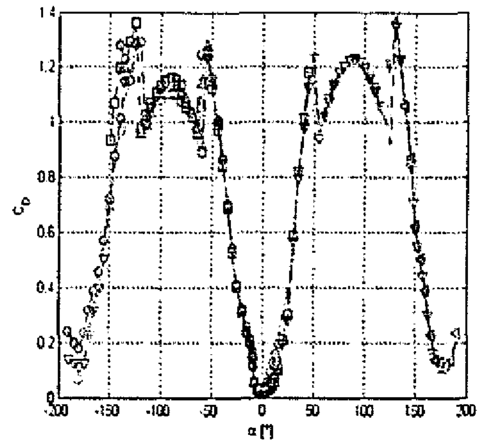


Figure - 26: CD comparison smooth and rough surface: -180° +180° (up) -20° +20° (down)

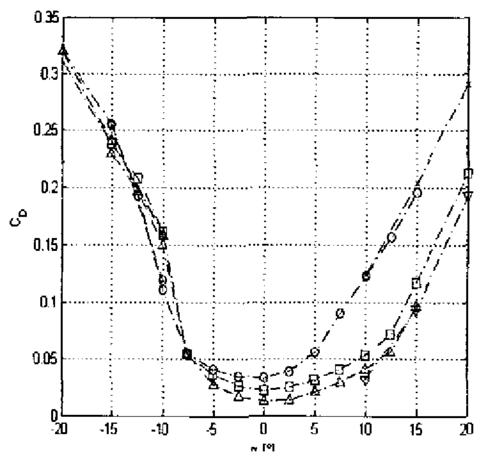
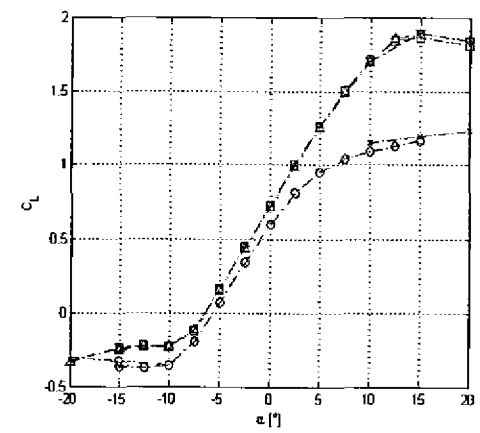
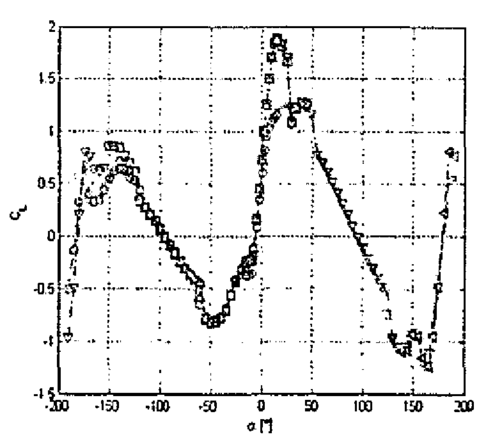


Figure - 27: CL comparison smooth and rough surface: -180° +180° (down left) -20° +20° (down)





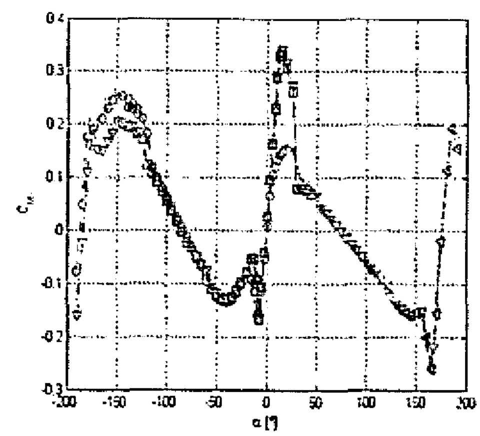
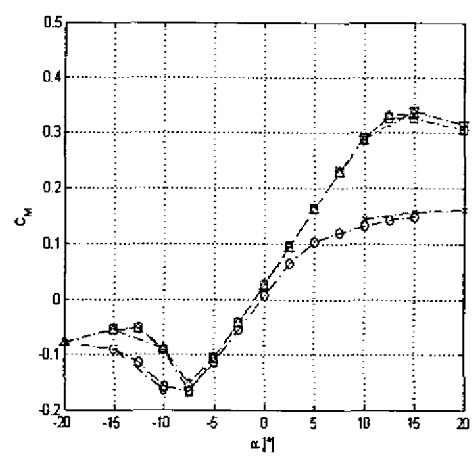


Figure - 28: CM comparison smooth and rough surface: -180° +180° (up) -20° +20° (down)



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 overall research plan has wide perspectives. Once the described preliminary steps have been run and the results have been achieved some further aspects are to be investigated.

To fully understand the real aim of the global work it is herewith given an outline of the various phases or tasks within each of the above mentioned research phases:

Mathematical modelling will be split into:

- *Model creation*
- *Parameter sensitivity analysis*
- *Simulation of the complete turbine*

Experimental tests on the complete turbine will consist of the following tasks:

- *Experimental set-up: complete turbine*
- *Wind tunnel tests*
- *Comparison between numerical simulation and experimental measurements*

Optimisation is going to be the final part, relying on the results of the previous phases.

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.

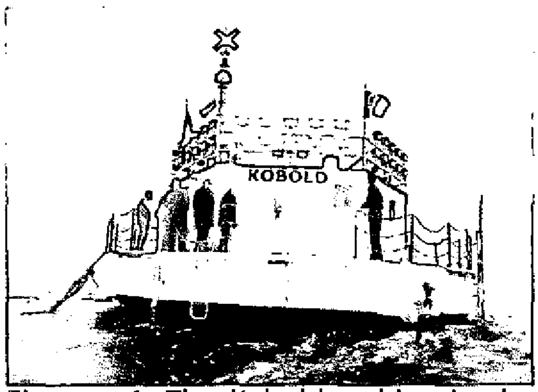


Figure - 1: The Kobold turbine in the Strait of Messina

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

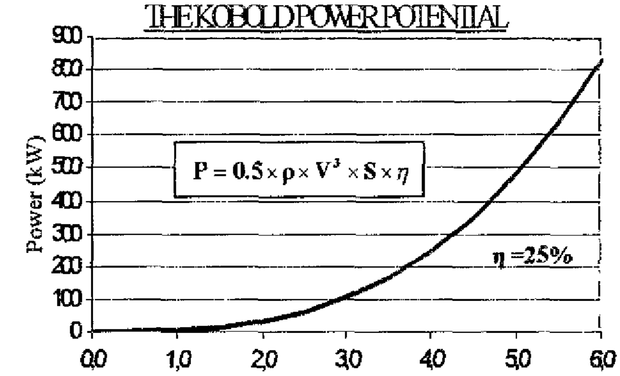
$$P = 1/2 \rho S V^3$$

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 m² 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.

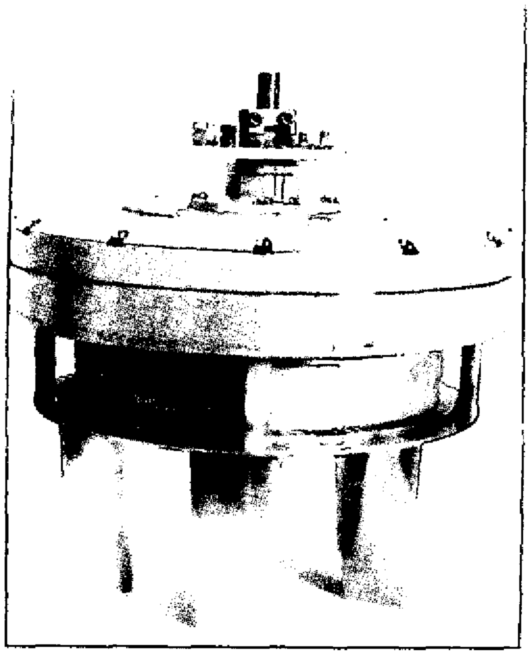
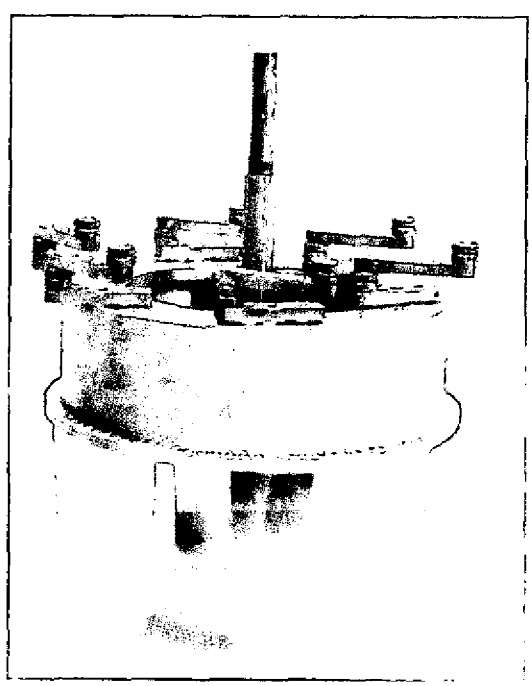


Figure - 3: Voith Schneider hydroturbine



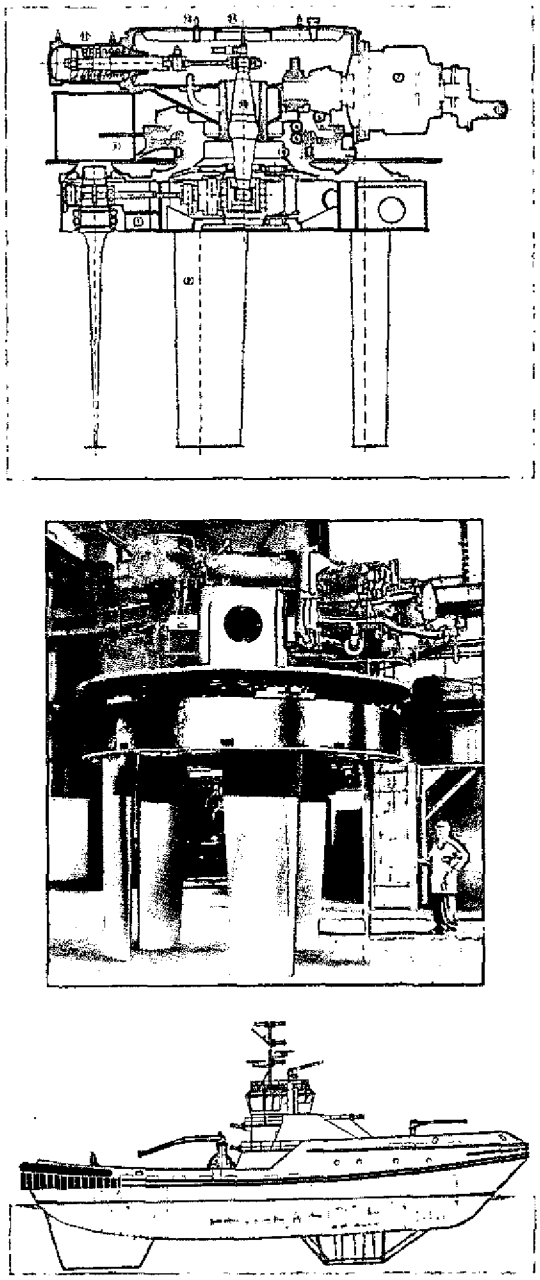


Figure - 4: Voith Schneider marine propeller

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.

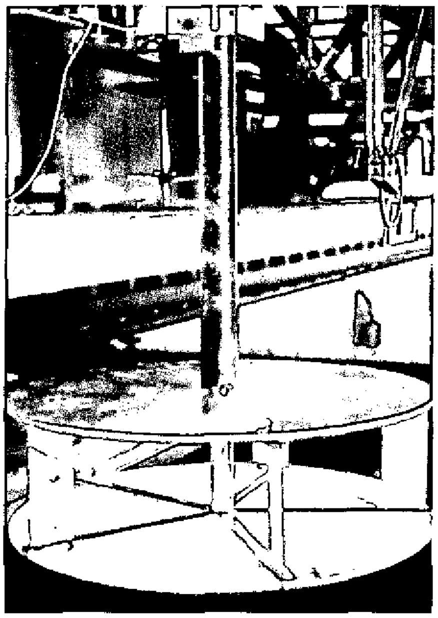
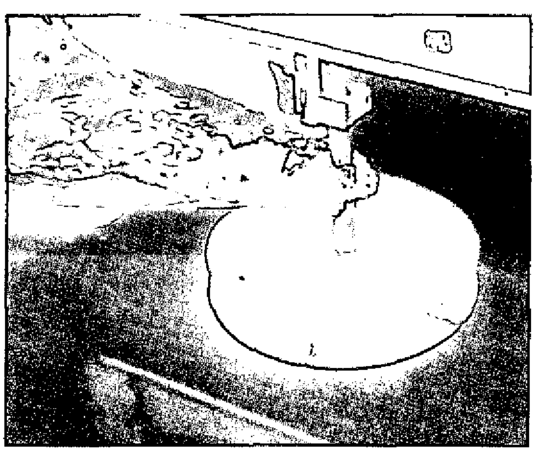


Figure - 5: Kobold turbine model (5 blades) tests in the towing tank of Dept. of Naval Engineering of University of Naples



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).

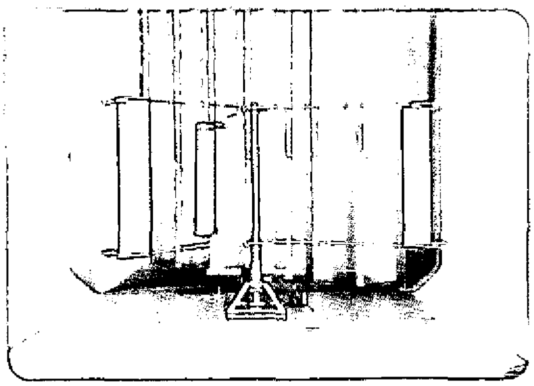
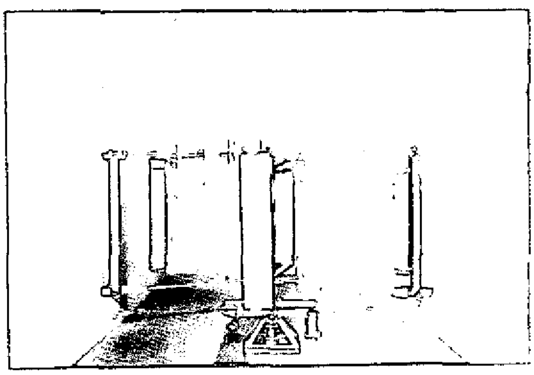


Figure - 6: Model of Kobold turbine in the wind-tunnel of the Department of Aeronautical Engineering of University of Naples (3 blades, up; 6 blades, down)



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.

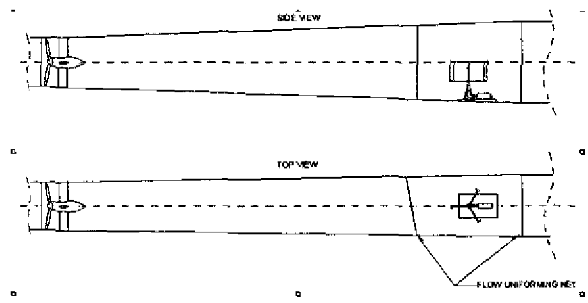


Figure - 7: Wind Tunnel tests arrangement

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).

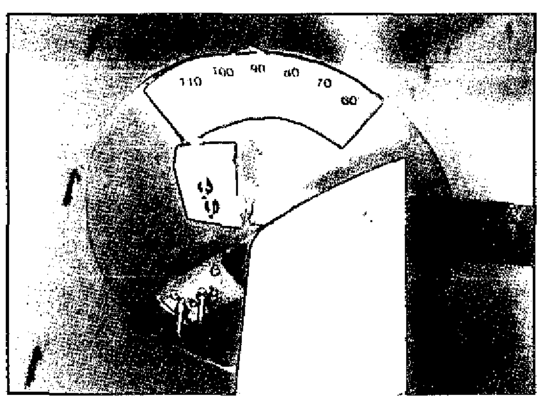
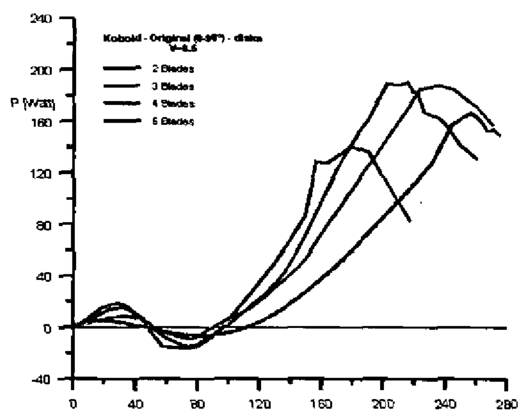


Figure - 8: Details of the blade tip with counterweight. Arrangements to optimize blade pitch angle

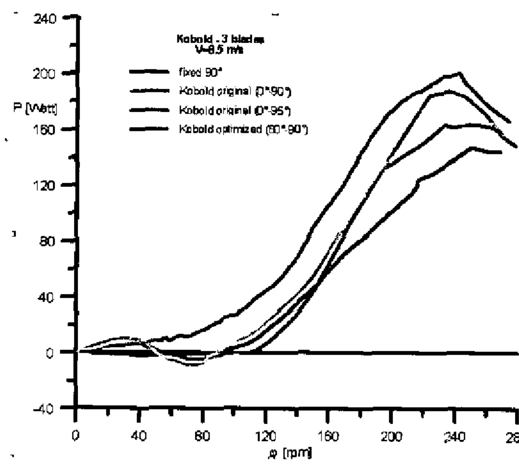
In the following graphs a significant summary of the experiments is reported in Graph - 1 it can also be seen the effect of blades number on produced rotor gross power. This graph clearly shows why a 3-blade configuration was chosen for the real prototype (in fact the maximum rotor gross power is the 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.

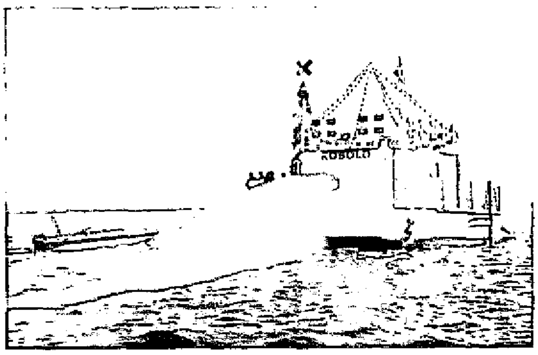


Figure - 9: The Kobold turbine in the Strait of Messina

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

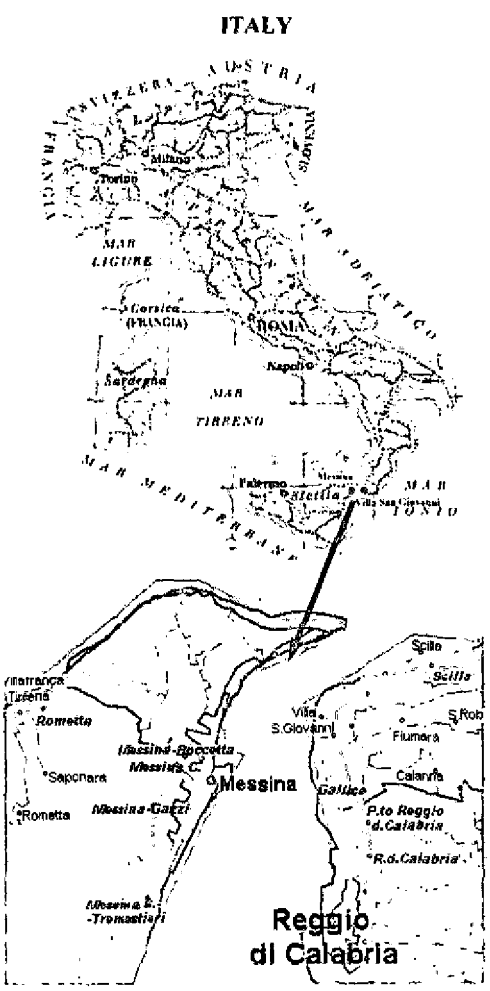


Figure - 10: The location of the Kobold prototype

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.

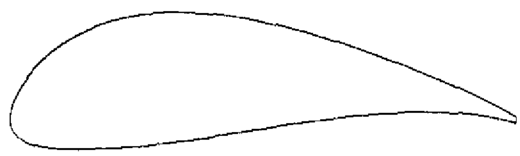


Figure - 11: HILIFT 18 profile

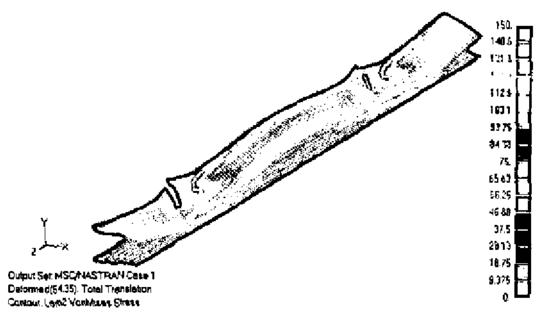


Figure - 12: Blade stresses

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

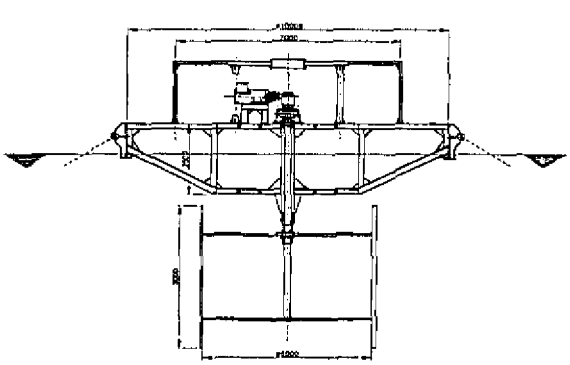


Figure - 13: The ENERMAR system

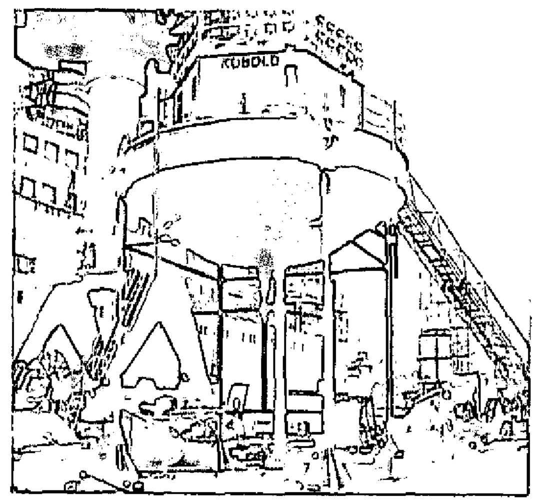


Figure - 14:- The ENERMAR system on the dock

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:

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

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

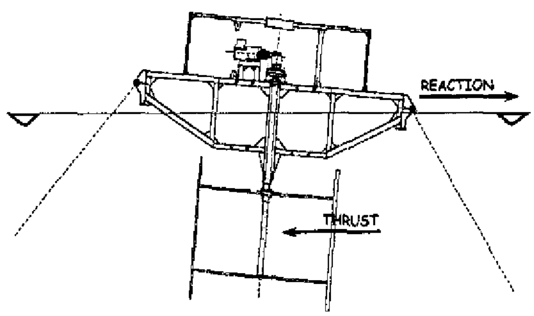


Figure - 15: Trimming moment in working conditions

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.

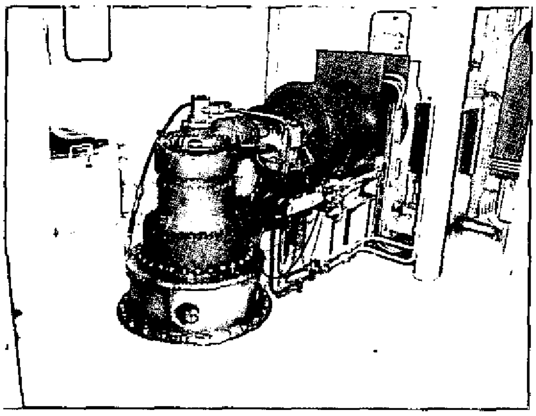


Figure - 16: Machinery room - Generator and gearbox

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:

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

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.

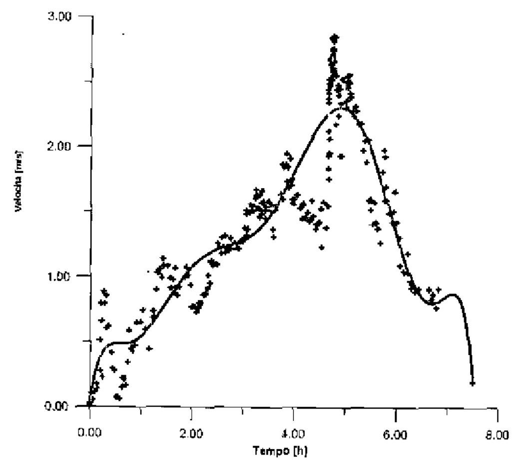


Figure - 17: Current velocity in the Strait of Messina

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 sailor*men 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

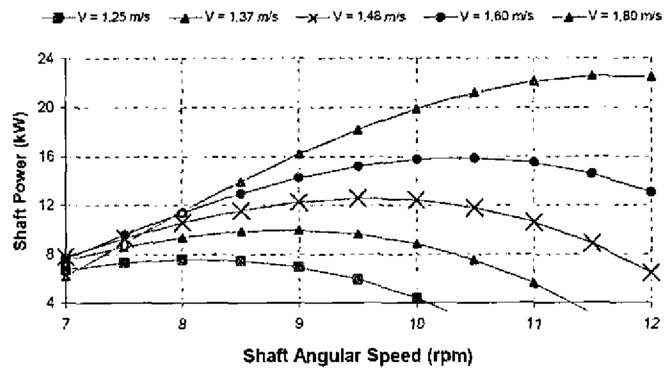


Figure - 18: Kobold power output

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.

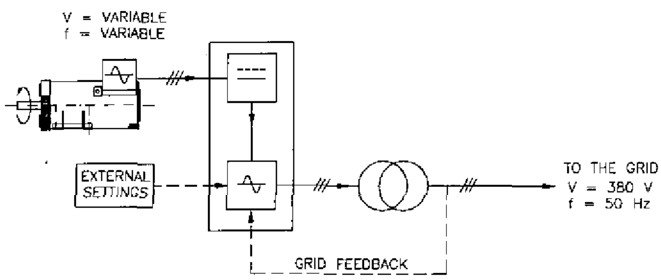


Figure - 19: Main scheme of the electric part

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.*

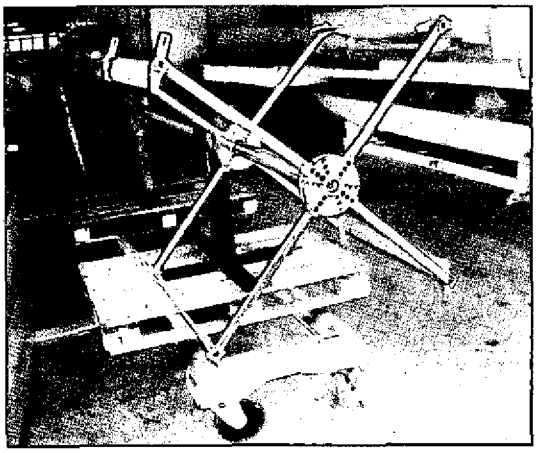
The visual impact of the plant is very low and, in case of plant removal, the works for the site reclamation are of a small amount: there are no permanent structures on the seabed and the bigger components, the mooring blocks, are easily removable using a normal crane.

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.



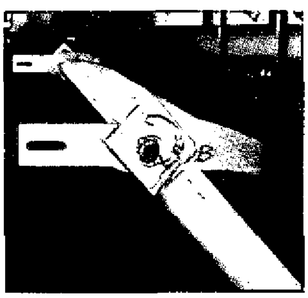


Figure - 20: Kobold model at INSEAN

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.

Abstract: A theoretical and computational methodology to study vertical-axis turbine hydrodynamics

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INSEAN - The Italian Ship Model Basin (Italy)

ABSTRACT

The current energy demand and its dramatic rate of growth related to the impact of developing countries, clearly indicate the necessity to consider renewable energy as a primary mean to alleviate the needs of a large number of communities all over the world.
Among renewable energies, marine currents represent a relatively new and almost unexploited source with a worldwide diffusion of potentially highly-productive sites. Recent research on both horizontal-axis and vertical-axis hydroturbines have demonstrated the feasibility and advantages of power generation plants based on those concepts.

Scope of the present work is to address the hydrodynamics of a power generation plant based on the Kobold turbine concept. This term denotes a vertical-axis multi-bladed rotor that is fully submerged below a floating platform moored to the sea bed. The blades have a rectangular, high-span planform and are free to oscillate around a spanwise axis (variable-pitch mode).
A research activity aiming to develop computational tools to predict the hydrodynamic performance of a 'Kobold' turbine is under progress at INSEAN, in the framework of a collaboration with Ponte di Archimede S.p.A., the Italian company that develops this particular hydroturbine concept.

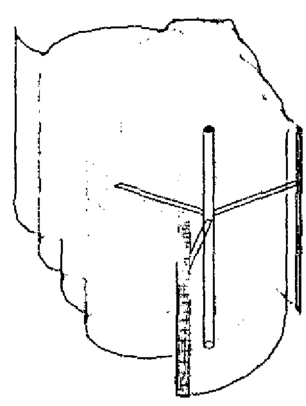
In order to provide a realistic model of the turbine flow under operating conditions, a very general hydrodynamic model is proposed. This is a distinguishing feature of the present work, in that classical hydrodynamic tools used to estimate the performance of vertical-axis hydroturbines are typically limited to simplified models as blade-element theory and isolated vortex methods (see, e.g., Pawsey, 2002). Two major

aspects affecting the turbine hydrodynamic performance are deeply investigated here. One aspect is related to predicting the blade kinematics in the variable-pitch operating mode. The second aspect addresses the interactions among the turbine blades and the effect on the performance of blade-generated wakes approaching and impinging on the blade surfaces.

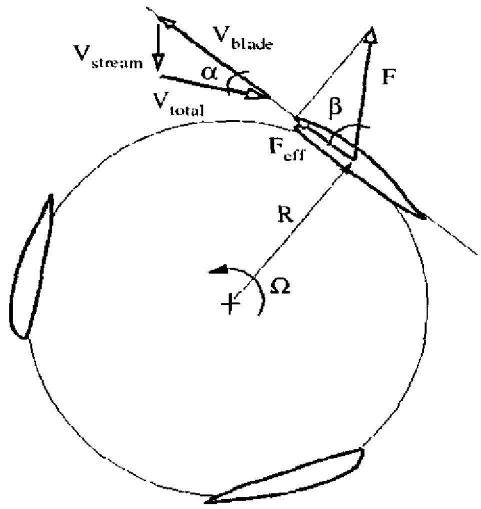
In order to focus on these two aspects, two theoretical models are separately developed and then integrated.
First, a blade dynamics model is used to determine the blade pitch angle as a result of the hydrodynamic forces acting on the blades during a turbine revolution. A simplified quasi-steady hydrodynamics approximation is used in which lift, drag and moment of a isolated blade in uniform translation at given angle of attack are prescribed. Blade pitch angle variations along a turbine revolution are then obtained by studying the response of an equivalent mass-spring-damper model.
In parallel to this, a general unsteady hydrodynamic model of a multi-bladed rotor assembly with prescribed blade pitch is developed. By combining the blade dynamics model and the turbine unsteady hydrodynamic model, an integrated performance prediction tool for variable-pitch operating turbines can be derived.
Both quasi-steady and full three-dimensional unsteady hydrodynamic models are based on a boundary element formulation that is valid for potential flows (see, e.g., Greco et al., 2004, addressing marine propeller hydrodynamics). Vorticity shed by the blades and associated to hydrodynamic force generation is described through a suitable trailing wake model. In the case of multi-bladed turbine studies, the trailing wake model allows to account for trailing-vorticity/blade-surface interactions. Viscous-flow contributions to turbine torque and power are estimated through equivalent flat-plate approach to evaluate the friction drag on the surface of the blades.

In order to assess the proposed methodology, the present research also includes an experimental activity aiming to provide benchmark validation data. Specifically, model hydroturbine tests at the INSEAN towing tank facility are planned to characterize the turbine working conditions (rotation speed, torque, power) over a wide range of variation of the simulated current speed. A detailed review on this experimental activity is presented by Calcagno et al. (2006).

Three-bladed Kobold turbine:
Three-dimensional view of computational grid on blade surfaces (in red) and trailing wakes (in cyan).



In the final paper, numerical predictions of the performance of a real-shape hydroturbine will be presented and compared with experimental data from towing tank tests.



Description of the turbine kinematics and hydrodynamic forces in a horizontal plane.

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Calcagno, G., Salvatore, F., Greco, L., Moroso, A., Eriksson, H. (2006), `*Experimental and Numerical investigation of an Innovative Technology for Marine Current Exploitation: the Kobold Turbine*,'submitted to the 2006 Conference of the International Society of Offshore and Polar Engineers (ISOPE).

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Experimental and Numerical investigation of an Innovative Technology for Marine Current Exploitation: the Kobold Turbine

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ABSTRACT

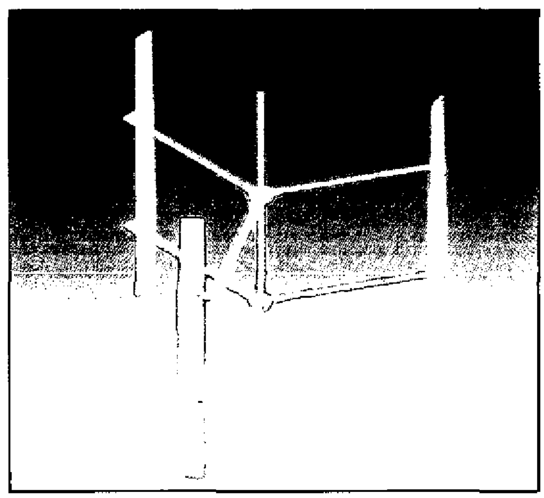
Marine currents represent large renewable energy resources and have the potential to give a significant contribution to fulfill the worldwide energy demand.
The possibility to extract power from both air and water currents is well known to the human beings since thousands of years, and modern technology makes the exploitation of this type of renewable energy more and more reliable, safe and cost-effective. An innovative technology for marine current exploitation based on the Kobold turbine concept is addressed here. Basically the Kobold Turbine is a vertical-axis multi-bladed rotor that is fully submerged under a floating moored buoy and which is subject to an incoming flow originated by a tidal sea current. This kind of turbine has several advantages compared to the horizontal axis ones: designing and building simplicity, sense of rotation independent from the current direction, a very high starting torque and a high efficiency. A prototype has been realized and it is now successfully operating in the Messina Strait in Italy since 2001, producing, for the first time in the whole world, electricity from marine currents delivered to a local electricity grid.

In this paper we describe the activity in the framework of a research project. Aims of the project are to achieve a better understanding of hydrodynamics aspects involved in the Kobold turbine operation and to develop prediction tools to assist design of high-performance Kobold turbines. The primary role of hydrodynamics studies stems from the fact that the successful design of a Kobold power generation plant is necessarily related to maximizing the energy transfer from water to the shaft through the turbine blades. In

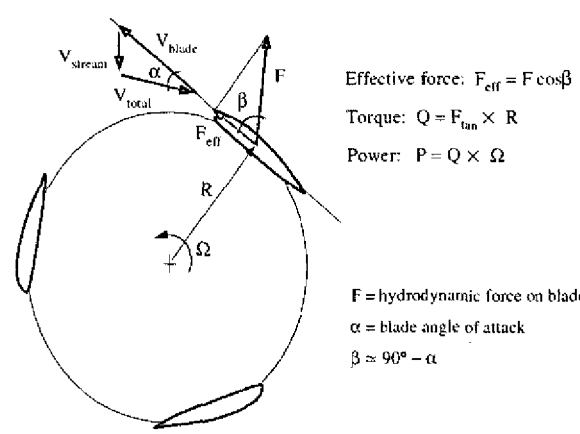
the present work, both experimental techniques and theoretical/computational models have been used to address such aspects.

In order to determine strategies to optimise the turbine's design we have tested different models of Kobold turbine at the INSEAN towing tank, simulating the marine current with the turbine towed by the carriage. Measuring torque and angular velocity for each current speed and for different number of blades, we have defined the overall hydrodynamic performances in terms of the delivered power on the shaft. These experimental results on the model have been compared with data available for the full scale prototype recorded along its operational life on the sea-site.

From a theoretical and computational perspective, a fully three-dimensional unsteady hydrodynamic model has been developed based on a Boundary Element Method. This methodology allows to include in the performance analysis the unsteady effects of the vortical wake shed by each turbine blade and to understand the influence of the blade-wake interaction on the torque generated by the turbine.
The theoretical model has been implemented into a hydrodynamic performance prediction software that has a low computational cost and thus represents a practical design-oriented tool. As a matter of fact one of the major problems with such a kind of turbine is that it has to be site-tailored according to the different marine current conditions which, albeit largely available worldwide in coastal regions, can greatly differ both in intensity and in time duration from one site to another one.
In the final paper, the experimental methodologies as well as the theoretical models used in the project will be described. Turbine performance measurements from towing tank tests will be analysed. Next, numerical predictions by the proposed computational tool will be presented and validated through comparisons with experimental data.



Sketch of a three-bladed Kobold turbine



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.

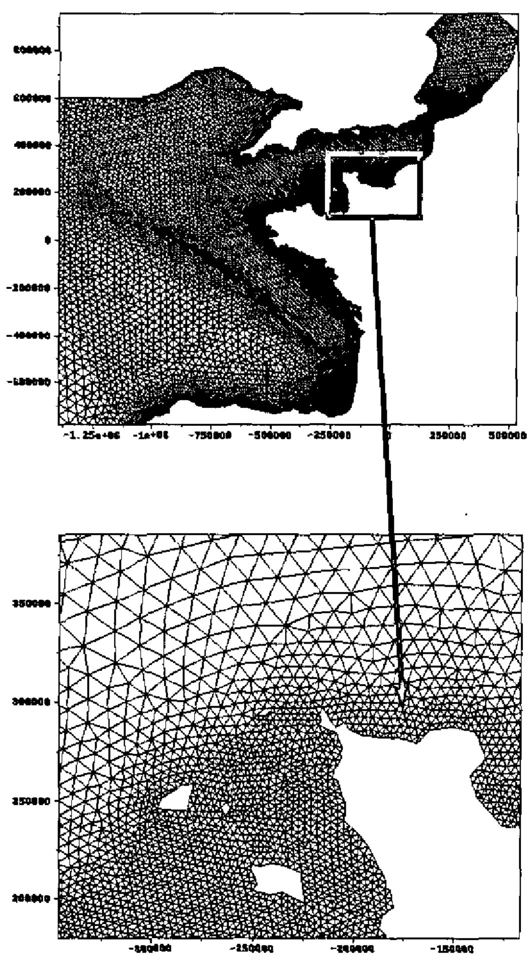
2 - FRENCH "MARINE CURRENT ENERGY RESOURCES" ANALISYS

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.



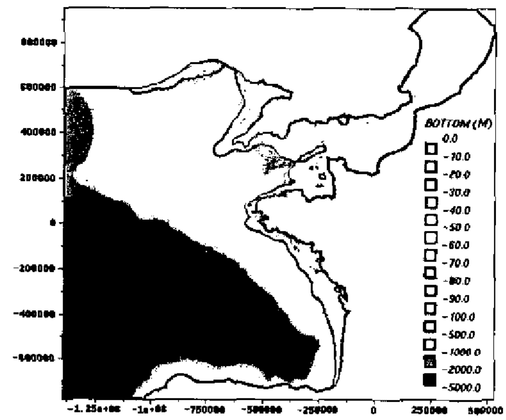


Figure 1 - Bathymetry (right) and mesh of the North Sea, Channel and Atlantic Ocean "*Large TELEMAC Model*" (up)

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.

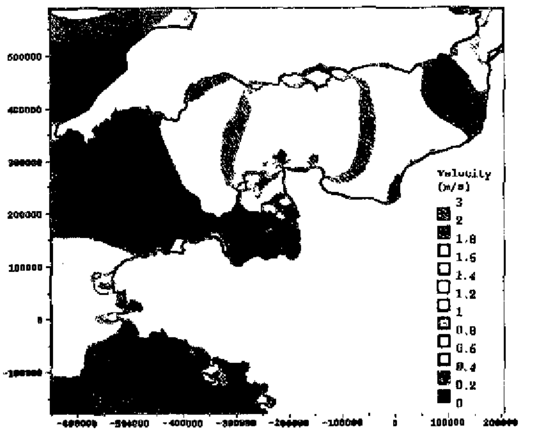


Figure 2 - Instantaneous velocity along the French coast, obtained with the Telemac-2d large model.

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 :

- *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).

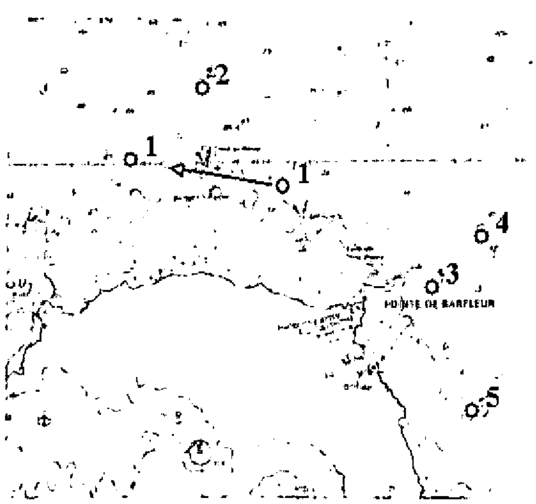


Figure - 3 a: Location of the devices during the Normandy measurements in January 2005. The modification of the point 1 illustrates the "consultation process" with local fishermen.

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.

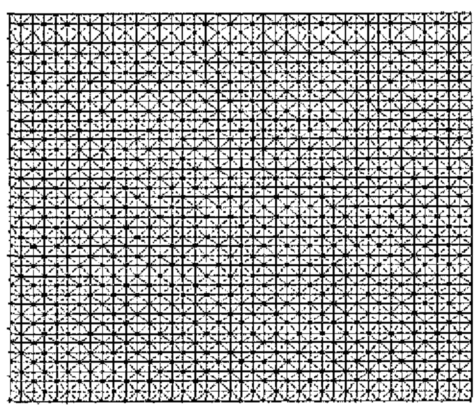
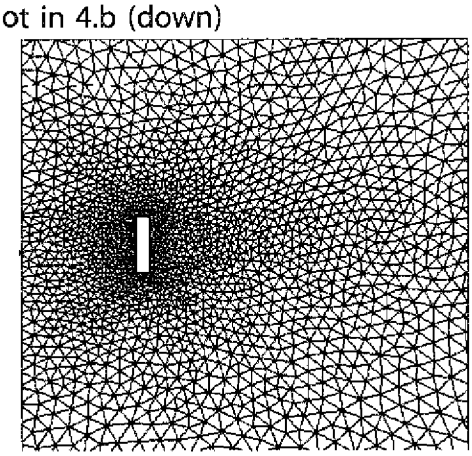


Figure - 4: Two finite elements meshes used to computed the velocity field in the vicinity of a square structure. In 4.a (up), the structure is meshed, while it is not in 4.b (down)



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.

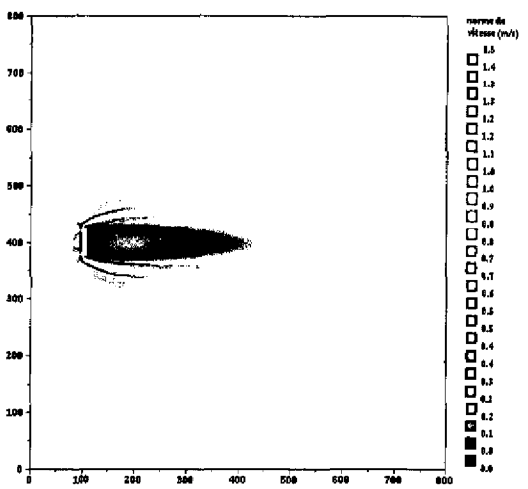
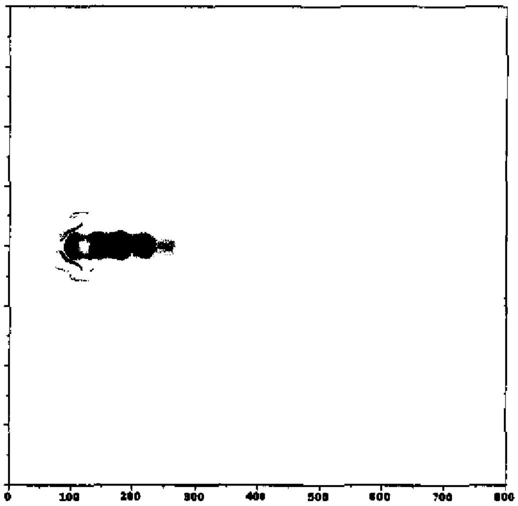


Figure - 5: Finite elements computation of depth-averaged velocities behind a square structure, using both meshes presented in figure 1. Comparison between the case of a meshed structure (5.a, up) and the method consisting of the additional shear term appearing in equation (1) (5.b, down).



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.

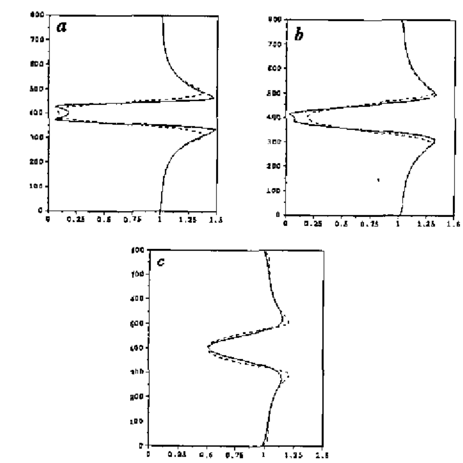


Figure - 6: Velocity profiles obtained from the 2-D computation presented in figures 1 and 2, at 150 m (a), 300 m (b) and 600 m (c) downstream. Comparison between the case with a meshed structure (solid lines) and the case with an additional shear force (dotted lines).

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.

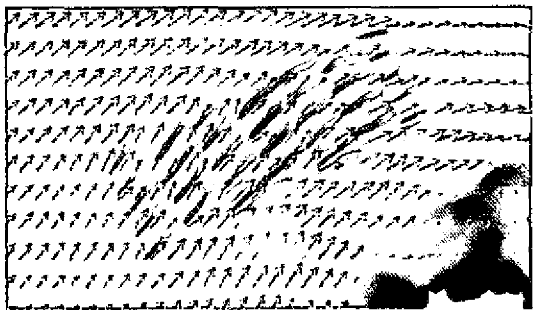


Figure - 7: Depth-averaged velocity field during flood in a potential area for marine current turbines, simulated with the telemac-2d code. The wake effects are considered through equation (1).

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.*

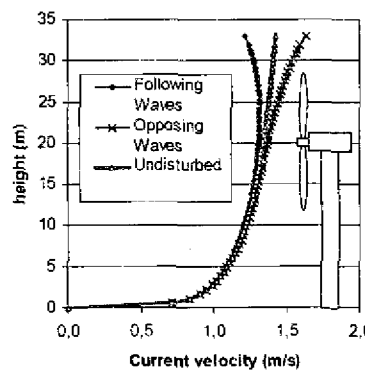


Figure - 8 : simplified modeling of the velocity vertical profile

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 structure. 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

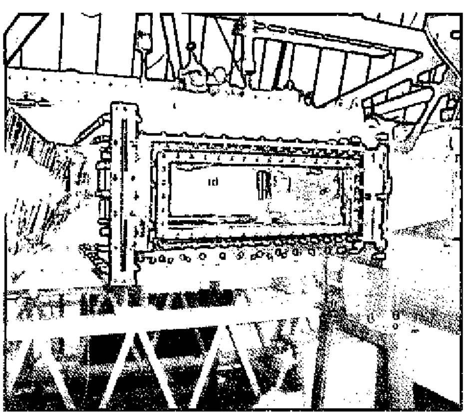


Figure - 9 : Photo of the tunnel

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.**

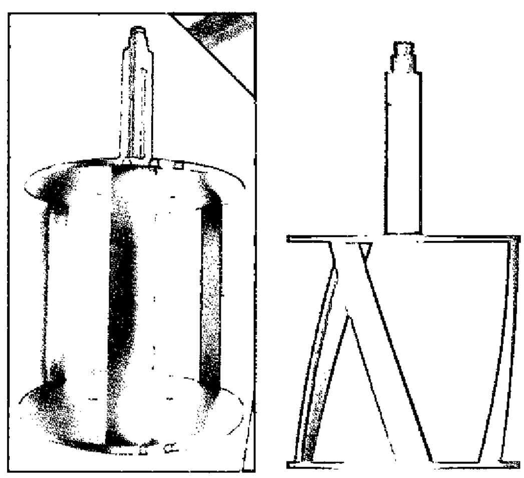
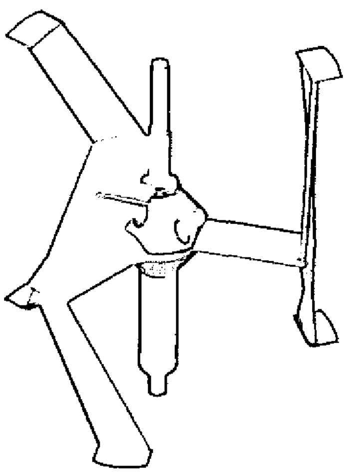


Figure - 10 : Photo of Darrieus turbine (left) and drawings of Gorlov (right) and

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.*

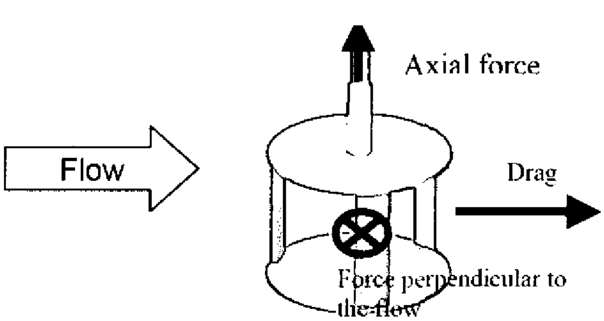


Figure - 10: Schema of the measured forces

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

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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).

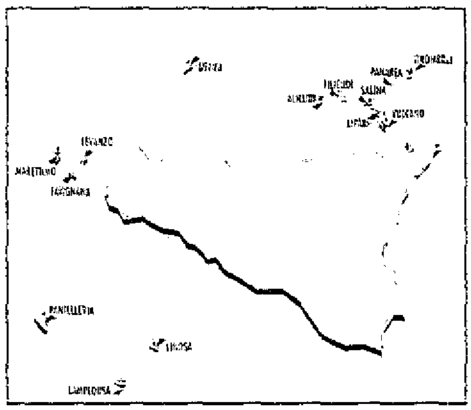

Figure - 1: Sicilian islands layout

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.

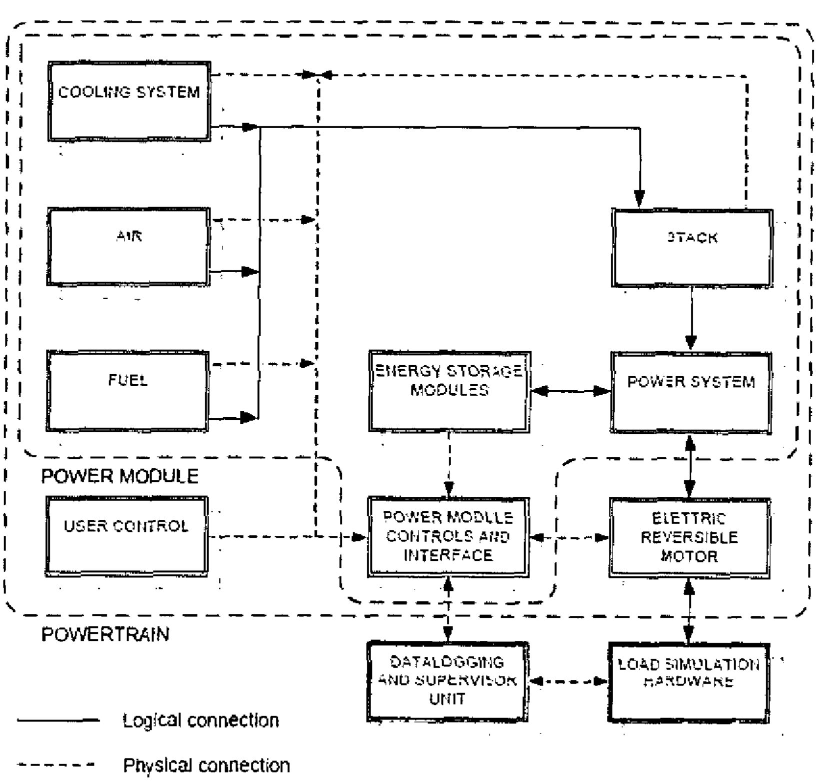

Figure - 2 : General scheme of the powertrain

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).

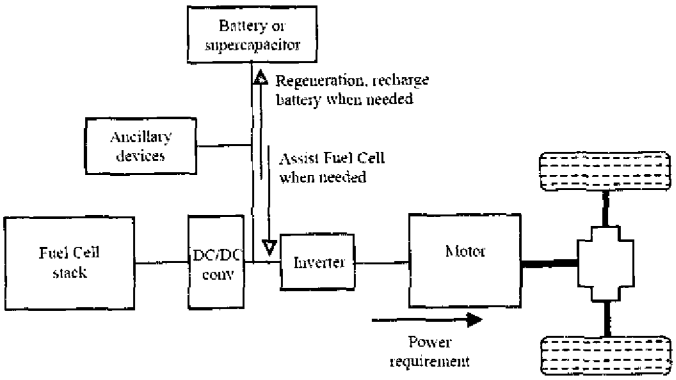

Figure - 3: Fuel cell parallel hybrid power train configuration

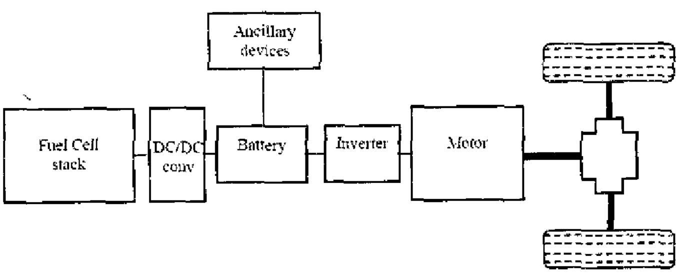

Figure - 4: Fuel cell series hybrid power train configuration

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.

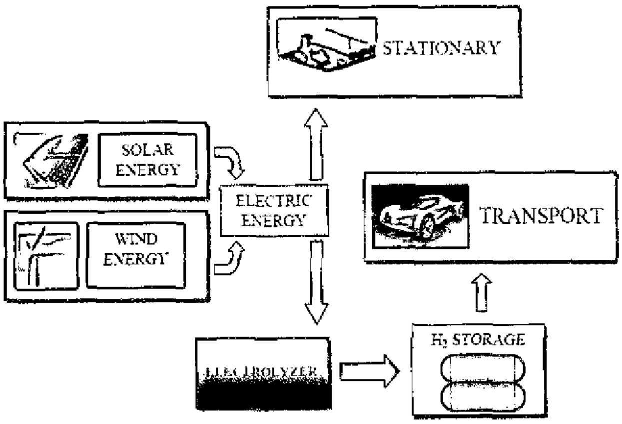

Figure - 5: General scheme of the envisaged system

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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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

V.05-87071—August 2005

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