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Name of the scientific representative of the project's co-ordinator

Name: Mr Domenico Serpella

Organisation: Labor Srl

Tel: +39 06 40040354

Fax: +39 06 40040357

E-mail: d.serpella@labor-roma.it

Project website address: **www.seakers.eu**

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Summary

1. Executive summary

SEAKERS originates from a joint initiative of top level SMEs and players of the marine yachting sector, aiming at introducing a high impact potential innovation, which it is expected to provide a valuable market and economic return.

SEAKERS intended to develop an innovative device, both in is concept and in its functions, consisting in a K**inetic Energy Recovery System (KERS) for sailing boats, exploiting undesired boat body movements caused by the sea**, in order to produce free electricity through a linear magnetic generator oscillating on a stator fixed to the boat, used to charge batteries.

The results produced by project consist in:

1. A numeric computational **design tool** which will allow to calculate design characteristics of SEAKERS and expected performance in dependence of different forcing conditions
2. SEAKERS **executive design**, including:
    - design of the linear electromagnetic generator
    - power conditioning stage and control system
    - mechanical design of the SEAKERS envelope
    - selection of materials, BOM of components
3. **Prototype** of the SEAKERS, including the architecture of the electro-magnetic core of the generator: a **linear MFSPM (Magnetic Flux Permanent Magnet Machine**), which allows the use of the typical cogging force of this architecture to suspend the mass without any additional mechanical devices (springs), therefore maximizing the available stroke. Since the working principle of the SEAKERS generator implies that the magnetic machine has to act as an electric motor several times during a period of operation, both for optimising the energy recovery, given an almost arbitrary forcing by the waves, and to release the engagement of the moving part with the magneto-static field due to the permanent magnets, the generator is designed to work also as a motor section, to unlock the slider from top and bottom dead centres and restart the energy recovery. The prototype includes the electronic, software and mechanical design of the SEAKERS system, for the complete assembly, including battery, energy converting units, sensors and control electronics, making SEAKERS prototype easy to install and startup.
4. Automated **test-bed**, able to perform testing o the device, simulating an adequate range of sea wave conditions.

Measured generator conversion efficiency during testing summed to about 50%, but there are several areas for straightforward improvement, which allow to estimate that overall generator conversion efficiency can raise up to > 80%, by means of engineering, consolidated solutions.

2. Project context and the main objectives

Sailing boats have been always considered as an ideal application for using Renewable Energy Sources as a mean of electricity production. The main reason is that during long sailing trip it is necessary to recharge the on-board battery, which is used for navigation, emergency and other equipment.

The recharge process is usually achieved by a fossil fuel generator, with several drawbacks.

1. Fossil fuel is not renewable (amount of fuel limits the autonomy of the boat).
2. Generators are noisy, thereby disrupting the sailing experience
3. Engines are started with batteries. If they are drained for whatever reason, the boat has to be taken ashore to recharge them, without electrical equipment.

There exist on the market various components based on Renewable Energy Sources (RES) and their market is expanding, however they present non negligible limits and drawbacks.

- Water turbines: a submersible propeller is dragged by the boat in water and is attached to an alternator. They are the simplest and most reliable design, but also the least efficient; furthermore they subtract power available for cruising, their operating speed is limited, and do not generate when the boat is anchored
- Wind turbine: they are installed on the main deck, and generate power with the available apparent wind speed. Their main problem is that they usually generate maximum power at wind speeds which are excessive for cruising, and their output decreases rapidly with wind speed reduction.
- Solar photovoltaic: solar PV panels have a few advantages over competitors, like reduced maintenance and produce electricity without wind and in case of a still yacht, but there are also problems to be addressed like their fragility, placement (to avoid sails shading over panels), and large area on the deck.

SEAKERS is therefore addressing a known unsatisfied requirement of yacht owners: green energy without visually and spatially intrusive components, providing an advantage over the competing technologies.

SeaKERS is an innovative solution for generating electricity on boats by recovering the inertial energy created by pitching, the longitudinal movement of the boat caused by waves. This solution is indeeed a **Kinetic Energy Recovery System (KERS) for the yachting sector**, able to generate a surplus of clean, free energy for recharging batteries when under way. Unlike other on board generators, SeaKERS recovers energy that is completely free and eco-friendly, and what's more its operation does not affect the performance of the boat.

SEAKERS intended to develop a kinetic energy recovery system targeted at the installation onboard of sailing boats and yachts, which act as an inertial absorber, recovering as much kinetic energy as possible from the natural movements of a boat (typically a sailing one) on the sea; such a movement can be ideally split as follows:

- vertical oscillations due to the **buoyancy** of the boat in the presence of sea waves, both when the boat is still or sailing
- **rolling** and **pitching** movements of the boat originated both by sailing in wavy waters (going up and down over the surface of the waves) and by the normal boat dynamics due to the sails propulsion

SEAKERS introduces the innovation of looking at a sailing boat as a moving wave energy converter with energy harvesting capacity The concept proposed is truly innovative; nothing similar has been found though a worldwide patent search, a search in databases of scientific publications and on the Internet.

It is essential to stress out that the energy involved in the phenomenon described is true free energy; it does not originate from the propulsion of the boat, due to the sails or to the propeller, but it originates from sea conditions. This is a very distinctive and unique feature; in fact, as a comparison, existing competing solutions are:

- small sea turbines dragged by the boat, which extract energy from the forward movement: although this is a very interesting application, since it produces electricity thanks to a very efficient linear wind converter (the sails), the energy recovered is subtracted to the boat, therefore it is not a genuine recovery.
- micro wind generator on a boat is moved by the so called apparent wind, which is the wind experienced by an observer in motion and is the relative velocity of the wind in relation to the observer; it results that a major part of the energy generated by a wind generator on a boat while sailing is subtracted to the lift of the sails; in addition, relevant sizes of the wind generator are necessary to achieve an appreciable power output; they also generate noise at annoying high frequencies.

The technical and scientific objectives of SEAKERS are:

1. Development of a numerical **model of the system**, composed of:
   a. Mechanical modelling
   b. Electrodynamical modelling (power conditioning, in dependence of the known electric characteristic of the linear generator)
   c. Control (real time adaptive matching with sea conditions, driving of power conditioning stage)

d. Modelling of forcing oscillations due to the sea

e. Dynamic effects on the boat generated by the inertial dumping effect of the SEAKERS

The model is an essential part of the project; SEAKERS is a novel concept, susceptible of being applied and integrated in several ways inside the boat and expected to operate in various sea conditions; a tool able to support boat designers to make the right choice is indispensable. The simulation tool is needed to search for optimum configuration and to simulate the SEAKERS behaviour in correspondence of different boundary conditions and configurations and in dependence of different size, weight and operational constraints; the spectrum of forcing frequencies in different sea and sailing conditions.

2. Implementation of a **linear MFSPM (Magnetic Flux Permanent Magnet Machine**), which allows the use of the typical cogging force of this architecture to suspend the mass without any additional mechanical devices (springs), therefore maximizing the available stroke. Since the working principle of the SEAKERS generator implies that the magnetic machine has to act as an electric motor several times during a period of operation, both for optimising the energy recovery, given an almost arbitrary forcing by the waves, and to release the engagement of the moving part with the magneto-static field due to the permanent magnets, the generator is designed to work also as a motor section, to unlock the slider from top and bottom dead centres and restart the energy recovery.

3. **Power conditioning stage** – the linear generator delivers irregular and fluctuating voltage which will have to be rectified and stabilised before being delivered to the load; in addiction, the dumping factor of the SEAKERS is to be modulated by changing the electrodynamical characteristics of the generator by means of the power conditioning stage; the electrical power generated will be varied in real time, thus changing the resistance of the moving piston inside the generator

4. **Mechanical design**, aimed at the best trade-off between life, robustness, cost-effectiveness, maintenance requirements

5. **Adaptive control system** – the power conditioning stage will be driven by a real time control system, to perform the variation of impedance described in point 3; it will have the aim to maximise energy extraction, modulating the operation of the linear generator in accordance with the forcing conditions imposed by the sea; the control system will be adaptive, i.e. it will estimate the specific conditions in which the system is operating, considering the data gathered during a previous timeframe

6. **SEAKERS integration concepts** – SEAKERS is a novel concept which is susceptible of being integrated and installed inside a boat in several ways; a first option is retrofit/first equipment; the point where SEAKERS can be installed provides several options, involving

different degrees of revision of the boat design; for instance, in a future embodiment, it could potentially be integrated inside the bulbs which has usually a weight in the order of tons; in any case, the point of integration always involves the availability of adequate fixing structures, which have to be calculated and implemented.

7. **Testing and validation** – a test bed was meant to be developed and produced in the project; it will submit the prototypes to variable forcing oscillations, associated to different sea conditions; in this way a wide amount of data will be gathered, overcoming obvious limitations of performing test in real conditions inside a boat; the test bed will be also a valuable equipment which will remain available to the beneficiaries after the project.

The main result expected from the project for exploitation were:

1. **simulation tool for the evaluation of the boat motion and of the electromagnetic response of the generator**
2. **Design and implementation of the SEAKERS generator, electronic and software control, case and integration.**
3. **Design and implementation of a test bed for the realisation of forced vertical oscillation tests**
4. **Testing of the SEAKERS device and evaluation of results**

The specifications for the SeaKERS device, defined to allow the onboard integration were:

- SP1 **Typology of linear generator**: flux-switching permanent magnet linear generator
- SP2 **Modularity**: The best option is to design the system in a modular way, in order to produce a lightweight module that can be integrated in different sizes for the different applications options and/or distributed in different parts of the boat to exploit different movements and to avoid concentrated weight.
- SP3 **Max Weight**: The target weight for the single module is < 60 kg, that could be a weight acceptable also for 40'' boats.
- SP4 **Rated Power**: The target power for this single module is 50 W at normalised wave conditions
- SP5 **Max height**: 1 meter total size (including the springs and the case)
- SP6 **Max width**: 60 cm for flat configuration
- SP7 **Benchmark cost**: benchmark for the SEAKERS can be considered to be other kinds of renewable generators for on-board integration (i.e. PV and wind). Cost of such solutions can be considered as reference, when normalised for the energy produced in average conditions, being the power size indicative only in relation to certain generation conditions.
- SP8 **Reference wave conditions**: height = 1 m; period = 4.5 – 7.5 s (0.13 – 0.22 Hz)

3. Main S & T results/foregrounds

3.1. Simulation model

A computational model allowing to calculate design characteristics and expected performance of Seakers in different conditions.

The model includes:

1. A **kinematic and mechanic models** that have been used to set up the most relevant physical parameters for the SEAKERS device. The yacht's vertical motions are then used as input in the mechanical model that describes the linear generator's behavior. In this result, the basic equations of motion for a boat were derived and the model realized by the use of the commercial software package Seakeeper that has been used to carry out the computation of the yacht's motions under different wave conditions.
2. A **numerical electromagnetic model of a permanent magnets linear generator**, composed of a linear stator and an oscillating mass, to simulate and study the complete model to estimate the dynamic behaviour of the forces exchanged between the stator and the oscillating mass, as a result of both electromagnetic and dynamic phenomena b) the energy produced at varying forcing values; c) the influence of different system configurations for the mechanical suspension

3.1.1. Kinematic model

The main purpose of the kinematic model is to provide reasonable data about the response of a generic yacht to different sea conditions, in order to have reliable information on the motion which the SEAKERS device is subjected to. Since the project does not address a particular yacht model, nor even a specific size of boat, there was no point in developing a focused in-house software: hence the choice of adopting a commercial software that has a proven record of reliability, using it to simulate the response of a yacht of adequate length included in the extensive library provided. For this reason the commercial software package Seakeeper[1] was used.

The yacht's model used in the numerical simulations is one of the library models that can be found in Seakeeper's library, since it has geometric and mass properties comparable to those of commercial sail yachts of interest for the SEAKERS project. The most relevant hydrostatic properties of this yacht are given in table 1, while the linear generators' position is represented in the figure.

[1] Seakeeper is a software by Formation Design Systems Pty Ltd (trading as FormSys); website: http://www.formsys.com/maxsurf/msproducts/seakeeper.

Property	Value	
Displacement	6.531	t
Volume (displaced)	6.372	t
Overall length	11.5	m
Draft amidships	2.475	m
Immersed depth	3.054	m
Waterline length	10.64	m
Max beam on waterline	2.866	m
Max section area	1.213	m^2
Waterplane area	21.21	m^2
Prismatic coefficient (Cp)	0.494	
Block coefficient (Cb)	0.068	

Table 1: boat characteristics

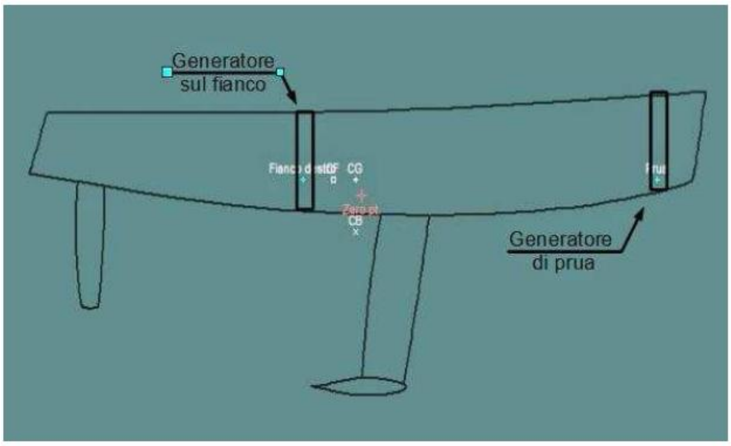


Fig 1: Generators' positions considered in the simulations

Reference wave conditions were chosen (Capo Linaro near Civitavecchia - Italy) and, considering random waves, a particular set of parameters that make the JONSWAP spectrum suitable to represent sea conditions in the location of interest were defined.

The ship's response was calculated by means of Response Amplitude Operators (RAO) and phase shifts, with reference to sinusoidal wave excitation and to random waves, for each motion (heave, pitch and roll) and for different boat's speeds.

3.1.2. Mechanical Model of the Linear Generator

The linear generator that was meant to be used in the SEAKERS device to recover energy from the wave-induced motions of the yacht was first analysed as a simple linear mechanical oscillator where the damping element represents a linear approximation of the effect of the electromagnetic force exerted by the generator as it provides a voltage difference proportional to the square of its relative velocity with respect to its basement, and the spring represents the stiffness of the generator's support.

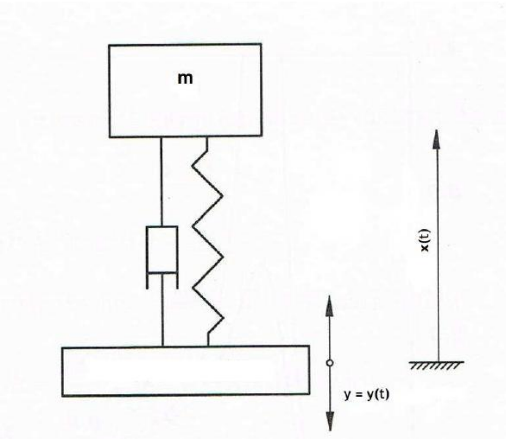


Fig 2: mechanical model used for preliminary simulation of the response of SeaKERS

Simulations were carried out with the kinematic and mechanical models of the yacht's response to different wave excitations (both sinusoidal and random wave have been considered), and of the linear generator taken as a simple mechanical linear system which extracts power from the wave-induced motion by means of an ideal linear damping.
These preliminary evaluations, even though based on a rather simplified model of the generator, has produced some important insights on system dynamics and on the range of values to be1 assigned to several significant parameters, such as mechanical stiffness and damping ratio.
In particular, given the particular range of forcing frequencies, the mechanical stiffness must be chosen so as to obtain a natural frequency within the range of most forcing frequencies, and a value of 0.25Hz has been considered in this document; the resulting stiffness must therefore be around
2.5N~(mkg). As a consequence, it has been pointed out that a simple mechanical spring cannot simultaneously play the static and dynamic roles required by this application.
With this simplified model, power generation of up to 0.85W/kg have been obtained in the most favourable conditions, while values higher than 0.5W/kg are available in most cases, which represent interesting results for this particular application.

3.1.3. Electromagnetic model of a permanent magnets linear generator

The results achieved with regards to the development of the electromagnetic model are

1. development of a numerical electromagnetic model of a permanent magnets linear generator, composed of a linear stator and an oscillating mass
2. coupling the electromagnetic model with equations describing a mechanical suspension of the oscillating mass
3. coupling the electromagnetic model with kinematic equations related to the phenomenon of linear sea wave forced oscillations
4. simulate and study the complete model composed of 1., 2. and 3., in order to estimate:
    a. the dynamic behaviour of the forces exchanged between the stator and the oscillating mass, as a result of both electromagnetic and dynamic phenomena
    b. the energy produced at varying forcing values
    c. the inuence of different system configurations for the mechanical suspension
5. define a control strategy and corresponding control algorithms for optimal energy harvesting, in relation to possible system layouts
6. define optimal system layout with respect to maximum energy harvesting and compatibility with physical constraints, and corresponding control strategies

The model of a linear kinetic energy recovery system and the numerical tools were used to simulate its response to the external forcing of waves. We have shown how to find the profile that the mass should follow during its motion in order to make available for recovery the largest energy possible, given a certain forcing.

An electronic control system has been modelled and tested on a proof-of-concept case. The electric machine on which the recovery system is based has been modelled in 3D. Magneto-static properties have been numerically computed directly on that 3D model. Time dependent simulations have been accomplished on a 2D axial-symmetric model retaining all the features of the parent 3D model.

Simulations where no electronic control is implemented show that in case of low frequency forcing the system can undergo a small-oscillations regime, during which no energy is recovered. That phenomenon can occur irrespective of the closeness of the system to a resonance condition.

Simulations implementing a control on the instantaneous position and motion of the mass show that almost all available energy can in principle be recovered irrespective of the suspension system.

The knowledge acquired on the values of the electromagnetic fields in each domain of the electric machine constitutes a fundamental reference for the sizing of both mechanical and electric components.

Pictures showing some results are here reported.

Fig 3: 3D model of the generator

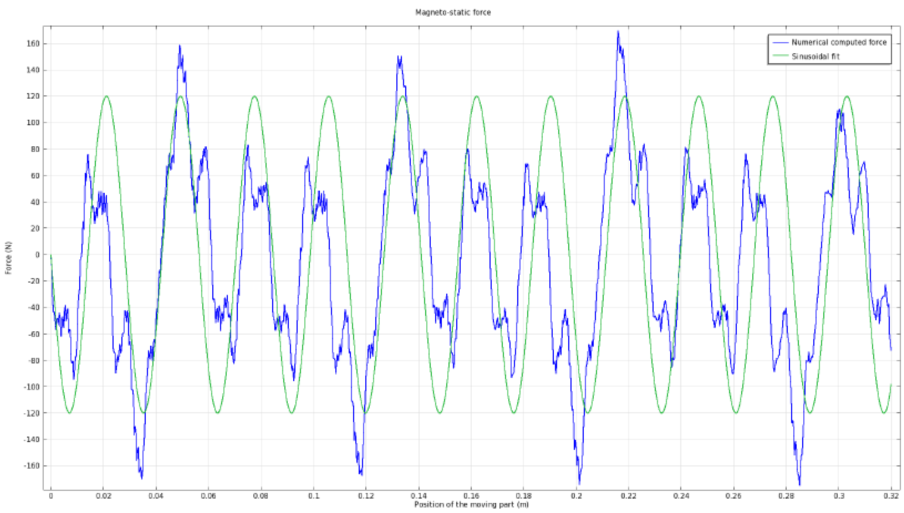


Fig 4: simulation of the magneto-static force acting on the moving part

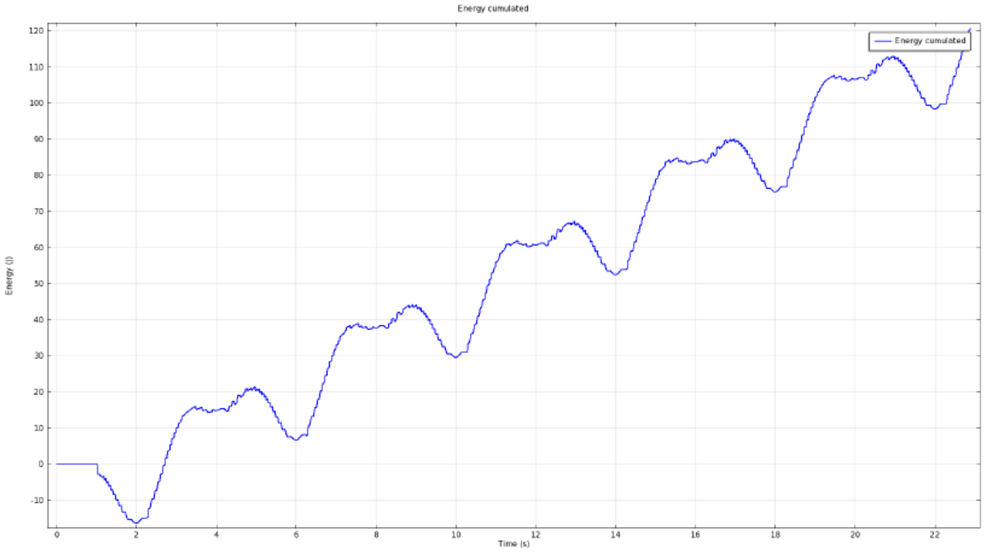


Fig 5: Energy cumulated for ks = 200N/m

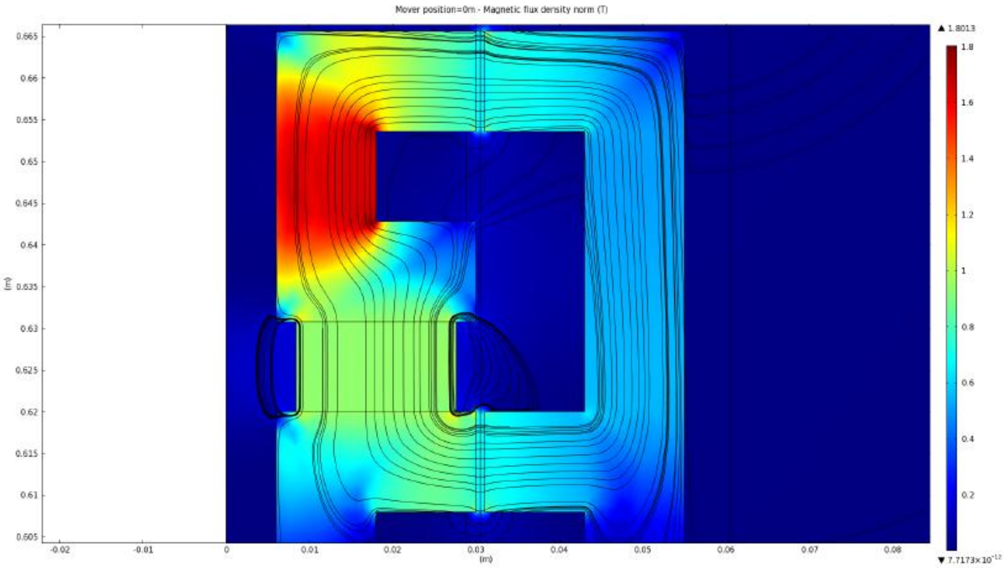


Fig 6: results of electromagnetic simulations of a module of the linear generator

3.2. SeaKERS design

The design of the SeaKERS has been defined and implemented. This includes:

- The architecture of the electro-magnetic core of the generator: a linear MFSPM (Magnetic Flux Permanent Magnet Machine) has been selected and specifically designed. This allows the use of the typical cogging force of this architecture to suspend the mass without any additional mechanical devices (springs), therefore maximizing the available stroke. Since the working principle of the SEAKERS generator implies that the magnetic machine has to act as an electric motor several times during a period of operation, both for optimising the energy recovery, given an almost arbitrary forcing by the waves, and to release the engagement of the moving part with the magneto-static field due to the permanent magnets, the generator is designed to work also as a motor section, to unlock the slider from top and bottom dead centres and restart the energy recovery.
- The Mechanical design of the SEAKERS system has been defined, to allow a thin design of the generator, completely enclosed in a light and waterproof case. Reluctance of the magnetic path has been kept to a minimum with low clearance between stator and slider, through the interposition of a PFTE coating, which is also used as linear bushing. The slider includes also battery, energy converting units, sensors and control electronics, making SEAKERS prototype easy to install and startup.
- The electric and electronic design, including the system architecture and each module:
    - A very high dynamic AC-DC stage, capable of converting very low to high voltage for battery charging has been designed and is used as a system load for recovering energy from the slider, applying a braking force to the mobile mass. It features remote control from the main control system, which is able to switch the unit on or off and set the voltage output to load the battery.
    - forcing and a parking units for slider unlocking (from dead centres) and locking (to avoid battery overcharging).
    - the electronic control system based on a commercially available OEM board has been designed. The system includes front-end to acquire signals and operate the different electric units, an ARM microprocessor, with enough power to perform computation and calculate the optimal recovery trajectory
- Control algorithm and firmware based on a software operating on a customized linux kernel is used for implementing the SEAKERS control system, with the possibility of granting different priorities to processes and threads. Data are acquired from all the available sensors and are used for logging and computation purposes.

In Fig 7 and Fig 8 the stator and the motor modules are shown.

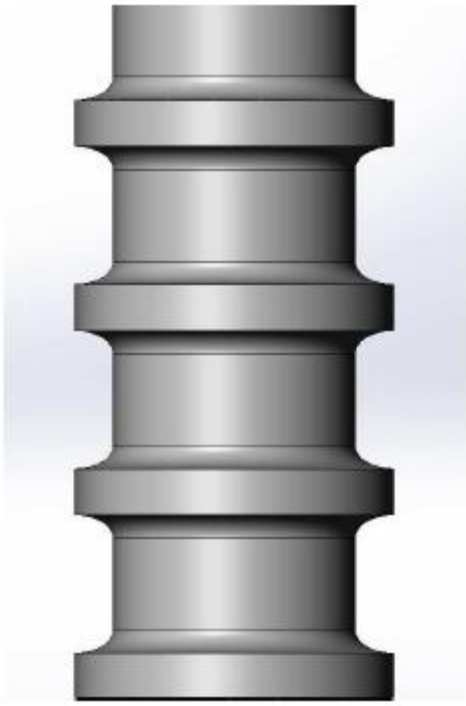


Fig 7: stator of SEAKERS. It does not hold any coil or permanent magnet

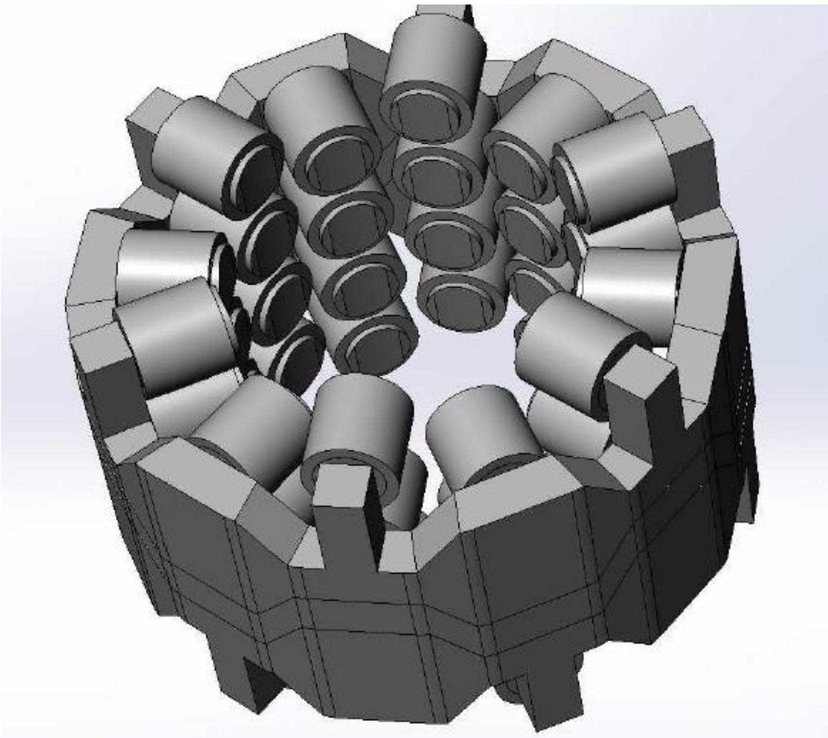


Fig 8: Perspective view of the electric motor module. The pairs of poles and coils are clearly visible

In Fig 9 CAD section of the real stator/cursor joint model is represented.

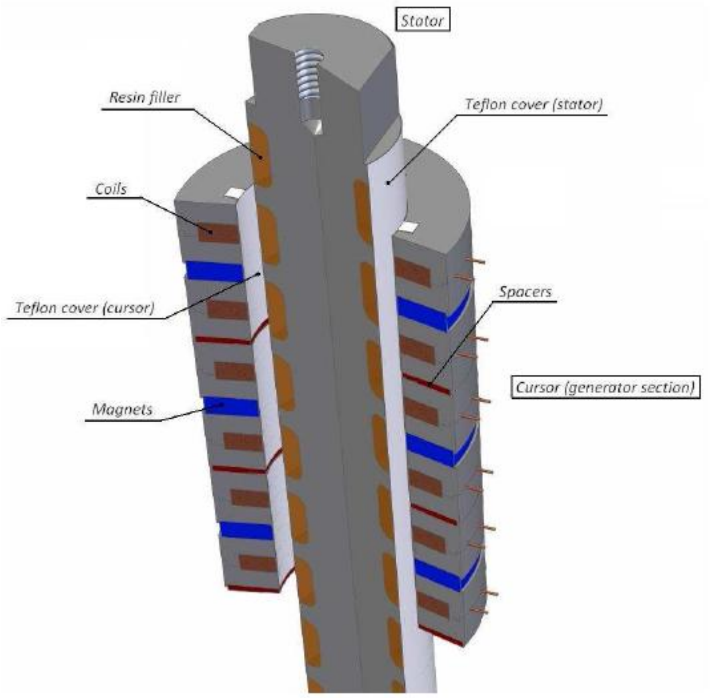


Fig 9: stator/cursor CAD joint model

Fig 10: Stator/Cursor manufacturing

In Fig 11 the design of the assembly of the system and the rendering of the whole device are presented.

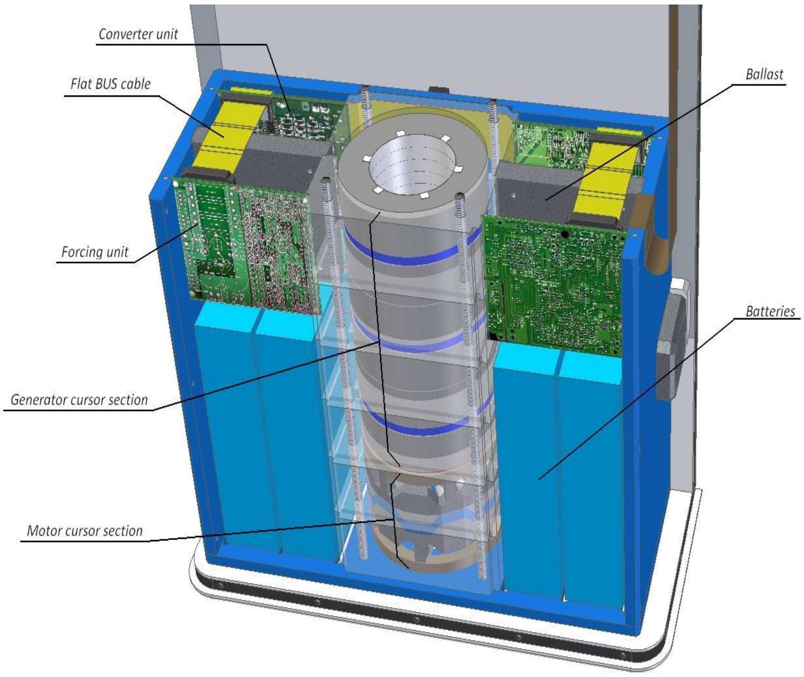


Fig 11 - ***Mobile equipment content detail – rendering of the device***

Concerning the prototype realized, the main features are:

- External dimensions (W x L x H): 360 x 157 x 1108 mm
- Complete weight: 45 kg
- Mobile equipment weight: 19,5 kg
- Mobile equipment stroke: 788 mm

In **Fig 12** the architecture of the system is presented, with indication of the different functional blocks and relationships.

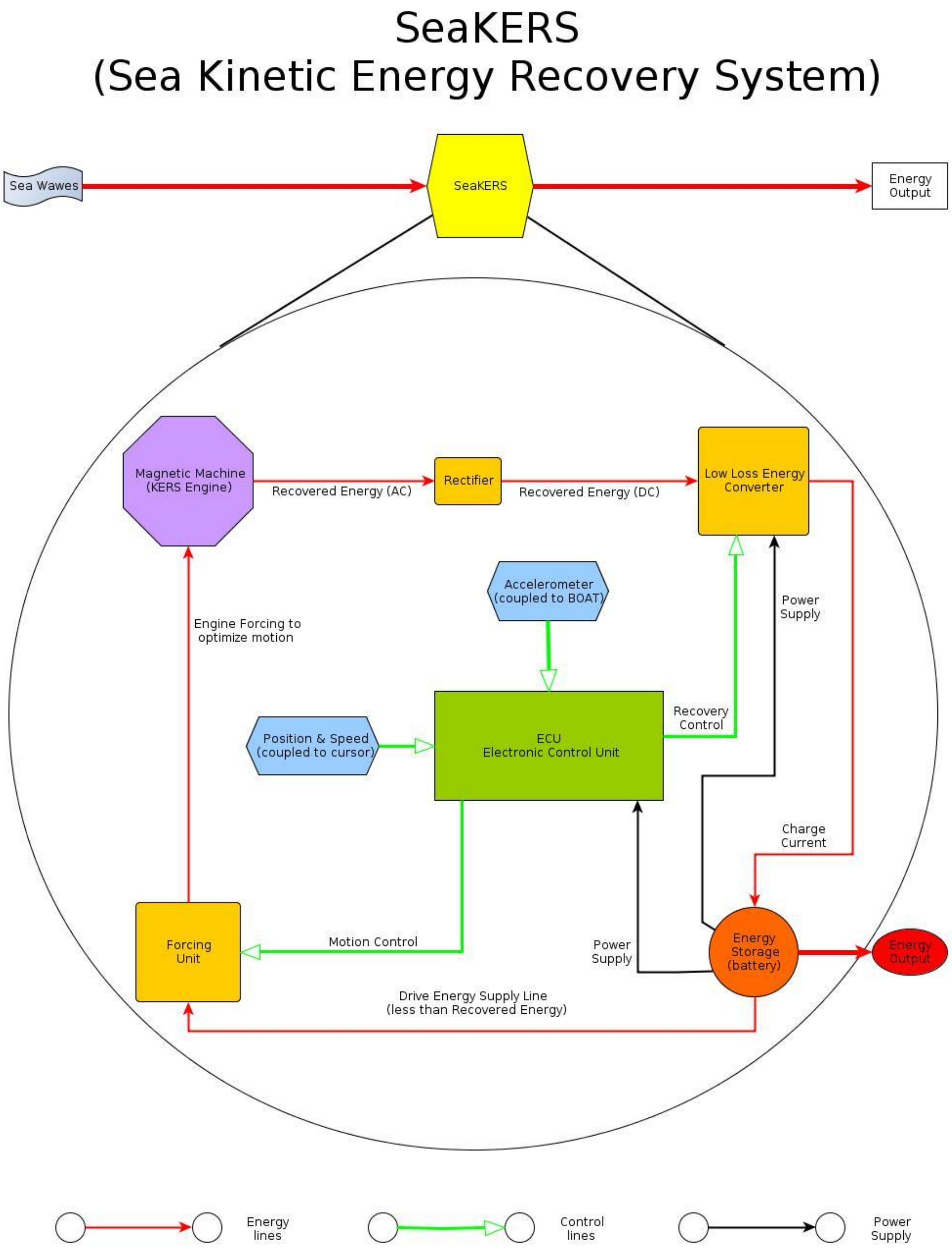


Fig 12: architecture of the SEAKERS system

3.3. Test bed

A dedicated test bed was designed and implemented, able to force the prototype to vertical oscillation tests, with imposed wave energy spectra.

The test bed was realized with a frame and the counter weight frame that slide between vertical aluminum system profiles. A toothed belts (rubber material with steel wires reinforcement) was used to drag the frames. These belts are guided around cogged wheels at the top and the bottom of the structure and connect the frames both top-to-top and bottom-to- bottom.

The concept design is reported in **Fig 13** while some details of the test bed design are shown in **Fig 14**.

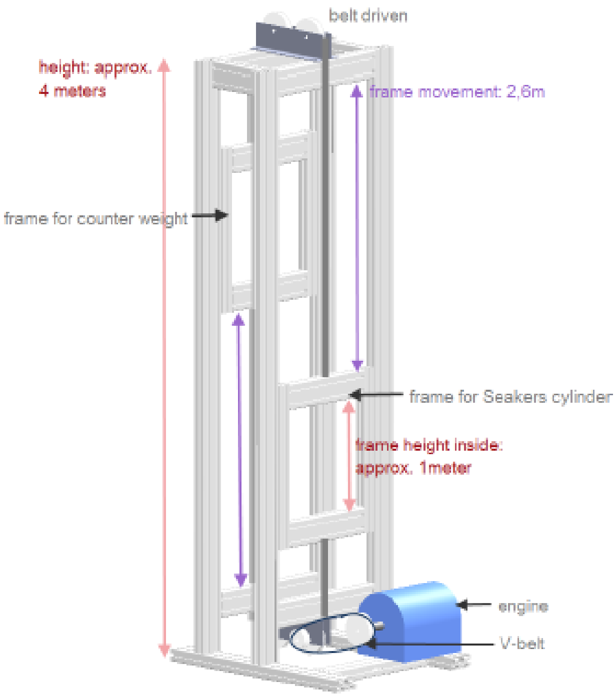
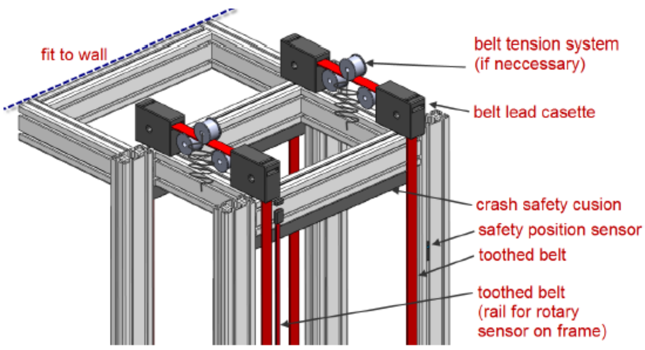


Fig 13: concept design of the Seakers test bed



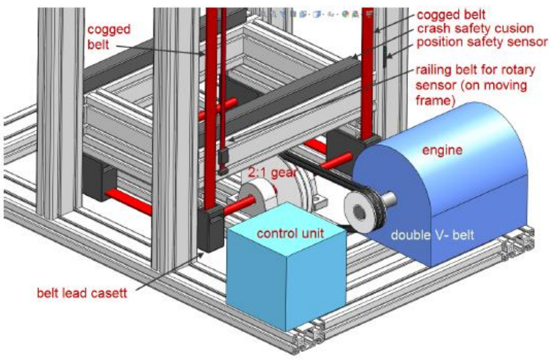


Fig 14: rack details top

The test setup was meant to simulate the boat movement resulting from waves on the sea. In order to generate these wave patterns, LabVIEW was used in combination with a National Instruments DAQ unit. The interface allows the user to select which hardware channel to use, as well as set the PID parameters (parameters for the regulator). It is also possible for the user to take manual control of the ramp, in which case a simple knob is displayed that allows the user to move the ramp. The test bed is an approx. 5 meter high construction, on which the SeaKers energy device can be installed for oscillating vertically with maximum amplitude of approx. 2,6meters. The Test bed has its own control system which can be integrated into an overall control system.

The picture shown in Fig 15 shows the details of the moving frame and the picture of the test bed.

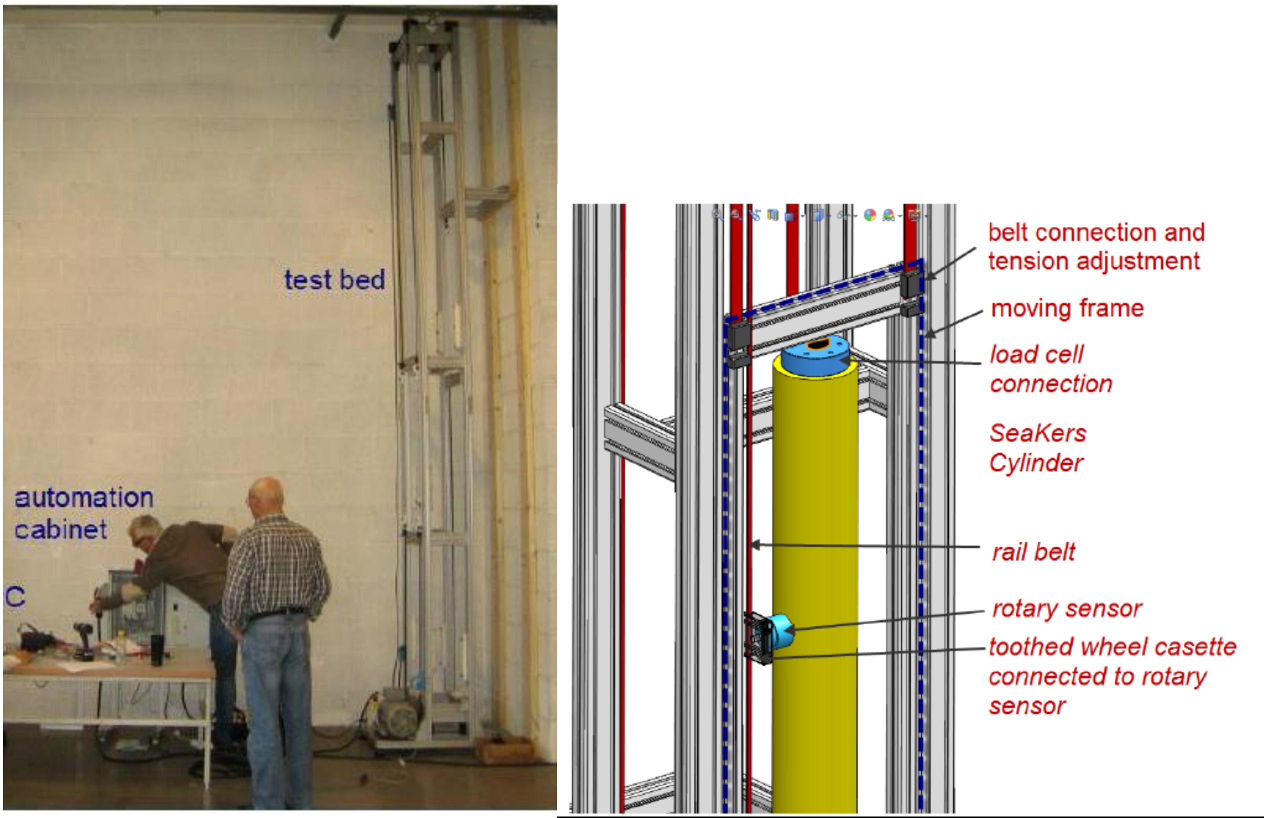


Fig 15: test bed during tests in Norway and details of the moving frame

3.4. Results of prototyping and testing phase

During the project, 2 prototypes were realised and tested successively:

- A first shorter version of the SEAKERS stator was implemented and mounted in an early working prototype used for preliminary tests, as shown in Fig 16.
- The final prototype of the stator was implemented with a length of 1 m, after modifying the configuration of the coils and of the magnets in the stator. The electric generator module was implemented, where the active magnetic section of the cursor (c-shaped rings, coils, and magnets) have been enclosed in a PVC structure. Plates surrounding the cursor are used to build an enclosure, where all the electronic components and board, batteries and ballast are hosted. The stator and the cursor box with the electronic and accessories were then integrated and mounted in the test bed for first validation and successive testing, as shown in Fig 17.

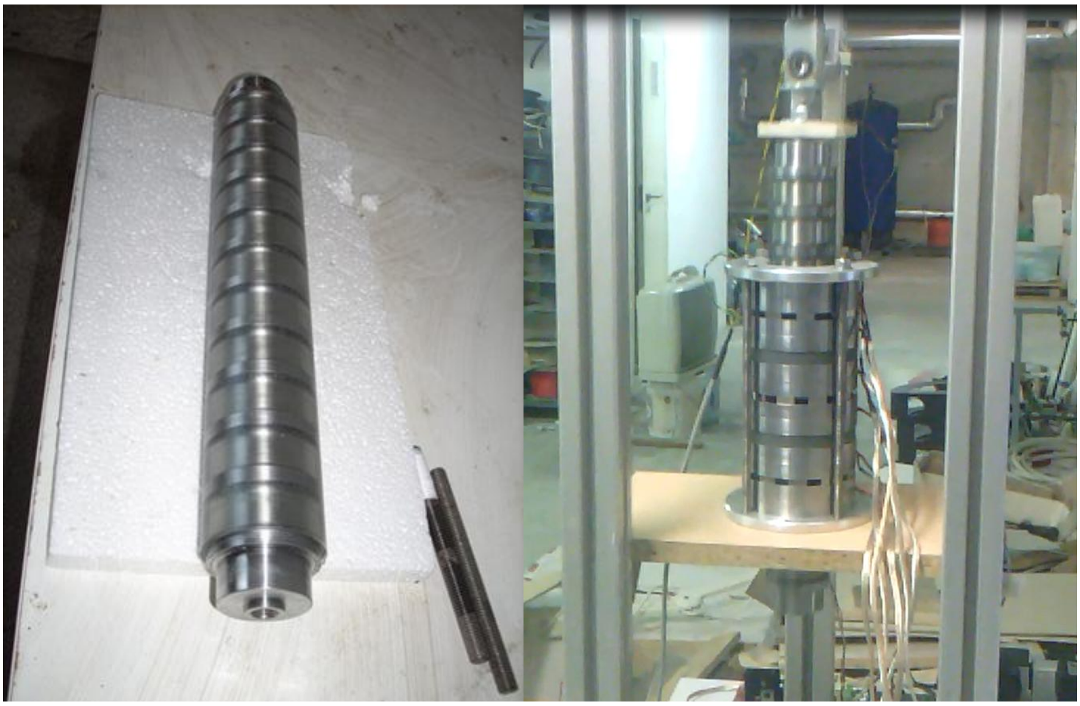


Fig 16 : SEAKERS preliminary version of the stator and testing prototype

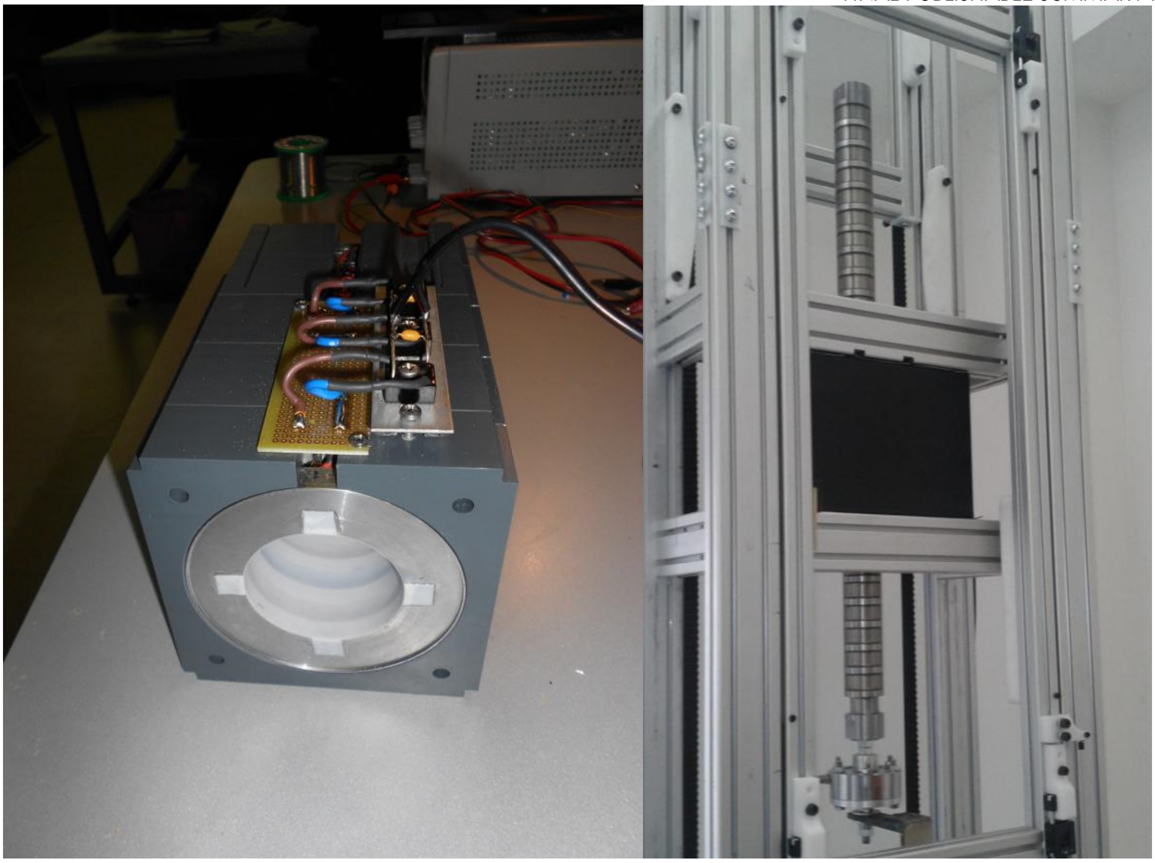


Fig 17: Slider of the SEAKERS and final prototype mounted on the test bed

Tests were carried out on the 2 prototypes evaluating different type of coils and different working parameters, allowing the evaluation of:

- performance of the magnetic core
    - Static characterization of the prototype
    - Dynamic characterization of the recovery
- Energetic characterization of the electric conversion stages
    - bridge rectifier
    - recovery unit
- Algorithm and firmware
    - Simulated environment for algorithm automated testing
    - Parameter optimization

Comparison of results of simulation and results of tests allowed to reach a refined understanding of the electromagnetic behaviour of the prototype.

Like many other electric machines SEAKERS magnetic core can work as a generator or a motor. In the first set of tests the static behavior of the SEAKERS electric machine was assessed, working as a motor (a transducer from electric to mechanical energy). The aim of this study was to discover whether the motor is able to deliver enough force to move the slider along the stator, to allow the same device work so as to move the slider in specific conditions, through a forcing unit. These experimental data were therefore fundamental to determine if an additional electric motor module was needed or not in the design of the slider, and to refine the design of the coils and the related electric converter (recovery and forcing units). Results showed that forces are indeed mostly produced by the interaction between current flowing in the coils and the induced magnetic field. Since this force is, for its own definition, a vector product between current and induced field, only the z component of this last vector will produce a force in the desired direction, and therefore that a part of the induced field is not exploited. Moreover the windings of the coils are not involved at the same rate due to a non-uniform distribution of the field.

The dynamic characterisation tests have been performed to get an evaluation of the performance of the generator, with particular focus to its efficiency. Tests have been targeted at investigating a map of the generator, evaluating input and output power. To put the generator into motion it was necessary to have a dynamic force applied on the generator (slider or stator) and a structure fixing the stator and allowing the relative movement between slider and stator. The forced oscillation has to be remotely controlled by a PC using the test bed

The simulated $F_{em,tot}$ was evaluated to be proportional to speed. This behaviour is clearly confirmed by measurements, and shown in the following figure, where measured and calculated force are compared (Fig 18).

Dynamic characterization of the Seakers with forced non-inertial oscillations has been performed, and the efficiency was mapped against relative speed and external load resistance (Fig 19).

These tests lead us to conclude that efficiency data are disrupted by test-bed misalignments and vibration, and that the internal efficiency of the prototype tested (KERS + rectifier) can be estimated to a more optimistic 25% which is the one shown in the upwards sliding. Taking into account losses of the rectifier (around 45÷50% at these very low voltages) the generator conversion efficiency can amount to about 50%.

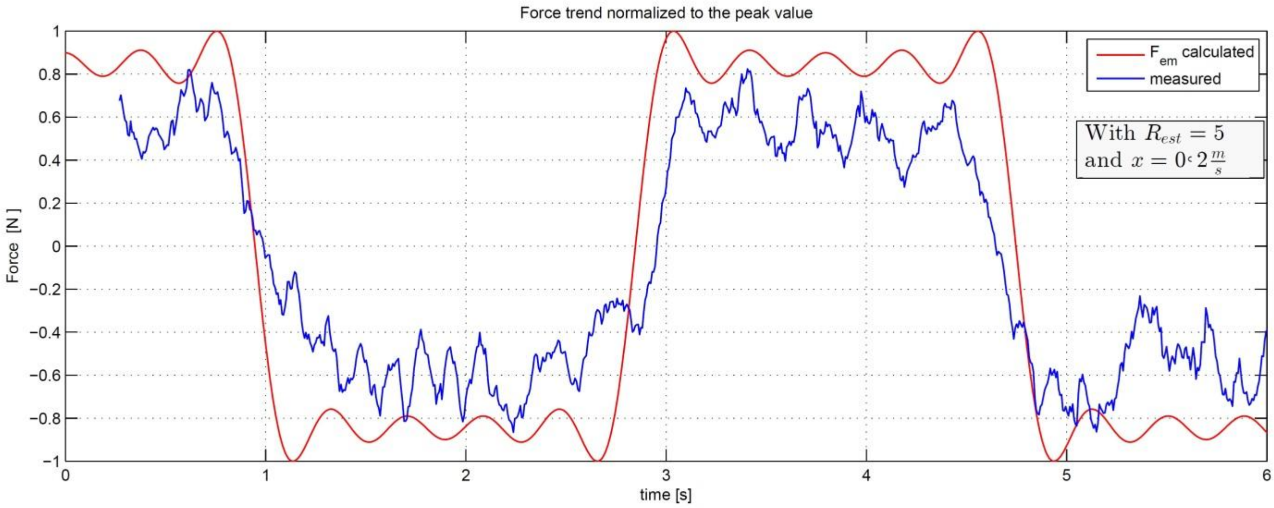


Fig 18: Fem measure and simulated in the dynamic tests

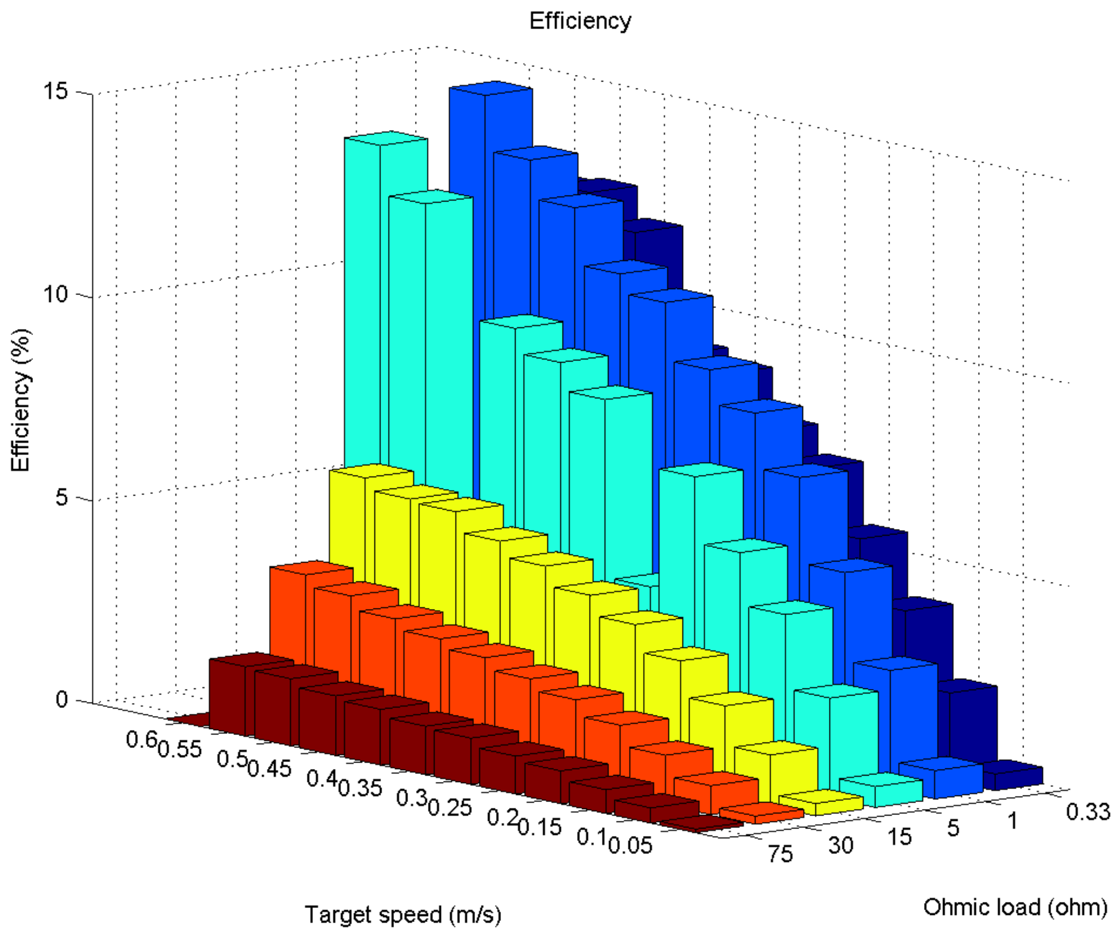


Fig 19: Efficiency map of the SEAKERS generator as a function of relative speed and load resistance

Tests of the electric conversion modules were carried out.

- tests on the rectifier unit have been completed successfully and show a potential efficiency up to 90% @ 20V input voltage. More refined designs with active components are certainly possible and their benefit will be evaluated
- Tests of the DC/DC converter have been completed, showing an efficiency of more than 90% over a very wide range of input voltage. However a new version of the DC/DC stage designed to charge a newer higher voltage battery pack (24V nominal) could not be tested in time for the preparation of this report. It will be integrated in the prototype as soon as the forcing unit will be available

The control system was tested against mathematical analysis and a specifically designed simulator. This allowed us to develop the firmware fully and the final test on the physical device has confirmed the correct approach of the control system.

SeaKERS was based on operative and technical boundary conditions stemming from preparatory work performed jointly by industrial and research partners, prior to project submission. Project activities and planning were devised accordingly, in compliance with an estimated complexity of system architecture and corresponding system performance; in particular, the contribution of all hull movements (pitch, roll, buoyancy) were supposed to contribute to generate kinetic energy useful for energy harvesting.

The extensive and accurate R&D activities performed during the project provided a deeper understanding of the following phenomena:

- average sea waves spectrum, calculated from an extensive set of wave height measurements, matching the actual profile of use of the boat proved to be balanced on lower frequencies and amplitudes than initially expected
- the use of a professional tool to simulate in a wide range of conditions the set of hull movements and their combinations, revealed that the resulting kinetics useful for energy harvesting is smaller than initially estimated
- installation criteria produced by industrial partners fixed stringent requirements for system size, limiting the vertical displacement available for the generator

Three main consequences had to be tackled:

- the elastic suspension required very low stiffness, impossible to be actually provided by mechanical springs
- the overall kinetic energy content to be potentially harvested was lower and at lower forcing frequencies.

- the broad spectrum of forcing frequencies required also to devise innovative and sophisticated solutions to increase energy harvesting.

Seakers reacted to such challenging requirements devising a brilliant set of solutions:

1. the electromagnetic configuration of the generator was selected in the number of architecture belonging to the so called "magnetic parallel path" effect, to introduce reduced dependency of generator efficiency from piston speed, limited by onboard installation related constraints
2. an advanced adaptive control algorithm has been devised and developed, demonstrating the overall advantage of making the generator working for short transients as a motor, in order to match its oscillation with the variable forcing spectrum
3. as a consequence of 2), the generator has been designed to be reversible, able to operate efficiently also as a motor, without the need to integrate into the generator a specific motor section, saving system compactness.
4. both elastic suspension and damping have been implemented through the quickly variable impedance of the power conditioning unit, able to tune constantly the electric power extracted from the generator with the kinetic requirements for matching forcing spectrum

Overall, the number of technical solutions required to solve efficiently the problem of kinetic energy recovery substantially exceeded what was initially foreseen, but have been thoroughly developed.

The parallel path linear generator has been simulated, designed and tested in forced conditions (i.e. the piston is forced to move by the test bed, being the stator section fixed); the unit has been also fully characterised as far as its capability to operate as a motor is concerned.

The need to achieve reversible operation (generator and motor in the same unit), keeping good efficiencies for both functions, has been achieved; this required a number of design + prototyping iterations much higher than expected, since this requirement was not identified at proposal level; finally, the generator prototype has been delivered, encompassing all required features.

The special power conditioning unit has been designed, prototyped and tested independently; the advanced spectrum following control algorithms have been developed, validated at simulation level, and their compliance for computational power requirements with the power conditioning unit has been ensured.

A final comprehensive testing of the device as a kinetic energy recovery system has not been possible, due to different issues:

- unexpected limited compatibility with the test bed, introducing in some regimes relevant vibrations, interfering with piston/stator relative motion and the onboard accelerometer, which would have jeopardised the correct operation of control algorithms

- unavailability of the revised release of the forcing unit, i.e. the section of the power conditioning unit in charge of making it work as a motor for short transients; this has occurred because of the longer development time required by the increased complexity of the system, and the need of several design and testing iterations, which also determined the unavailability of COTS components for the electronic board, compliant with the ultimate specs of the forcing unit, determined by the final configuration of the reversible generator.

In spite of the substantially increase of technical complexity, originated by the more accurate boundary conditions delivered, Seakers has delivered a remarkable amount of innovative and technically advanced solutions, and arrived very close to the full demonstration of system operation:

- the availability of the parallel path reversible linear generator, showing limited dependence on piston speed, is a novel results at world level; beyond its application as a sea KERS, it shows promising potential as point adsorber (an electric generator placed at sea bottom and force by a buoy) and as generator for special engines, like Stirling and Sulzer engines, strongly benefitting of the reversible operation capability to stabilise their operation
- forcing spectrum following algorithms, based on simplified accelerometer dataset, and the underlying approach for maximised energy harvesting from broadband forcing spectra, constitute a worldwide innovation as well; they address brilliantly the Seakers application but can be applied similarly to the technologies described at the previous point
- the fast adaptive power conditioning unit, enabling the simulation of a mechanical suspension, constitutes a further remarkable result, replicable in other dynamic energy harvesting applications

Measured generator conversion efficiency during testing summed to about 50%.

There are several areas for straightforward improvement:

- friction losses - magnetic cores and coils have been designed and prototyped in several successive iterations; typical sizes have changed consequently; in order to speed up prototyping and testing, fast solutions for friction reduction between stator and piston have been used, consisting in the encapsulation into a thin teflon envelope; this choice proved to be excellent to speed up development; nevertheless, different mechanical solutions can be implemented in a final configuration, which can easily provide an efficiency increase up to 20%
- Test bed - a better coupling with the test bed will allow to reduce the significant vibrations occurred, which resulted in unwanted friction losses; we can estimate that some points of increased efficiency can be recovered

- parasitic losses can be reduced switching to sintered materials, but this makes sense only in a preindustrial prototype; further 5% efficiency increase can be estimated
- further optimisation likely remains for coils and cores size specifications, which can be contribute to some further 5% efficiency improvement

Through these reasonable estimation, we believe that overall generator conversion efficiency can raise up to > 80%, by means of engineering, consolidated solutions.

It is remarkable that these results have been achieved with a maximum relative speed between the piston and the stator of only 0.5 m/s, in compliance with application related specifications, and represents a challenging operating condition for a similar device.

Once the remaining obstacles will be solved, the set of novel technologies, all of them validated independently, will be joined together to provide industrial proposers with the Seakers technology and then target further relevant energy harvesting and energy efficiency applications.

4. Potential impact, dissemination activities and the exploitation of results

4.1. Socio economic impact

The world market composition of pleasure crafts is reported in Fig 20; Italy and UK are the main European manufacturers, covering also a leading position at world level, dominated by USA.

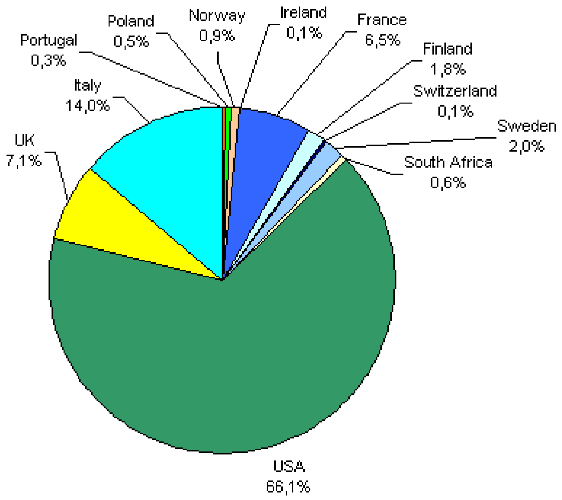


Fig 20– Units of pleasure craft production per country (source ICOMIA data 2008)

The market segment covered by European manufacturers, especially Italian ones, is the upper end one; the value of the Italian annual production of pleasure boats is around 3 billion Euros.
The market is composed of a galaxy of small manufacturers of boats, engines, accessories, etc.; the capability to introduce individually a substantial innovation is limited, and competition is mostly played on the ground of design, cost effectiveness, with marginal and incremental innovation.

USA production is characterised by a higher presence of technological accessories and special devices, which are showing to be more and more appreciated by the customers; onboard energy generation systems based on RES are enjoying a constant growth during the years; official market data about this trend are not available, but it can be clearly detected at international marine exhibitions; within such a technological segment, European manufacturers are running after and have to improve their technological and market portfolio.

RES based energy generation systems are moving from add-on devices supplied by third parties and with limited product quality, to original equipment accessories proposed by manufacturers; the trend which is noticed in the sector is to study the best integration into the boat and look for innovative solutions, like dragged water turbines integrated in the hull, which are expected to be rewarded by the customers; one should not forget that the leverage for customers to look for onboard RES based generators is only partially emotional and is instead based on the well known and common perception of the problem of energy availability onboard.

An "invisible" device, delivering free energy without subtracting it to boat motion, with also the secondary capability of inertial dumper, certainly meets the highest expectations of the end-users customer base, and nothing similar is available or has been announced or patented; it will also have a clear, well defined and easily communicable identity.

A study on the target application for the SeaKERS based on consideration about the target clients and the issues related to the technical integration onboard was carried out. Main results were:

- big size cruising sailboats (mono or multi-hulls), typically above 60 feet size, should be considered the natural target market of the SeaKERS system; avoiding any problem of additional weight and sailing performance deterioration;
- motorboats (mono or multi-hulls) might also be considered an interesting option, pushing the idea that even if power can easily be produced onboard thanks to the boat engines, clean generators can save fuel anyway; especially in this case, pushing on the appeal of a high-tech device to be proud of can be an interesting marketing strategy;
- racing sailboats (mono or multi-hulls) should be completely excluded from the target;
- sport mono-hull sailboats might be considered an option just in case of an express request of customers; sport multi-hull should be excluded anyway;
- concerning proper onboard integration, which is the main argument of this deliverable, in order to reduce complexity and concentrate on the optimization of power generation, the first prototypes had better be first of all conceived for external installation only, with plenty of available height, like the forepeak or the helm(s) area; the afterpeak vanes could also be considered when available inside cockpit benches;
- a single mobile module of reduced height (about 60cm) might be advantageously considered in addition to the complete system, in order to easily test power production performances in many different positions on the boat, realizing a sort of "exploitation map".

As first application, retrofit systems should better be considered, as the first installations will have to be driven on existing boats. In this way, future first equipment systems will benefit from results achieved in retrofit system field tests, allowing designers to count on a much more rich and reliable knowledge: this appears to be extremely important when it comes to influencing boat design for SeaKERS integration. Concerning the first installations, even if big cruising sailboats have been recognized as the most proper target for the SeaKERS, it can be considered to build the prototype and install it for tests on any kind of 40 feet boat: this in order to simplify testing, as this size of boat can be more easily available. Once the technical value of the system will be assessed and confirmed, a very important activity to be carefully planned and performed for a wide success in nautical world, will be the realization of a proper product marketing campaign.

4.2. Dissemination of results

Planned /actual Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
Available	*Web site*	*General public*	*ALL*		*AGT*
June 2012	*Brochure n.1*	*Boat producers /users*	*English*	*115*	*AGT*
June 2012	*Newsletter n.1*	*Boat producers /users*	*Europe, USA, Australia*	*115*	*ALL*
June 26, 2012 – June 29, 2012	*ECOS 2012 Renewable Energy Conversion Systems and Sustainable Technologies*	*Scientific*	*International*		
August 2012	*Presentation in the Boat Magazine Seilas*	*Boat designers and users*	*Norway*	*1000*	*TI*
October 12th 2012	*Training*	*Internal presentation*		*SMEs*	*UTV, LABOR, TI*
December 2012	*Brochure n.2*	*Boat producers /users*	*English*	*115*	*AGT*
December 2012	*Newsletter n. 2*	*Boat producers /users*	*Europe, USA, Australia*	*115*	*ALL*
January 2013	*Paper submitted to the Journal of Renewable Energies*	*Scientific*	*International*		*UTV, LABOR*
2012	*Boat sponsorship*	*Races in Italy*	*Italy*		*AGT, ESTE*
February 2013	*Technical publication on NauTech Italy*	*Boat designers and users*	*Italy*	*5.000*	*ESTE, LABOR*
February 2013	*Technical publication on NauTech World*	*Boat designers and users*	*World*	*15.000*	*ESTE, LABOR*

Web Site

A dedicated SEAKERS web-site was produced at month 3 to increase the visibility of the project, with useful information, images and technical specifications, links to partners web pages. After the end of the project, it will be maintained to give specific information about the SEAKERS project's scientific results and products technical specifications, in order to provide a proven scientific background to potential buyers of the devices.

Brochure and newsletter

Two releases of the project brochure were produced and sent in electronic way through a project newsletter to potentially interested targets in the sailing and boat sector.

Press presentations

Pubblications on the technical magazine NauTech (in Italian) and Nautech World (in English) were issued on the number 1/2013. These are the official magazine of the Italian Association of naval designers of pleasure crafts and targets the technical operators of the sector: engineers, designers, naval architects, construction companies, providers and manufacturers of plants and accessories, providing information about the innovative technologies in the pleasure crafts design. The link to the electronic versions of the magazines are here included:
http://viewer.zmags.com/publication/b848b3f8#/b848b3f8/36
http://viewer.zmags.com/publication/d8be8eeb#/d8be8eeb/12
The SEAKERS was also presented in the Norwegian boat magazine «Seilas» in the number 8-2012. Also a larger follow up article concerning Seakers in the same magazine is planned in the next future.

Scientific pubblications

The simulation model for the evaluation of the wave conditions and the calculation of the available inertial energy on boat with specific design was presented by UTV at the International Conference ECOS 2012 "EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS" held in Perugia (Italy) on June 26-29, 2012. The paper was titled "Kinetic energy recovery system for sailing yachts" authors Prof Guizzi and Prof Manno from UTV and was included in the proceedings of the conference.
A paper named "Preliminary study on a kinetic energy recovery system for sailing yachts" was submitted to the scientific journal Renewable Energies by UTV and Labor and still pending the approval for publication.

Boat Racing sponsorship

Seakers logo sponsored a Este24 boat realized by Cantieri Navali d'Este and run by AGT during the Italian championship during 2012. Picture of the boat at pier with the winning team is presented.

Fig 21: SeaKERS boat winning team

4.3. Exploitation of results

Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Time for Commercial use	Patents or other IPR protection	Owner & Other Partners involved
Design Tool	Numerical computational model for the evaluation of the kinetic conditions of the boat and the electromechanical response of the generator	Design of SEAKERS for specific applications (boat and wave conditions)	2015	No	AGT, GT, SOLBIAN
Executive design of SEAKERS	Executive design (electromechanical, mechanical, control)	Design of the SEAKERS and other possible linear energy recovery systems	2015	Possible	AGT, ESTE, AND and PLASMA
Prototype of SEAKERS	Prototype of SEAKERS, including data acquisition and control system	Validation of SEAKERS and other possible applications of linear energy recovery systems	2014	No	ESTE, PLASMA and SOLBIAN
Test bed	Prototype of test bed to perform tests on SEAKERS under imposed simulated wave conditions	Validation of SEAKERS and other possible applications of linear energy recovery systems	2014	No	AGT and GT

4.3.1. Design tool

Description of result

A computational model allowing to calculate design characteristics and expected performance of Seakers in different conditions.

The model includes:

1. A kinematic and mechanic models that have been used to set up the most relevant physical parameters for the SEAKERS device. The yacht's vertical motions are then used as input in the mechanical model that describes the linear generator's behavior. the commercial software package Seakeeper has been used to carry out the computation of the yacht's motions under different wave conditions.
2. A numerical electromagnetic model of a permanent magnets linear generator, composed of a linear stator and an oscillating mass, to simulate and study the complete model to estimate the dynamic behaviour of the forces exchanged between the stator and the oscillating mass, as a result of both electromagnetic and dynamic phenomena b) the energy produced at varying forcing values; c) the influence of different system configurations for the mechanical suspension

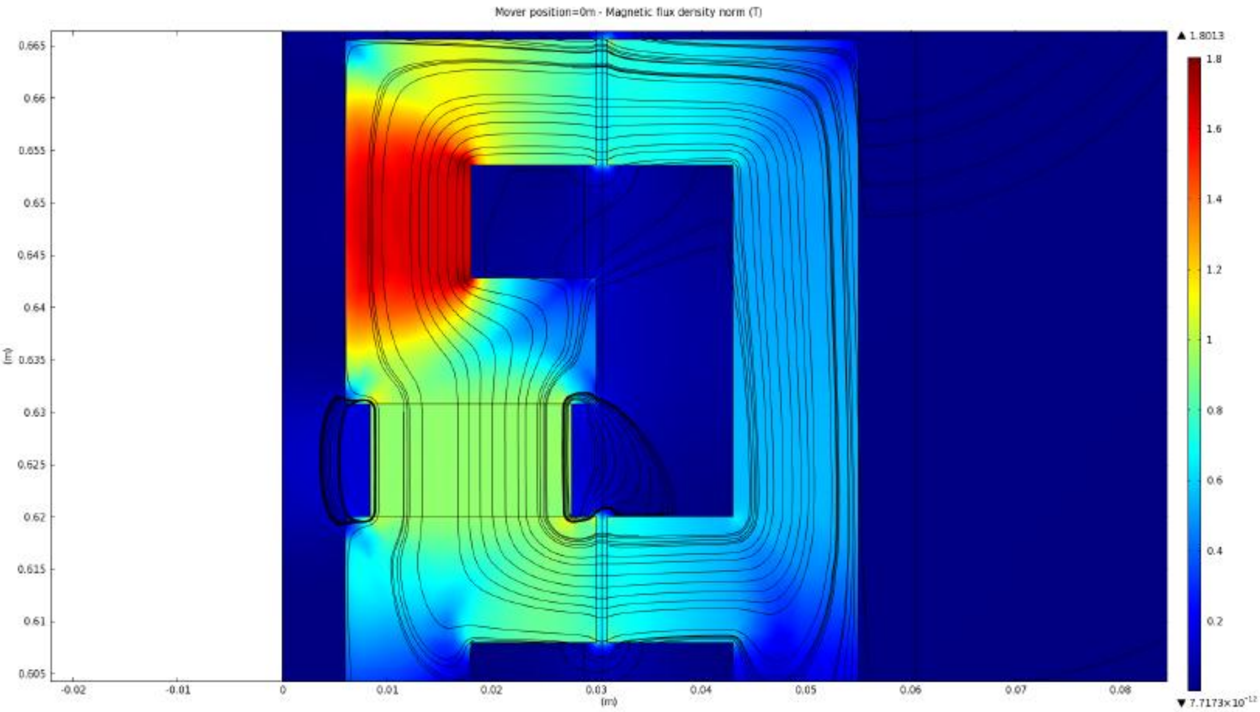


Fig 22: results of electromagnetic simulations of a module of the linear generator

Possible exploitation

Beneficiaries will retain ownership of the design tool, and will use it to investigate further applications of the SEAKERS system and will license it (under royalties) for the use or commercialization of the system by third parties.

The kinematic model can be used to

- simulate and study yacht's motions in different points of the boat, under different wave conditions

The electromagnetic model can be used to simulate and study the optimal architecture of a linear MFSPM (Magnetic Flux Permanent Magnet Machines) for energy generation. In particular to evaluate:

- the dynamic behaviour of the forces exchanged between the stator and the oscillating mass, as a result of both electromagnetic and dynamic phenomena
- the energy produced at varying forcing values
- the influence of different system configurations for the mechanical suspension
- define and optimize a control strategy and corresponding control algorithms for optimal energy harvesting, in relation to possible system layouts
- define optimal system layout with respect to maximum energy harvesting and compatibility with physical constraints, and corresponding control strategies

4.3.2. Executive design of Seakers

Description of result

The design of the Seakers includes:

- The architecture of the electro-magnetic core of the generator: a linear MFSPM (Magnetic Flux Permanent Magnet Machine) has been selected and specifically designed. This allows the use of the typical cogging force of this architecture to suspend the mass without any additional mechanical devices (springs), therefore maximizing the available stroke. Since the working principle of the SEAKERS generator implies that the magnetic machine has to act as an electric motor several times during a period of operation, both for optimising the energy recovery, given an almost arbitrary forcing by the waves, and to release the engagement of the moving part with the magneto-static field due to the permanent magnets, the generator is designed to work also as a motor section, to unlock the slider from top and bottom dead centres and restart the energy recovery.
- The mechanical design of the SEAKERS system: the generator and motor modules, the mechanical design of the SEAKERS complete assembly, including battery, energy converting units, sensors and control electronics, making SEAKERS prototype easy to install and startup.
- The electric and electronic design, including the system architecture and each module:
  - AC-DC stage, capable of converting very low to high voltage for battery charging, used as a system load for recovering energy from the slider, applying a braking force to the mobile mass.
  - forcing and a parking units for slider unlocking (from dead centres) and locking (to avoid battery overcharging).
  - The electronic control system based on a commercially available OEM board, including front-end to acquire signals and operate the different electric units, with enough power to perform computation and calculate the optimal recovery trajectory
- Control algorithm and firmware based on a software operating on a customized linux kernel is used for implementing the SEAKERS control system, with the possibility of granting different priorities to processes and threads. Data are acquired from all the available sensors and are used for logging and computation purposes.

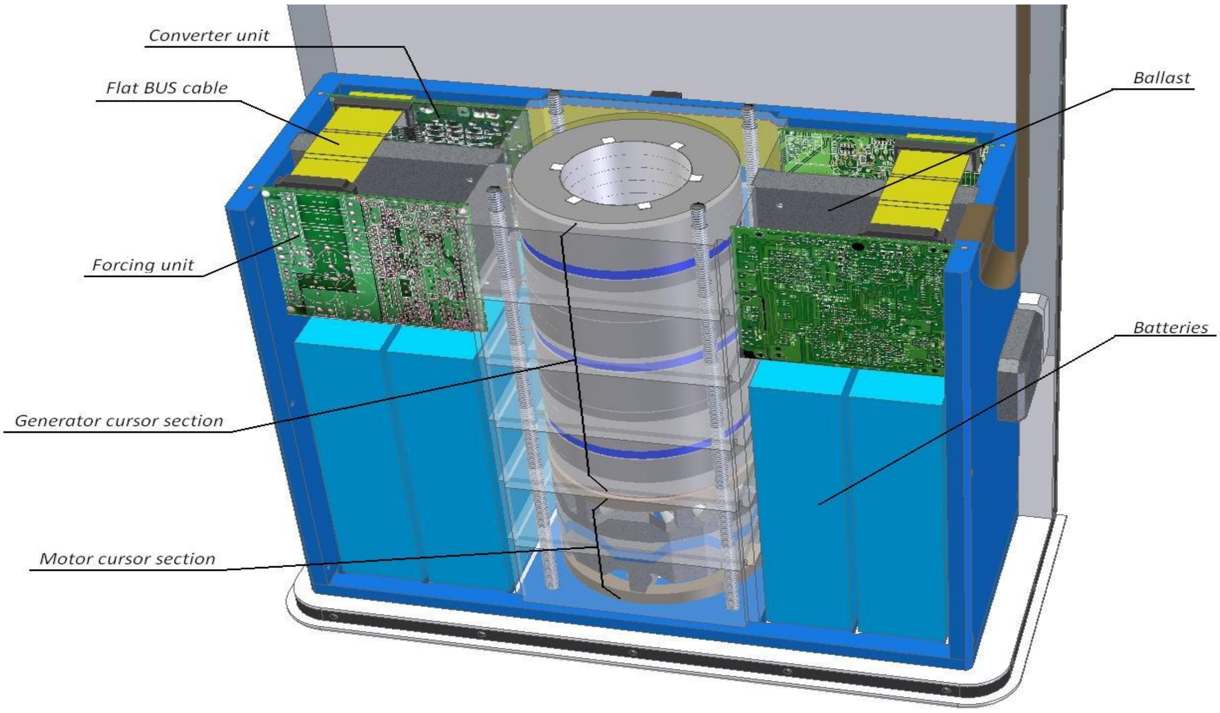


Fig 23 - ***Mobile equipment content detail***

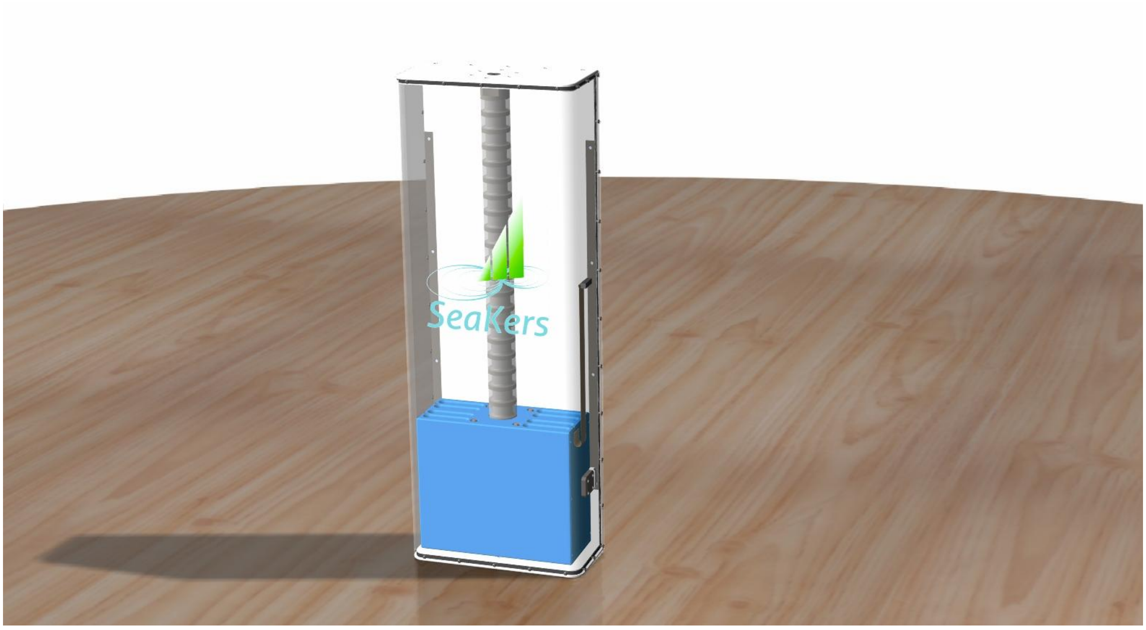


Fig 24: rendering of the SEAKERS device

Possible exploitation

The Consortium will evaluate if manufacturing internally or giving license for production to third party, and will evaluate commercial agreements for the design and integration of the SEAKERS in the yacht sector and in other sectors in which the device could be applied.

4.3.3. Seakers prototype

Description of result

SEAKERS deviced a full scale prototype which was produced in the project and installed in the test bed (refer to **Fig 25**). The prototype of the stator was implemented with a length of 1 m, after modifying the configuration of the coils and of the magnets in the stator. The electric generator module was implemented, where the active magnetic section of the cursor (c-shaped rings, coils, and magnets) have been enclosed in a PVC structure. Plates surrounding the cursor are used to build an enclosure, where all the electronic components and board, batteries and ballast are hosted. The stator and the cursor box with the electronic and accessories were then integrated and mounted in the test bed for first validation and successive testing

The parallel path linear generator has been simulated, designed and tested in forced conditions (i.e. the piston is forced to move by the test bed, being the stator section fixed); the unit has been also fully characterised as far as its capability to operate as a motor is concerned.

The need to achieve reversible operation (generator and motor in the same unit), keeping good efficiencies for both functions, has been achieved; this required a number of design + prototyping iterations much higher than expected, since this requirement was not identified at proposal level; finally, the generator prototype has been delivered, encompassing all required features.

The special power conditioning unit has been designed, prototyped and tested independently; the advanced spectrum following control algorithms have been developed, validated at simulation level, and their compliance for computational power requirements with the power conditioning unit has been ensured.

A final comprehensive testing of the device as a kinetic energy recovery system has not been possible, due to different technical issues. However, SeaKERS has delivered a remarkable amount of innovative and technically advanced solutions, and arrived very close to the full demonstration of system operation:

- the availability of the parallel path reversible linear generator, showing limited dependence on piston speed, is a novel results at world level; beyond its application as a sea KERS, it shows promising potential as point adsorber (an electric generator placed at sea bottom and force by a buoy) and as generator for special engines, like Stirling and Sulzer engines, strongly benefitting of the reversible operation capability to stabilise their operation
- forcing spectrum following algorithms, based on simplified accelerometer dataset, and the underlying approach for maximised energy harvesting from broadband forcing spectra, constitute a worldwide innovation as well; they address brilliantly the Seakers application but can be applied similarly to the technologies described at the previous point

- the fast adaptive power conditioning unit, enabling the simulation of a mechanical suspension, constitutes a further remarkable result, replicable in other dynamic energy harvesting applications

Once the remaining obstacles will be solved, the set of novel technologies, all of them validated independently, will be joined together to provide industrial proposers with the Seakers technology and then target further relevant energy harvesting and energy efficiency applications.

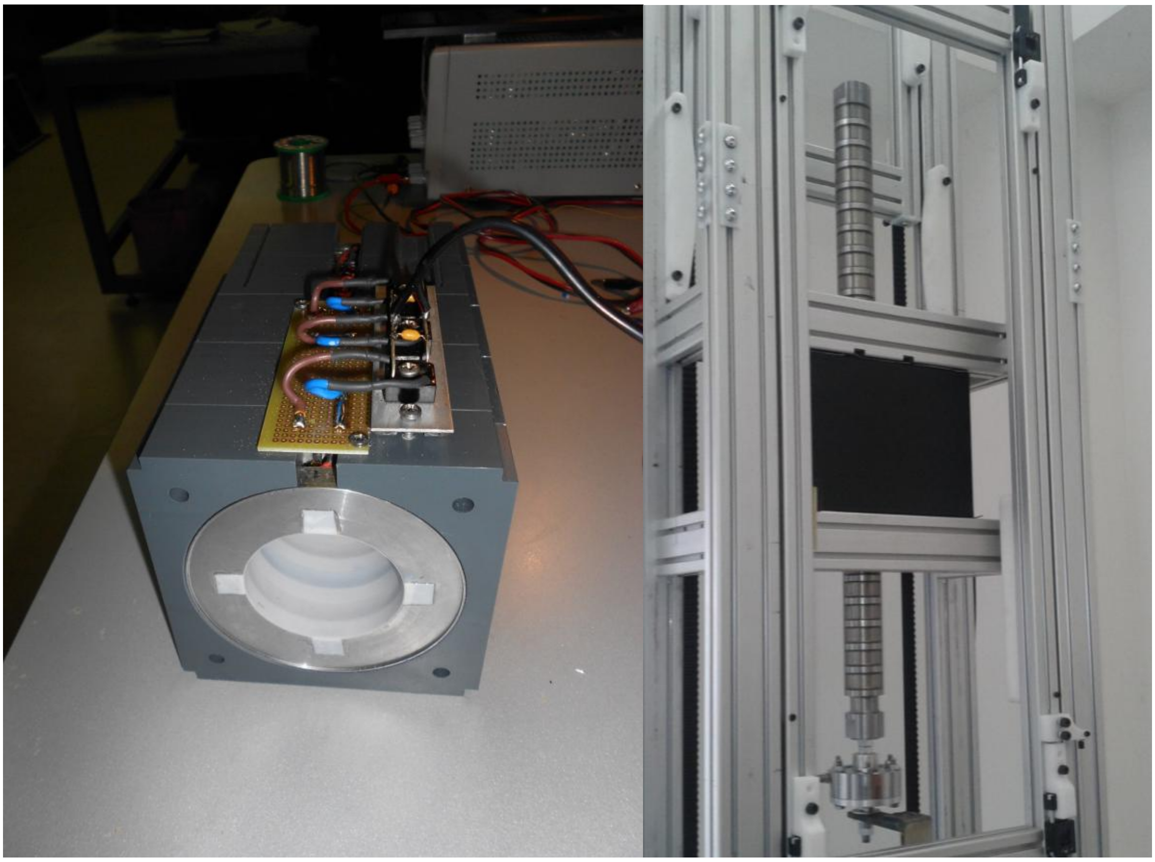


Fig 25: Slider of the SEAKERS and final prototype mounted on the test bed

Possible exploitation

Further testing is planned to evaluate the performance of the device as inertial recovery device, and to optimize the design for the optimal control and to get higher efficiency. The prototype will be used to this aims and also for further validation and demonstration after the completion of the testing.

4.3.4. Test bed

Description of result

The result consist in a test bed simulating the movement of the boat under a range of wave conditions. The test bed is equipped with sensors and control system that can be controlled via software interface.

The test bed is an approximately 5 meter high construction, on which the SeaKers energy device can slide (oscillate) vertically with maximum amplitude of approx. 2,6 meters.

The Test bed has its own control system.

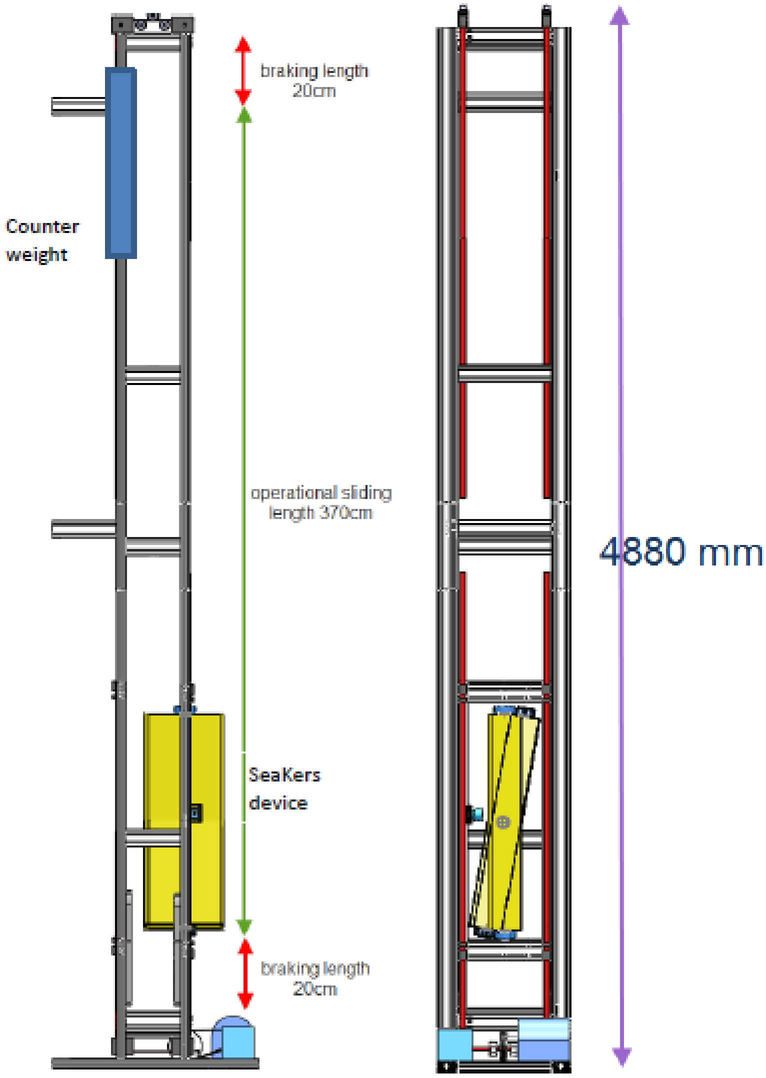


Fig 26: skecth of the test bed

Fig 27: test bed mounted

Possible exploitation

The beneficiaries can use the test bed for further tests on the SEAKERS.

On the other hand, the use of test bed for testing other devices in the naval sector will be evaluated as consultancy service.

5. Public website address and relevant contact details.

Project website: www.seakers.eu

Coordinator details

Name: Mr. Domenico Serpella
Organisation: Labor Srl
Address: Via Giacomo Peroni 386- 00131 Roma (Italy)
Web site: www.labor-eu.net
Tel: +39 06 40040354
Fax+39 06 40040357
E-mail: d.serpella@labor-roma.it

Exploitation manager details

Name: Mr. Filippo Ugolini
Organisation: AGT Engineering Srl
Address: Via Paolo Emilio 34 – Roma (Italy)
Web site: http://www.agtgroup.it
Tel: +39 06 45437023
Fax+39 06 32609007
E-mail: f.ugolini@agtgroup.it

SME participants:

- A.G.T. Srl. (Italy) http://www.agtgroup.it
- Cantieri Navali d'Este S.r.l (Italy) www.cantierinavalideste.it
- Andel Limited (UK) www.andel.co.uk/
- GreenUrban Technologies Ltd (UK) http://www.greenurban.co.uk/index.html
- Solbian Energie Alternative Srl (Italy) http://www.solbian.eu/it/
- S.C. PLASMA S.R.L (Romania) http://ambarcatiuni.ro/

RTD performers:

- Labor Srl (Italy) www.labor-eu.net
- Università degli Studi di Roma Tor Vergata Dipartimento di Ingegneria Industriale (Italy) - http://www.mec.uniroma2.it/
- Teknologisk Institutt AS (Norway) http://www.teknologisk.no/