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Design and performance analysis of a piezoelectric generator by Von Karman vortexes for underwater energy harvesting

用于水下能量收集的基于冯・卡门旋涡之压电发电机设计和性能分析

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***Abstract*—With the decrease in energy consumption of electronic sensors, the concept of harvesting renewable energy in a human surrounding, using piezoelectric technology seems promising to feed small sensors in several environments. The aim of this paper is to design a piezoelectric generator, optimized for magnetic sensors, able to work under the sea or into rivers, which can work with natural water vibrations generated by solid-fluid objects interactions (Von-Karman Vortex) and then to test the effectiveness of the device developing an electronic board to analyze the behavior of the generator.**

Keywords*—*energy harvesting; piezoelectricity; Von-Karman Vortex; fluid dynamics

I. INTRODUCTION

From the beginning of the XXI century the increment of the World Energy Consumption (WEC) strictly related to the technological progress has highlighted the necessity to produce energy from renewable sources. By 2008 renewable energy had ceased being an alternative, and more capacity of renewable energy was added than other sources in both the United States and in Europe. In this context, piezoelectric generators seems promising for small electronic equipments, especially if used in environments where human intervention is not so easy, as for underwater applications. The principle is to harvest energy from mechanical vibrations, connected to general human activities (cars, bicycles, ecc…), or from natural effects (wind, flows, ecc…) [1]. All studies performed at present time consists of designing an oscillator, operating nearby the natural frequency and therefore maximizing the oscillations amplitude. Various attempts to generate natural vibrations from "tree like" energy harvesters have been made [2-7], whose leafs are piezoelectric thin foils, able to vibrate because of the wind effect. When this investigation is brought into water, vibrations come from natural flow interactions [8,9]. Extensive studies about Hydrodynamic and Aerodynamic have been carried out for the last two centuries in this field.

The aim of this paper is to design a piezoelectric generator, optimized which can work with natural water vibrations generated by solid-fluid objects interactions (Von-Karman Vortexes) [10], in order to feed underwater magnetometers for port protection purposes [11], able to work autonomously for long periods; in particular, this prototype has been designed to work in combination with new magnetometer models (L.A.M.A. Project, National Plan for Military Research, Italy), designed to work inside underwater magnetic networks for harbour defence [12].

This paper introduces the theoretical principles and shows the design process of the mechanical structure, taking into account CFD and mechanical results; then considerations about the electronic aspect of the work are shown, in particular an electronic model of the system and the energy harvesting circuit for the evaluation of the performance of the generator. Finally the mounting operations and all tests campaigns are described, focusing on the results obtained.

II. MECHANICAL STRUCTURE

A. *Principles of Von Karman Vortex*

The first hydrodynamic aspects to be investigated is related to the interaction between a fluid and a bluff bodies submerged in the fluid itself [11-18]. This kind of study starts with Von Karman, who has described the emission of vortices generating from interaction between fluid stream and geometrical shapes, caused by friction and dissipative forces. The intensity and dimensions of these vortices is determined by several parameters, such as velocity, viscosity and object dimensions. In order to describe this phenomenon, the Reynolds number (Eq. 1) and the Strouhal number (Eq. 2) are paramount.

$$\mathrm{Re} = \frac{U \cdot d}{v} \tag{1}$$

$$fr = St\frac{U}{d} \tag{2}$$

Strouhal number allows to predict emission frequency (*fr*) of vortices around the cylinder. The emission of Vortices generated from interaction between a fluid (water or air) and the cylinder induces a vibrations in a path of cylinders downstream the first fixed cylinder.

B. CFD analysis

A first test of CFD analysis has been developed using FLUENT®. A cylindrical body has been put inside a uniform water current of 0.5 m/s, a typical velocity inside small channels or in proximity of maritime harbor gates, which will represent the typical environment for these applications. The aim of this test was to visualize the pressure field generated downstream the cylinder, and of course the behavior of vortices.

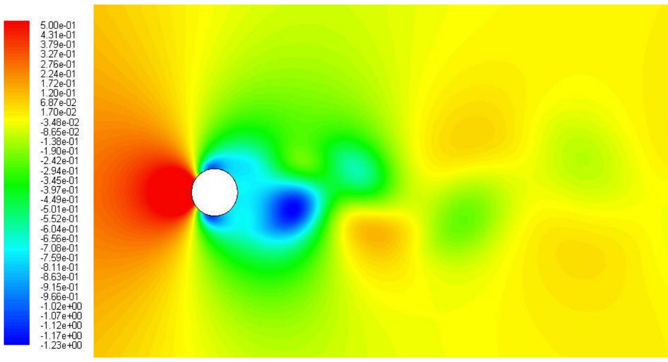


Fig. 1. Static Pressure field (Pa) around the cylinder generated by Von Karman Vortices in a fully developed stream

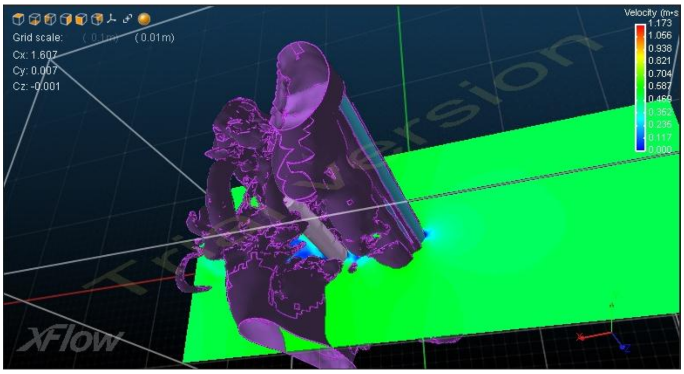


Fig. 2. Velocity simulation (m/s), showing a vortex behavior in a fully developed stream.

A second CFD test campaign, using a more innovative and powerful software, XFLOW®, has allowed the 3D analysis of the flow: the first cylinder was fixed to the structure and unable to move, the second one was allowed to oscillate vertically, so as to simulate the real behavior. The results can be seen in the following image (see Fig. 2).

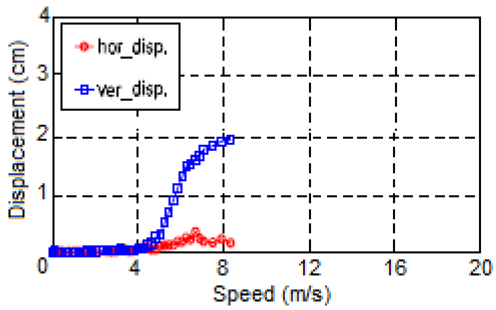
The results of both CFD studies has consolidated the result of a vibration of the second cylinder of 4-5 Hz, generally in agreement with the mathematical prediction using Strouhal number; this can be assumed as characteristic for speeds of 0.5 m/s.

C. Definition of the geometry of the structure of the prototype

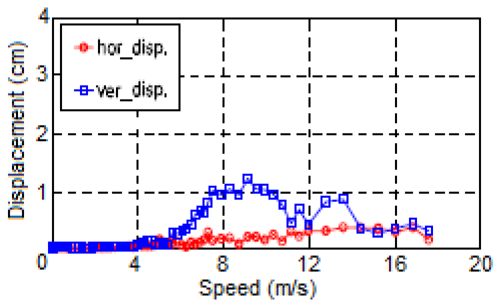
The construction of the prototype incorporates the results of previous CFD analysis, dictating guidelines of some technical solutions to maximize vibration amplitude from Von-Karman vortices, and consequently increase the energy harvesting through piezoelectric conversion.

The distance between the cylinders is a critical aspect to consider in order to compromise two opposite behavior of vortices, the full development and the subsequent dissipation for friction forces. It has been revealed from both analytical and CFD computation that the best distance is to be set at 4-5 D, with D the diameter of both cylinders (see Fig. 3).

In the schemes in Fig. 3 the trend of vibration amplitude is shown for different velocities and different distance D between the two cylinders.



A



B

Fig. 3. Amplitude of vibrations with different velocities for distances of 2D (A), 4D (B).

The vibrational structure design, as a result of all considerations made, has included the chosen shapes and a distance between the cylinders of 4D.

D. Materials

Regarding the choice of materials for the prototype realization, it is important to highlight some interesting aspects; first of all, as the oscillator must be capable of being tested both in air and in water, in order to verify the different behavior, a careful control of the two cylinders masses must ensure a not excessive difference in the two different test environments.

In addition, the cantilever bar oscillator must have a stiffness comparable to that of piezoelectric material that is to be installed: too high stiffness can dampen vibrations, and too low stiffness let the cantilever be too flexible and then to absorb itself the grand part of them, reducing piezoelectric material efficiency.

For these reasons, the cylinders were both made of carbon fiber, which in addition to possessing the required properties, is also particularly resistant to the effects of water corrosion in marine environment.

E. Mechanical modelization

An interesting aspect of vibrations behavior of the prototype is the mathematical modelization, using a second order system, commonly known as “mass - spring - damper”. The mathematical law that regulate the model behavior on the horizontal plane is the well known Eq. (3).

$$m \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t) = F(t) \tag{3}$$

where *m* is the mass, *x* the displacement from the initial position, *c* the viscous friction coefficient, *k* the elastic constant of the spring and *F* a known external force. It is possible then trough all data collected to simulate the real behavior using the software SIMULINK.

Mass and stiffness are already known, for damper it has been chose an average value of 0.2. It is also important to consider that around the cylinder an amount of fluid moves with it during vibrations: this quantity is known in fluid dynamic as Add Mass. As it is very difficult to calculate precisely this mass, negligible for air but not for water, the total mass of the system is to increase of 20%, which will affect natural frequency of the beam, causing its reduction.

The results of the SIMULINK run are shown in Fig. 4.

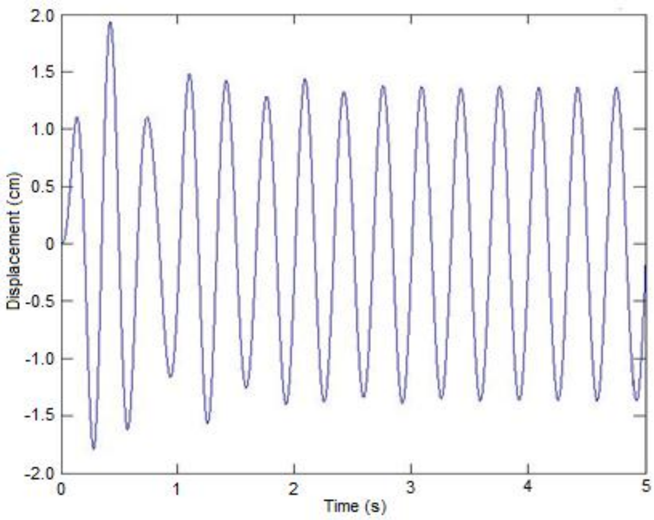


Fig. 4. Vibration of the cylinder simulated with SIMULINK.

After a brief transient, the system reach steady conditions; as it can be seen the vibration amplitude is about +/- 15 mm. These values are compatible with the test of Lunense canal.

III. ELECTRONIC ASPECTS

A. Electronical modelization

As shown in the previous Section, it is possible to model the system as a generic second order system. In particular, the equivalent of the mechanical “mass – spring –damper” model in electronic is the well known “R – L – C” circuit. By this way it is possible to simulate the behavior of the system with electronic simulation software. The equation (3) is equivalent to the following Eq. (4). in the electronic field:

$$L \cdot \frac{di(t)}{dt} + R \cdot i(t) + \frac{1}{C}\int_0^t i(t)dt = e(t) \tag{4}$$

that represents the Kirchhoff's Voltage Law (KVL) to the RLC circuit designed, where L,R and C are respectively the values of Inductance, Resistance and Capacity of the circuit and i(t) is the current intensity depending from time t (s)

Considering equation (4) as a function of the electric charge *Q* – which is obtained for the charge conservation principle by integrating the current *i* between 0 and t – equation (4) can be written as equation (5):

$$L \cdot \ddot{Q}(t) + R \cdot \dot{Q}(t) + \frac{1}{C} Q(t) = e(t) \tag{5}$$

Then the schematic is composed by a generator *e(t)*, two storage elements (*L* and *C*) and a dissipative element (*R*) as for the mechanical one. Every single element could be compared to one mechanical element of the equation (3) and in particular:

$$L = m \tag{6}$$

$$R = c \tag{7}$$

$$\frac{1}{C} = k \tag{8}$$

$$Q(t) = x(t) \tag{9}$$

$$e(t) = F(t) \tag{10}$$

It is possible to simulate and measure the value of *x(t)* for a particular *F(t)*. Moreover in the circuit are represented the mechanical-electronic conversion by a transformer and the capacity of the piezoelectric which is an intrinsic parameter of the component. The circuit response to a sinusoidal input is analogue to the one obtained with the mechanical model.

B. Energy harvesting circuit

By this way it is possible to include in the circuit the energy harvesting part and tests it. The first element of the harvesting circuit is represent by a rectifier and in particular by a diode bridge to obtain a full-wave rectification and a capacitor in parallel to the bridge to obtain a DC voltage from the AC rectified voltage. Then the DC voltage can be adapted to the one required by the load with the use of a DC-DC converter. The power obtained by this circuit can be stored in a storage capacitor such as a rechargeable lithium battery (see Fig. 55).

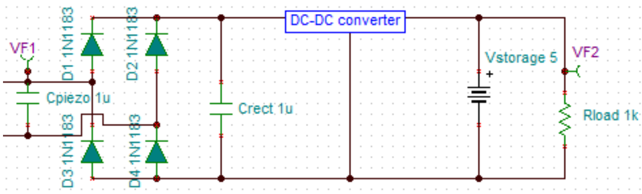


Fig. 5. Scheme of the energy harvesting circuit.

The design of electronic equipment in support has been focused with the aim of improving the generator efficiency and thereby increase the resulting power, with particular reference of power consumption of L.A.M.A. magnetometer, in order to reach longer period of autonomy of the system.

IV. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

A. Prototype mounting operations

The first step has involved the realization of the external support in plexiglass and of the two cylinder in carbon fiber.

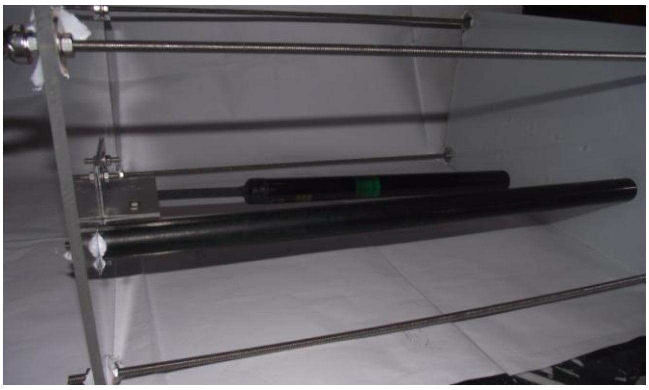


Fig. 6. Front view of the prototype

Subsequently the cantilever beam has been installed, with the piezoelectric sensor (MFC piezoelectric M2814-P2, produced by Smart Material Corp.).

B. Lunense canal hydrodynamic test

The aim of the test was to verify the prototype proper functioning, and to have experimental evidence of all results from the CFD analysis and from theoretical development of the mass / spring / damper model. The prototype has been raised with the aid of ropes and posed into the center of the canal, in order to avoid all edge contributes. To ensure complete stability of the prototype during the experiment, both ropes have been fixed at an equal height on the opposite sides of the canal (see Fig. 77).

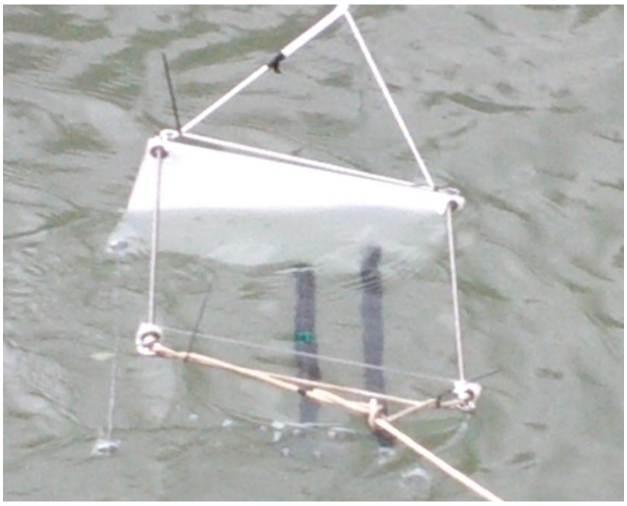


Fig. 7. Picture during the test: the prototype in Lunense canal.

Depending on days, the water flow rate varies, but always inside a typical range of values, a characteristic that makes it usable for small device testing in all seasons. In addition, water current has an average speed that is almost constant around 0.5 m/s, thanks to floodgates

The satisfactory results are listed below:

- The prototype has demonstrate to resist to water flow in all test conditions: in particular, integrity of cylinders, cantilever and piezoelectric material have been ensured

- The vortex generator cylinder induces a velocity field downstream as predicted
- The second cylinder, after a few second of transient effects has shown a vibration around 4-5 Hz, as predicted

C. *Complete prototype air preliminary test*

The aim of this second test campaign was to analyze the behavior of the full prototype after piezometer installation and insertion of electrical wiring, in order to connect the device to an electronic test rectifier, and consequently verify voltage output. As the whole system was not water-proof, the experiment was conducted outside water, using an industrial dryer to obtain a steady air flow inducing vibration.

An industrial oscilloscope has been used to analyze output voltage. The whole prototype and the oscilloscope are shown in Fig. 8

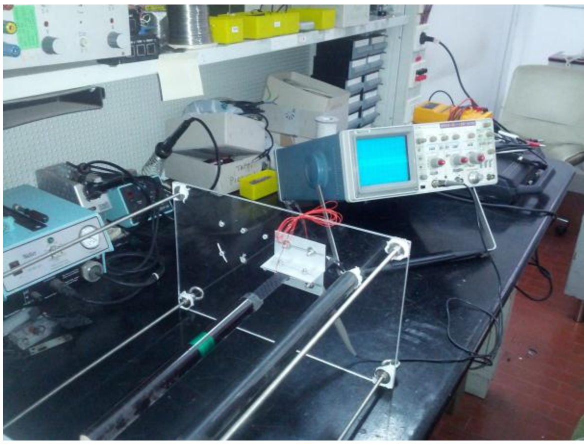


Fig. 8. The prototype during the test with the oscilloscope

As the flows of air started to interact with the device, the cantilever beam started to vibrate, with an intensity that was obviously less than that obtained with water flow in Canale Lunense, but enough to measure a moderate voltage output, with a peak of more than 30 V. The sinusoidal output is shown in Fig. 9.

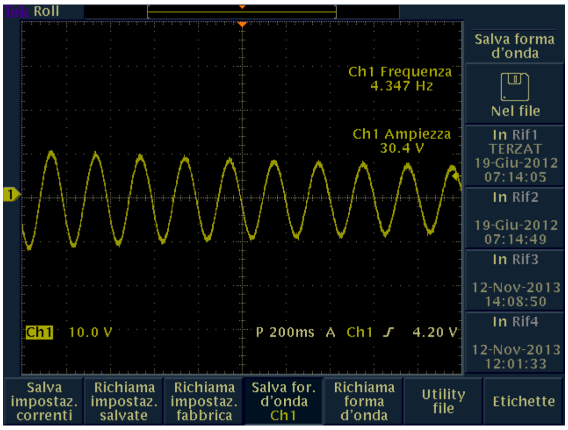


Fig. 9. Oscilloscope output screen

In the second phase of the test the rectifier has been connected to the piezoelectric thin foil, in order to obtain a DC output and supply various test LEDs. The rectifier used was a test platform, customized to select various output voltage (1.8 V, 2.5 V, 3.2 V and 3.6 V). (Fig. 10)

Fig. 10. Rectifier used for the test

After measuring the correct output with the help of a tester, a small LED of 1.6 V and an electrical resistance of 820 Ohm has been connected and the structure was forced to vibrate; after a brief transient phase, the LED remained alight.

The use of bigger LEDs led to less satisfactory results, with alternate phases of switching on and off. The use of a capacitor in support allowed to stabilize the lighting of the LED for a longer time, after a few second of recharge of the capacitor itself.

The results of this experiment are then summarized below:

- The prototype has demonstrated to successfully harvest energy from fluid-dynamic interactions
- Through the use of a rectifier it was possible to obtain a DC output to feed a small LED
- The estimated power output is 2-3 mW

V. Conclusions and Future Works

The aim of the project is to create a low cost energy harvesting device, which must be able to feed electrically a sensor or pack of sensors of modest power requires, especially magnetic sensors.

The actual development of this power unit has shown his real capability to-develop a synergy between the generator and the sensor-(Magneto-Variometer), with the aim of realizing an underwater systems for magnetic detection with high autonomy. All results obtained and described are encouraging.

The future objectives are to optimize the prototype in both aspects, fluid dynamic and electronic, in order to increase the power output, even with analysis of new possible configurations including multiple cylinders operating in sinergy.

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