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The Use of Compliant Surfaces for Harvesting Energy from Water Streams

Francisco J. Arias[a*] and Salvador De Las Heras[a]
[a] *Department of Fluid Mechanics, University of Catalonia, ESEIAAT C/ Colom 11, 08222 Barcelona, Spain*

The possibility for hydrokinetic energy harvesting from small water streams by using compliant surfaces is considered. The basis of the proposed idea is the deliberate bifurcation of a water stream into two streams separated by a compliant or membrane surface keeping an equalized static pressure in both sides but, however, with a relative velocity between both channels. Then, owing to this relative velocity of the water stream Taylor instabilities appear which set in oscillatory oscillatory motion the membrane. This motion can be converted into into a small electrical output power. Utilizing a linearized flow theory an analytical expression for the attainable power as function of several parameters was derived. Actual experimental investigations were undertaken which show a good agreement with the theoretical predictions. It was found that for a water stream with velocity around 2 m/s an output power around 30 mW/ cm ^{2} of area of the membrane is attainable. Because large areas can be covered inexpensively by the use of membranes, the concept is worthy to be considered for hydropower harvesting in water flows which are not suitable to be turbined either because a reduced pressure or little depth which prevents the use of turbines. Additional R&D is required in order to arrive at a reliable practical and commercial design.

Keywords. *Energy harvesting; Residual waters; Waste waters*

1. INTRODUCTION

Energy harvesting (EH), also called as energy scavenging, is a process that captures small amounts of energy that would otherwise be lost. Typical energy outputs from energy harvesters are from 1 μ W up to a few mW and can be derived from external sources such as solar power, thermal energy, wind energy, salinity gradients, and kinetic energy. The captured energy is then stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks, [1]-[3]. Methods of generating electrical power from those external sources include photovoltaics; thermoelectric generators (TEGs),[4]; micro wind turbine, [5], and deserving special mention vibrational generators which include a broad range of devices using piezoelectricity and capacitors [6]-[23] or travelling wave walls [24]. For those readers interested in the research aspects of energy harvesting technologies as well as the current state of knowledge in this field, the book edited by Priya and Inman (2009),[25] is recommended.

As regard to hydrokinetic power harvesting, almost all the technology are based in the used of micro turbines which although with a high efficiency, robustness and relative simplicity, nevertheless, can not be suitable for some applications in which the water stream either is of relatively low energy (reduced total pressure) or because the water stream is flowing in a very large area with a small depth and is not possible its canalization. Such could be the case, for residual waters which have been previously turbined, or for example, the water streams which can be found in watercourses.

The object of this work was to investigate a simple but reliable concept to extract hydrokinetic energy from those water streams which are not suitable to be turbined. The basis of the proposed idea is the deliberate bifurcation of a water stream into two streams separated by a compliant or membrane surface keeping an equalized static pressure in both sides but, however, with a relative velocity between both channels. Then, owing to this relative velocity of the water stream Taylor instabilities appear which set in oscillatory oscillatory motion the membrane. This motion can be converted into into a small electrical output power

* Corresponding author: Tel.: +32 14 33 21 94; francisco.javier.arias@upc.edu

I. MATERIALS AND METHODS

Although several designs can be envisaged in which a stream of a given fluid is separated into two regions by a compliant surface located in between and oscillating due to the relative velocity between both sides of the membrane, and then the specific result will depend, of course, on the specific design which is manifested in the equation of motion by the specific boundary conditions determined by the specific design. However, if a first estimate is desired, it is almost mandatory to represent the most general model which in addition unavoidably result from idealizations which are almost mandatory at least if analytical expressions are desired.

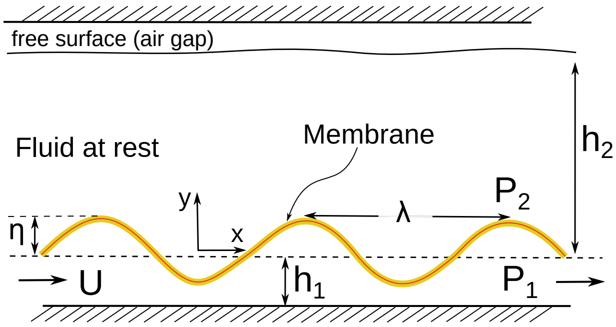

FIG. 1. Physical model for the oscillation of the membrane.

Nevertheless the objective of such general model is not typify estimates but rather to provide a first order of magnitude and then such idealizations are a powerful tool for a first test of proposed concept as is the case of the present paper. In pursuance of this objective, let us consider, the most general model for a compliant surface or elastic membrane which is separating a given fluid into two regions with a relative velocity between them as is sketched in Fig. 1.
Referring to Fig. 1, an elastic membrane is located at a distance h_1 from the bottom and bifurcating a stream of a given fluid into two regions (the bottom and upper region or region 1 and 2 respectively.) which are now moving with a definitive relative velocity between them, the velocity in the bottom region U is much more higher than that in the upper region (in order to maximize the oscillation of the membrane which depends on the relative velocity between the sides) and then, in comparison, it can be assume the the upper region is at rest. In addition, the upper second region is extended vertically a distance h_2 where $h_2 \gg h_1$ and for the sake of generality we assume that the upper fluid ends at a free surface which is desired in order to allow the free vertical motion of the fluid and then avoiding the damping of the oscillatory motion of the membrane (strictly speaking this is valid for an open system but in practice this may be promoted for closed system by allowing a certain air gap between the fluid and the top wall as depicted in Fig. 1). Now, because the relative velocity between both sides of the membrane, this is subject to disturbances which are manifested into a oscillatory motion. If we denote by η the vertical displacement of the membrane from the equilibrium in the plane $y = 0$ and the displacements of the membrane are small an then fluid behaves according to linearized flow theory. Mathematical treatment of linearized theory can be found in the classical treatise of Lamb (1945) [26], for our purpose suffice is to say that within the framework of the linearized theory the oscillatory motion of the membrane can be represented according to the infinitesimal disturbance.

$$\eta = \eta_o \cos(\kappa x - \omega t) \tag{1}$$

where η is the amplitude of the membrane wave at time t; η_o is the small-disturbance amplitude; $\kappa = \frac{2\pi}{\lambda}$ is the wave number with λ the wavelength; $\omega = \frac{2\pi}{T}$ the wave frequency with T the wave period; and x is the length co-ordinate. Now, if the thickness of the elastic membrane is so thin that it is allowable to assume that its stiffness and then its resulting restoring force caused by the displacement from its equilibrium position is similar than that from interface with a certain surface tension Γ, we obtain that the difference of pressure between both sides of the membrane at is given by [27]

$$P_1 - P_2 = \left[\frac{(\coth(\kappa h_2) + \coth(\kappa h_1))\omega^2}{\kappa} + 2U\coth(\kappa h)\omega + \kappa\coth(\kappa h)U^2\right]\rho\eta_o\cos(\kappa x - \omega t) \tag{2}$$

wavelengths for the oscillating membrane could be around millimeter or centimeter and then if $\kappa h_1 \gg 1$, and $\kappa h_2 \gg 1$ we have

$$\coth(\kappa h_2) = 1 \quad ;$$

$$\coth(\kappa h_1) = 1 \tag{3}$$

Natural frequency of oscillation for a membrane stretched may be expected to be around 100 hertz at most, on the other hand wavelengths for the oscillating membrane could be around millimeter or centimeter and then $\kappa \approx 10^3\ \mathrm{m}^{-1}$, thus if it is allowable to assume $\kappa U \gg \omega$ Eq.(3) further simplifies as

$$P_1 - P_2 \approx \kappa\eta_o\rho U^2\cos(\kappa x - \omega t) \tag{4}$$

The *pressure force* F_p on the rectangular membrane is obtained by integrating the pressure expression Eq.(4) over the membrane area. For extraction of energy from the sinusoidal motion of the membrane, for example by moving a magnet attached at the membrane, the dedicated length of the membrane L should be $L = \frac{N\lambda}{2}$, with $N = 1, 3, 5, \ldots$ otherwise there will be not net vertical motion, [28]. Taking $L = \frac{\lambda}{2}$ with the x origin at the center o the membrane we have

$$F_p = b\int_{-\frac{\lambda}{4}}^{\frac{\lambda}{4}} (P_1 - P_2)dx$$

$$= 2b\eta_o \rho U^2 \cos\omega t \quad (5)$$

and the *average force* over the wave period

$$\bar{F_p} = \frac{4}{T}\int_0^{\frac{T}{4}} F_p dt$$

$$= \frac{4b\eta_o\rho U^2}{\pi} \quad (6)$$

and the *average power* per unit of width of the membrane as

$$\bar{W_b} = \frac{\bar{F_p}}{b} v_y \quad (7)$$

where v_y is the average vertical velocity. If the converter consists, for example, in a magnet with small dimensions attached at the membrane and moving up and down and extracting energy by electromagnetic induction on a coil, then, the beverage velocity is approximately given by $v_y \sim \frac{4\eta_o}{T}$, i.e, traveling an amplitude η_o during a quarter of period. Thus, Eq.(7) becomes

$$\bar{W_b} \sim \frac{16}{\pi T}\eta_o^2 \rho U^2 \quad (8)$$

Given a fluid stream with a certain velocity U, then in Eq.(8), the only parameters which are unknown are the amplitude η_o and the period of the oscillations, nevertheless, plausible ranges for velocities of water streams up to 1 m/s the amplitude expected for a hydro-harvester could be less than 1 cm, frequencies up to 50 Hertz or thereabouts. For the sake of illustration, Fig. 2 and Fig. 3. show the range of power attained as function of the water stream velocity (for a fixed frequency of 10 Hz) and as function of frequency (for a fixed water stream velocity of 1 m/s) and for the practical range o amplitudes of oscillation expected.

- **Experimental setup**

Actual experimental investigations were undertaken by using several cavities and configurations until the best design was attained. The experiment was performed in a rectangular narrow cavity 7.5 cm long, 5.5 cm high

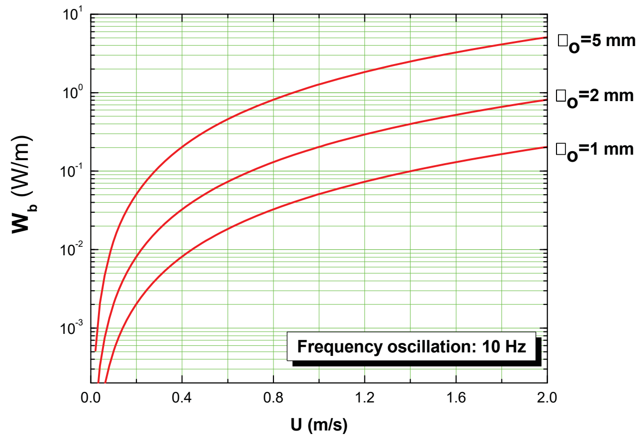

FIG. 2. Plot of power per unit of membrane width $\bar{W_b}$ as a function of water velocity U for a frequency of oscillation 10 Hz and several values of the amplitude calculated from Eq.(8)

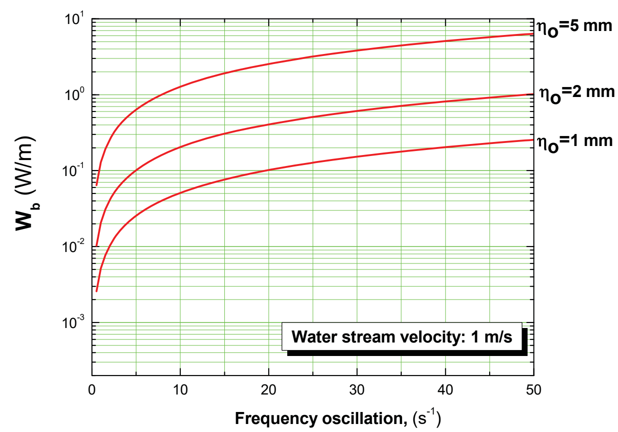

FIG. 3. Plot of power per unit of membrane width $\bar{W_b}$ as a function of frequency of oscillation for a water stream velocity 1 m/s and several values of the amplitude calculated from Eq.(8)

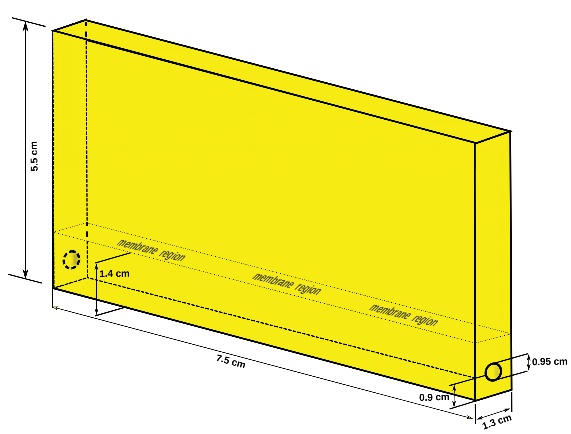

FIG. 4. Sketch of the experimental setup

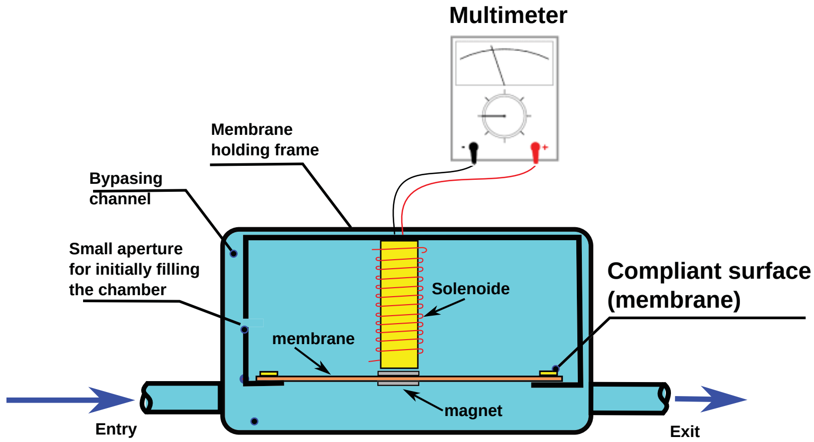

FIG. 5. Sketch of the experimental setup.

and 1.3 cm in width, and with two perforations of 0.95 cm in diameter (for the entry and exit of water) and centered in the sides of the cavity at 0.89 cm from the bottom, and the region of the membrane was located at 1.4 cm from the bottom, see Fig. 4. A stream of fresh water of density $\rho = 1$ g/cm^3 and kinematic viscosity $\nu = 0.01$cm^2/s from a domestic water intake with with a 3.5 bar exit pressure and 290 K of temperature was used for the experiment. The cavity was built with methacrylate for visualization.

The compliant surface was of rubber membrane 6 cm long and 1.2 cm in width and attached to an aluminium frame at the edges in such a way that a gap between the membrane and the wall around 0.05 cm was allowed. This gap has two important contributions, namely: on one hand allows the free transverse motion of the membrane; and on the other hand allows an entry of water from the bottom chamber (the bottom of the membrane region) to the upper chamber (top of the membrane region) and then allowing to equalize the static pressure in both sides of the membrane which is one of the key requirements for the proposed hydro energy harvester. The rubber membrane was with a thickness on 1 mm and with a surface tension around 5.5 N/m for small displacements from its untensioned position. Finally, in order to extract the energy of the vibrating membrane a *linear inductance generator* was chosen which simply consisted of a permanent magnet attached at the surface of the membrane and moving through a coil located vertically, see Fig. 5. The single coil was a conducting copper wire loop 2 .5 cm long, and with an external diameter 1.0 cm, and internal diameter 2.35 mm, electrical resistance $R = 1000\ \Omega$ and situated in front of the permanent magnet attached at the membrane and at a distance of 0.4 cm. The coil was fixed at the top of the aluminium frame and aluminium was chosen as non-magnetic material and then avoiding damping effects in the system.On the other hand, the permanent magnet was a strong neodymium magnet of 20 grams in weight, 1.2 cm in diameter and with a magnetic field at its surface of 0.2 T. Fig. 6 shows the real configuration of the system.

The electrical current was produced in the coil as a result of the relative motion of the permanent neodymium magnet in vibrating motion attached at the membrane when the water is circulating according with our preceding discussed theory.

The voltage ΔV , resistance R and frequency ω was measured by using a multimeter and oscilloscope and the electrical power W_e by applying the well know formulae:

$$W_e = \frac{\Delta V^2}{R} \tag{9}$$

The water velocity in the cavity u was calculated indirectly by measuring the volumetric flow Q in the water intake by using a simple test-tube and chronometer and then dividing by the cross section of the cavity as $u = \frac{Q}{A_c}$.

II. RESULTS AND DISCUSSION

The resulting curve is shown in Fig. 7 for the power per unit of area of membrane as a function of the velocity of water. It is seen, that up to 30 mW/cm ^{2} may be extracted from water streams with velocities around ~ 2 m/s, which has merit if it is considered that the experimental device was by no means optimized and then some important parameters with a clear influence on the power are not maximized a sis the case for the amplitude of oscillation and the quadratic dependency of the power with it as we can be seen in Fig. 2. The quadratic dependency with the amplitude of the power is a general feature for power from waves,[28]. Finally, by comparison, typical harvesters of high performance can extract up to 0.1

FIG. 6. Experimental setup of the cavity used

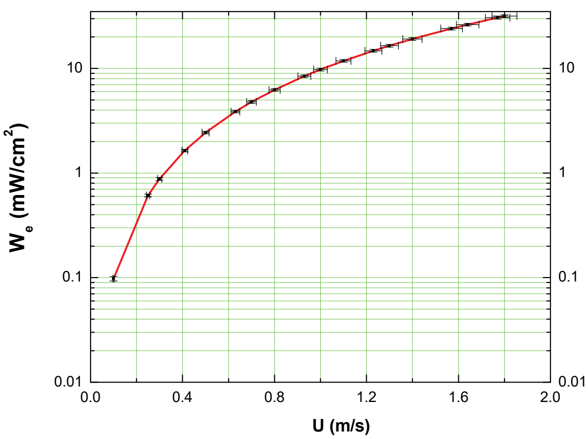

FIG. 7. Plot of the power per unit of area of membrane as a function of the water stream velocity.

W cm^2 or thereabouts,[29], and therefore, the proposed concept can be competitive. Furthermore, it must be considered that large surfaces can be covered by the use of membranes with a relative low cost, the conversion of energy from the motion of the membrane can be as easy as used in the experimental setup, i.e., by attaching small mini magnets along the surface of the membrane and using micro-coils for electromagnetic induction, and thus, it could be specially attractive for covering water streams with large free surfaces as for example in shallows river streams.

III. CONCLUSIONS

The possibility of extracting small power outputs from water streams by the use of compliant surfaces was discussed. By using a simple no optimized electromagnetic converter it was found that for water streams with velocities up to ~ 2 m/s power outputs around ~ 30mW/ cm ^{2} of area of the membrane could be attained and then the idea is worthy to be considered for energy harvesting. Additional R&D is required in order to arrive at a reliable practical and commercial design.

5. NOMENCLATURE

b = width of the compliant surface
h = depth
P = pressure
R = electrical resistance
t = time
T = wave period of small disturbance
U = flow velocity
ΔV = voltage
W = power
x = length co-ordinate
y = transverse co-ordinate measured from the membrane

Greek symbols
κ = wave number
η = amplitude of the membrane waves at time t
η_o = small-disturbance amplitude
λ = wavelength of small disturbance
ρ = density of the fluid
ω = wave frequency

subscripts symbols
1 = bottom fluid region
2 = upper fluid region (fluid at rest)
m = membrane/compliant surface
o = initial or reference value

6. ACKNOWLEDGEMENTS

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