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# Investigations into efficiency of vortex induced vibration hydrokinetic energy device

K. Narendran[*], K. Murali, V. Sundar

*Department of Ocean Engineering, IIT Madras, Chennai, India*

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ABSTRACT

A number of innovative concepts were proposed to harness energy from waves, currents, tides, and offshore winds. Over the past decade, the possibility of utilizing the oscillations due to VIV (vortex induced vibration) for possible power generation has received considerable attention. In order to understand the underlying physics behind this problem under high Reynold's number, a comprehensive physical model study was taken up. The present experimental set-up consists of a linear generator which has low mechanical losses, leading to a higher mechanical efficiency. The peak mechanical efficiency value of around 90% with corresponding time average value of about 50% are achieved using linear generator at $Re$ of the order ($10^5$). A new analytical model is proposed to predict the efficiency of the oscillating system from the field values such as maximum amplitude response ($Y_{max}$) and frequency ratio ($f^*$). Through validation with available literature, it is demonstrated that the proposed analytical model is a suitable tool in predicting the mechanical efficiency of the oscillating system. A detailed parametric investigation has been carried out over a wide range of system parameters such as mass ratio ($m^*$), damping ratio ($\zeta$) and Reynolds number ($Re$).

## 1. Introduction

There are several possibilities for harnessing energy from the ocean. A summary of clean renewable energy options is provided in Table 1. The most successful source in terms of both concept and technology is the tidal energy that depends on the tidal range. Due to the rise and fall of tides, water currents are generated. Kinetic energy contained in these currents could be significant for harvesting when the current exceeds 1.5 m/s. The concept of barraging is an alternative approach, which is a successfully proven concept, among other tidal energy concepts. The La Rance tidal power station of France is the best example for power generation through barrages currently operational with efficiency of about 28%. In the conditions where, barraging is not feasible, tidal stream energy could be an option using tidal stream turbines. The largest one of its kind is SeaGen tidal stream power generation system fixed to the sea bed located in Northern Ireland with efficiency of 66% and for floating type of tidal stream turbines the efficiency is around 60% (Atlantis Resources). There are ocean currents that are part of general ocean circulation, the chief example being Gulf Stream. Gulf Stream Turbines [1] is another concept-demonstration for conversion of kinetic energy.

Apart from tides, the wind-generated waves are capable of carrying energy over long distances. The wave energy is another possible option for energy generation. There are a number of devices proposed in the past to harness energy from waves. These are called WECS (wave energy converting systems). Among various WECS, OWC (oscillating water column) is a very promising one. The LIMPET (Land Installed Marine Power Energy Transmitter) shoreline OWC [2,3] of Islay, Scotland, is a key project presently operational with a conversion efficiency of 70%–84%. Installation of OWC in Vizhinjam at the coast of Kerala was a pilot project in India [4]. The possibilities of extracting energy from the oceans due to temperature differences between hot ocean sea surface and cold bottom water also exists. The technology based on this concept is termed as OTEC (Ocean Thermal Energy Converter), which is feasible only in the sea regions between Tropic of Cancer and Tropic of Capricorn. The estimated efficiency for OTEC is around 7%. The most successful OTEC based energy-harnessing device is located in Okinawa Prefecture, Japan [5] and it is currently operational. Further, the salinity differences between fresh and ocean water (at river mouths, tidal inlets, etc) aids in energy generation.

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[*] Corresponding author. Tel.: +919840043898.
*E-mail address:* knaren.27@gmail.com (K. Narendran).

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**Table 1**
Summary of various marine renewable energy options.

| Marine renewable energy technology | Sources | Mechanical efficiency (%) |
|---|---|---|
| OPT Power Buoy | [14] | Unavailable |
| Pelamis (2005) | [13] | Unavailable |
| OWC (LIMPET) | [2,3] | 70–84 |
| Offshore wind turbines | [12] | 40 |
| OTEC | [11] | 7 |
| VIVACE | [6,7] | 37 |
| VIVEC | Present case | 50 |

### 1.1. *Energy from vortex induced vibration*

VIVACE (Vortex Induced Vibration Aquatic Clean Energy) was an attempt for extracting ocean current energy [6]. The bluff bodies that are slender in nature such as mooring lines, offshore structures, transmission lines, chimney towers, etc., commonly undergo large oscillations due to boundary layer separation and formation of vortices, resulting in vibration. VIVACE was a demonstration of generating power from vortex-induced vibration of a cylinder. When the natural frequency of the structure is equal to vortex shedding frequency at the resonance condition, the structure experiences large magnitude of vibrations/oscillations. In order to take advantage of these phenomena, the cylinder is mounted over springs with suitable stiffness so that large sustained oscillations could be achieved. It was suggested that enormous power could be generated from an array of cylinders [6]. A comprehensive economical viability study based on the laboratory tests was reported [7].

VIVEC (Vortex Induced Vibration Energy Converter) is an attempt along the lines of VIVACE (Vortex Induced Vibration Aquatic Clean Energy) [6,7], for production of clean energy from water currents and streams. Since tide is the primary marine current generating mechanism of the ocean, it is conceived that, the VIVEC to be another potential technology for tidal current energy. The technology could be directly adapted to rivers and estuaries too. In VIV, Reynolds number (*Re*) usually defines the flow regime. In the field conditions, VIV commonly occurs in the critical *Re* regime of $10^5$-$10^6$. In the present effort, experiments are planned under the above stated *Re* regime. A cylinder with diameter ($D$) and aspect ratio ($L/D$) is mounted over a pair of springs. The stiffness ($K$) of the springs is chosen according to range of velocities ($U$) available in the Towing tank facility of Department of ocean engineering, IIT Madras, India. The present paper focuses on the demonstration of VIV energy conversion at *Re* closer to field conditions. Furthermore, an analytical model is proposed for estimating the mechanical efficiency of the system. In addition, the results from a detailed parametric study over a wide range of system parameters are reported.

## 2. VIVEC (Vortex Induced Vibration Energy Converter)

VIVACE and the present system work on principle of VIV. The transverse motion of cylinder due to VIV is proposed to be coupled to a suitable generator. The energy conversion has been successfully demonstrated in the laboratory [6,7]. In the previous study, the heave oscillation of the cylinder was converted to circular motion using rack and pinion mechanism coupled to a conventional D.C generator. One of the marked differences in the present effort compared to the previously published work is the application of a linear generator to have better mechanical efficiency. Thus, it is expected to improve the efficiency of the system as the losses in the linear generator would be lesser compared to the rack and pinion

**Table 2**
Nomenclature of variables and non-dimensional parameters.

(a) Dimensional variable and its definitions

| Notations | Definitions | Notations | Definitions |
|---|---|---|---|
| $m$ | Mass of the test cylinder (*kg*) | $f_s$ | Vortex shedding frequency (*Hz*) |
| $m_a$ | Added mass of the test cylinder (*kg*) | $C$ | Damping constant (*Ns/m*) |
| $D$ | Diameter of the test cylinder (*m*) | $K$ | Spring constant (*N/m*) |
| $L$ | Length of the test cylinder (*m*) | $y$ | Displacement of the cylinder (*m*) |
| $\rho$ | Density of water ($kg/m^3$) | $P$ | Power (*W*) |
| $U$ | Flow velocity (*m/s*) | $V$ | Volts (*V*) |
| $f_n$ | Natural frequency of the system (*Hz*) | $R_L$ | Load resistance ($\Omega$) |
| $f_{os}$ | Cylinder oscillating frequency (*Hz*) | | |

(b) Non dimensional variables and its definitions

| Notations | Definitions | Formulas | Values and ranges |
|---|---|---|---|
| $m^*$ | Mass ratio | $\frac{4m}{(\pi D^2 L\rho)}$ | 0.87, 1.01, 1.35, 2.52 |
| $Re$ | Reynolds number | $\frac{\rho UD}{\mu}$ | (0.22–2.52)x$10^5$ |
| $U_r$ | Reduced velocity | $\frac{U}{f_n D}$ | 2–14 |
| $St$ | Strouhal number | $\frac{f_s D}{U}$ | 0.2 |
| $\zeta$ | Damping ratio | $\frac{C}{\sqrt{(m+m_a)K}}$ | 0.058, 0.097, 0.131, 0.066 |
| $Y$ | Amplitude ratio | $\frac{y}{D}$ | |
| $f^*$ | Frequency ratio | $\frac{f_{os}}{f_n}$ | |
| $\alpha$ | | $(m^* + C_A)\zeta$ | |
| $\eta_{mech}$ | Mechanical efficiency | Power output/Power input | |
| $\eta_{electrical}$ | Electrical efficiency | | |
| $\eta_{overall}$ | Overall efficiency | | |