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Hydrodynamic and Electromechanical Simulation of a Snapper Based Wave Energy Converter

H. Bailey, R. C. Crozier, A. McDonald, M. A. Mueller, E. Spooner, P. McKeever

***Abstract* -- A coupled electromechanical and hydrodynamic simulation of a novel generator connected to a heaving buoy for wave energy conversion has been developed. The simulation is based primarily in MATLAB using its built-in Ordinary Differential Equation (ODE) solvers. These solvers have acted on the data derived from an electromagnetic finite element analysis and from the WAMIT wave interaction simulation software, to simulate the full system in the time domain.**

***Index Terms*--permanent-magnet generator, direct-drive, hydrodynamics, marine technology, wave energy.**

I. Introduction

WAVE energy has the potential to provide significant amounts of sustainable power if the associated engineering challenges of operating in the marine environment can be overcome whilst minimizing costs [1].

At near shore sites, such as those suitable for the Wave Energy Converter (WEC) described in this paper, there is less energy available than offshore locations. However, there is still a substantial amount of wave energy available. The slight reduction in the energy available due to the shallower water depths is compensated by the reduced occurrence of extremely large waves and very high energy sea states with the associated survivability problems [2]. Locating a device in shallower water will also result in reduced installation, maintenance and repair costs and furthermore reduce the length of expensive subsea electrical transmission gear necessary to bring the electricity ashore.

However, the cost of the inevitable repairs and maintenance throughout its lifetime faced by any WEC remains a major difficulty. One proposed method of minimizing the required maintenance is the use of a system based around a direct-drive linear generator [3].

WECs typically undergo high forces at much lower velocities than the optimum speed of conventional generator technologies. Therefore, to achieve reasonable efficiencies at these low speeds, direct-drive generators tend to require large amounts of high coercivity permanent magnet material and, as a consequence, bulky structures to maintain the airgap against the Maxwell stresses induced by the high strength magnetic field. Both of these requirements result in heavy and expensive machines which are difficult to construct and handle.

The WEC being discussed in this paper consists of a point absorber, heaving buoy attached via a tether to a translator which reacts against an armature. The armature is connected to a linear spring which is fixed to the seabed. An overview of the system is illustrated in Figure 1.

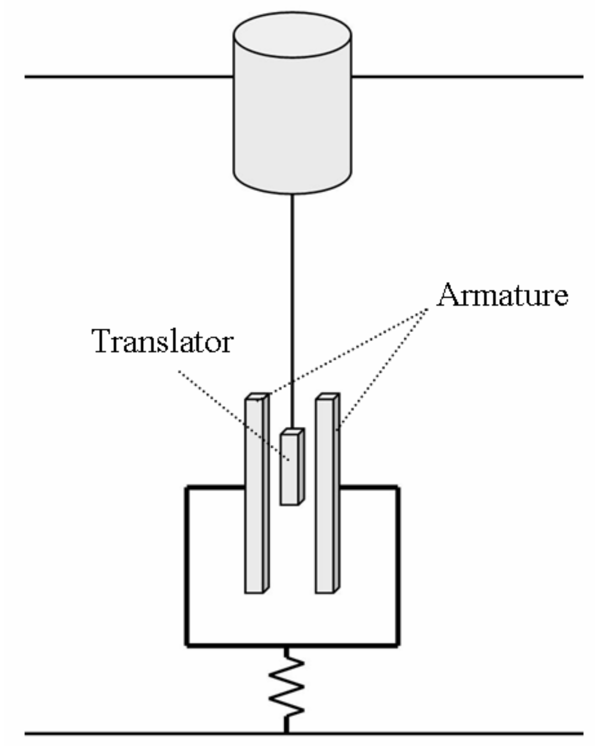

Fig. 1. Wave energy converter consisting of a snapper generator connected to heaving buoy and a fixed base.

This paper represents a novel contribution as it presents a combined electromagnetic and hydrodynamic simulation for this type of WEC. Currently the WEC discussed in this paper is theoretical, but a prototype is in the process of being designed and built.

II. Snapper

To reduce the weight and cost of the generator, a novel system incorporating a spring element and a snapping magnetic coupling has been proposed [4]. The generator consists of two members, the armature and translator, as presented in Figure 2. The armature sides are rigidly connected to each other and move as a single element. Both the armature and translator have magnets mounted along their length with alternating polarity, as illustrated by the arrows in the figure, with the power producing coils wound around the magnets on the armature. The armature is connected to a fixed base, i.e. the seabed, via a linear spring element and the translator is coupled to a heaving buoy, as shown in Figure 1. Several alternative topologies are possible with the spring, and coils in alternative positions, but this arrangement is the only type considered in this paper.

Initially, the translator and armature are locked together in the most stable configuration by the magnetic attraction forces, with the opposing magnet poles facing each other.

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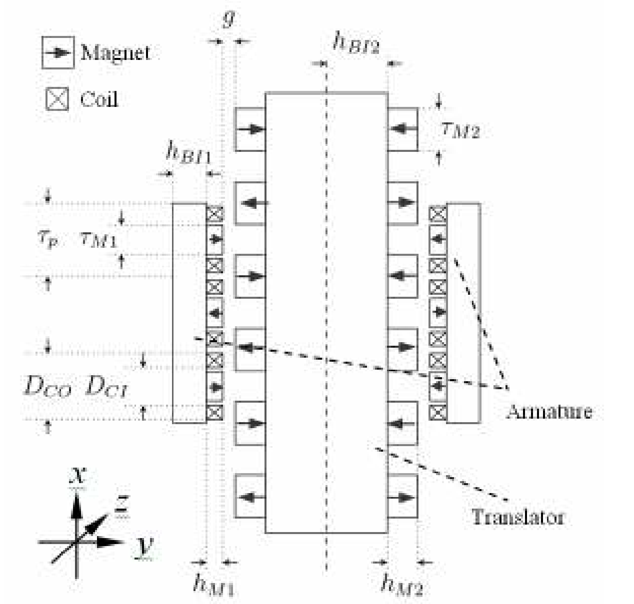

Fig. 2. Cross section of the snapper device showing major dimensions. The dimension in the z direction is the stack length with power producing motion in the positive x-direction. The spring is not shown.

When the buoy experiences an upward force due to the action of the waves, the armature and translator move upwards together, and continue to do so until the spring force exceeds the magnetic coupling forces. At this point, the snapping action takes place and the armature is rapidly accelerated at a high relative velocity in the direction of the spring forces, resulting in the generation of large EMFs in the coils as they are rapidly cut by the changing magnetic flux.

To fully exploit the described 'snapping' action and investigate the full dynamic behaviour of the system, a combined electromechanical generator and hydrodynamic buoy model has been developed.

III. Electromechanical Model

The relative positions and velocities of the armature and translator are required to determine the flux linkage and resulting EMF generated in the coils during dynamic operation. The positions, velocities and accelerations are defined in Table I. The relative positions and velocities of the armature and translator, x_R and v_R, are given by (1) and (2) respectively,

$$x_R = x_A - x_T, \tag{1}$$

$$v_R = v_A - v_T. \tag{2}$$

Within the machine, forces arise due to the interaction of the two sets of magnets and the electromagnetic damping forces due to the current carrying coils. The most accurate method of simulating the electromagnetic forces and other quantities of interest, such as the flux linkage (λ) in the coils, is to perform Finite Element Analysis (FEA). Taking this approach ensures the effects of magnetic saturation are accounted for and the profile of the forces at different relative positions is simulated accurately. Unfortunately FEA is computationally intensive, and time-stepped FEA would be practically infeasible.

Therefore, to minimize the necessary computational time, a look-up table of the values of interest is compiled from FEA results at different values of relative positions (x_R) and coil current densities (J). Polynomials are then fitted to this data with the independent variables being x_R and J and the dependent variable being the output values of interest. The FEA was performed using FEMM [5], an open source, finite element analysis package.

TABLE I
Definitions of Position, velocity and acceleration variables

Simulation Variable	Description
x_A	Position of the armature (relative to global)
v_A	Velocity of the armature (relative to global)
a_A	Acceleration of the armature (relative to global)
x_T	Position of the translator (relative to global)
v_T	Velocity of the translator (relative to global)
a_T	Acceleration of the translator (relative to global)
x_R	Relative displacement of the armature and translator
v_R	Relative velocity of the armature and translator

The flux linkage in the coils is the total flux passing through the closed loop formed by the conductor turns. Using a two-dimensional FEA formulation, this can be obtained from the vector potential (A) in the positive and negative parts of the coil. If we denote the cross-sectional area of the coil, S, and the number of turns in the winding, N, the flux linkage is then given by (3),

$$\lambda = \frac{N}{S}\left(\int_S A_+ dS - \int_S A_- dS\right). \tag{3}$$

The EMF produced in the coil is the rate of change of flux linkage with respect to time, which can be obtained from the following,

$$EMF = \frac{d\lambda}{dt} = \frac{d\lambda}{dx_R}\cdot\frac{dx_R}{dt} = \frac{d\lambda}{dx_R}\cdot v_R. \tag{4}$$

The derivative of the flux linkage with respect to relative position, in the previous equation, is found by taking the numerical derivative of the polynomial fitted to the look-up table mentioned previously with respect to x_R, while holding J constant.

The x-directed component of the electromagnetic forces between the two parts of the machine is denoted F_{EX}, which are defined as positive upwards for the armature and the spring forces be denoted F_S, where the spring forces are defined as positive upwards. The acceleration of the armature is given by (5), where m_A is the mass of the armature,

$$a_A = \frac{d^2 x_A}{dt^2} = \frac{F_{EX} + F_S}{m_A}. \tag{5}$$

If it is assumed that the machine is connected to a simple series circuit of lumped circuit elements as shown in Figure 3. The current in the resulting circuit can then be found by solving the differential equation obtained from nodal analysis, presented in (6), where R is the total resistance of the circuit, i.e. the combined load and coil resistance and L is the inductance,

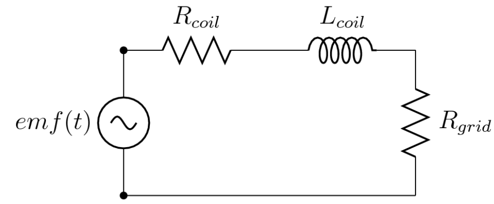

Fig. 3. Simple RL Circuit used to simulate connection to a resistive load, R_{coil} *and* L_{coil} are the the winding resistance and inductance, R_{grid} the load resistance.

$$\frac{di(t)}{dt} = \frac{EMF - i(t)R}{L}. \qquad (6)$$

The resulting system of equations can be combined with those describing the hydrodynamic simulation of the buoy, to form a complete model of the buoy and generator system.

IV. Hydrodynamic Forces

The motion of bodies in ocean waves have been initially simulated in the frequency domain, based on Stoke's linear wave theory, [6], [7], and modelled in the time domain, originally by Cummins [8] and Jefferies [9]. Time domain simulations have been used for various types of WEC, especially where nonlinear forces operate on the buoy, typically due to the control strategy used, [10], [11] or due to a nonlinear Power Take Off (PTO) system [12].

The hydrodynamic forces that operate on this axi-symmetric cylindrical buoy are the excitation, radiation and buoyancy forces. These forces and the resulting motions are only considered in heave at present. This is because the buoy has been tested with incident waves near its resonant heave frequency. Therefore, larger motions would be expected in heave compared to other directions and rotations, so the influence of these directions on the generator would be limited.

The relative position, from rest, of the buoy in heave is the same as the translator. This is because the total mass of the translator results in the flexible connecting tether never becoming slack, therefore, they are considered to be linked by a rigid light rod.

The buoyancy force, F_{BUOY}, is based on Archimedes' principle. It is equivalent to $\rho g \pi r^2 x_T$, where ρ is the density of water, assumed to be 1025 kg/m^3 for salt water, g the acceleration due to gravity and r the radius of the buoy.

The excitation force, F_{EXCIT}, is the force required to keep the buoy still when experiencing incident waves. When this force is combined, due to linear superposition, with the radiation force, the total dynamic forces from the incident waves are known. The excitation force is a function of the amplitude, frequency and phase of the waves and the shape and the mass distribution of the buoy and it depends on the current time only. The values are obtained from WAMIT [13], which is a boundary element method software, first developed by Newman's group at MIT.

The radiation force is the force required to move the cylinder in still water, in the same manor as it responds to incident waves and, in this paper, the Snapper generator. The radiation force, without a component which is related to the added mass at an infinite frequency, is denoted by F_{RAD}. It is a function of the velocities of the buoy at the current and all previous times and the shape and mass distribution of the buoy. It is calculated from (7) with the function K given by (8).

$$F_{RAD} = \int_0^t v_T \; K(t-\tau)\, d\tau , \qquad (7)$$

$$K(t) = -\frac{2}{\pi}\int_0^\infty \omega\left(M_B(\omega) - M_\infty\right)\sin(\omega t)\, d\omega \qquad (8)$$

Where ω is the angular frequency of the buoy, M_B is the added mass of the buoy and τ is a dummy variable related to time. M_∞ is the finite value of the added mass of the buoy, at an infinite frequency. As Sharpkaya [7] discusses, the added mass is the mass of water that moves with the body and hence needs to be accelerated with the buoy.

Prony's method [14] is used to significantly reduce the computational time taken for the calculation of the radiation force. This method has been used to calculate the value of *K(t),* by equating (8) into a summation of exponential functions, a finite number of these provide an approximately accurate result.

$$K(t) \cong \sum_{n=1}^{N} \alpha_n \exp(\beta_n t), \qquad (9)$$

where α_n, and β_n are the constants of the exponential functions.

By setting $F_{RAD} = \sum_{n=1}^{N} F_{RAD-n}$, the differential of F_{RAD} with respect to time is equivalent to the summation of the differentials of F_{RAD-n}, which, using the mathematical technique *differentiating under the integral sign* are calculated from,

$$\dot{F}_{RAD-n} = \beta_n I_n + \alpha_n v \qquad (10).$$

For this simulation, twenty α_n, β_n, couples have been used and were shown to have greater than 99% accuracy compared to the *K(t)* from (8).

The limitations of the hydrodynamic simulation are mainly due to the friction between different parts of the WEC not being accounted for and the assumptions of linear wave theory.

There will be friction and damping, which no attempt has been made to simulate, between the support structure and the tether, translator and armature.

The linear wave theory assumptions assume that the waves are small compared to their wavelength and the surfaces of the bodies and the seabed are smooth. It is based on an irrotational body of water, therefore eddies, turbulence, wakes and flow separation are not incorporated into the simulation.

All of these effects that are not included in this simulation will result in a reduction of the amplitude of the motion of the buoy. The reduction will be proportionally greater when the response of the buoy is large. Therefore, it can be assumed that all amplitudes seen in this numerical simulation, and hence voltage and power output, will be greater than the physical model.

V. Combined Model

The methodology used in this paper involves a summation of the different hydrodynamic, electromagnetic and spring forces. The equation of motion for the armature was given in (5) and similarly, the equation for the translator / buoy is given by (12) where m_{TB} is the mass of the translator and buoy combined.

$$(m_{TB} + M_\infty)a_T = F_{EXCIT} + F_{BUOY} - F_{RAD} - F_{EX} \qquad (12)$$

A simulation of the combined system has been performed for an unoptimised prototype size machine described by the variables shown in Table II, where l_s denotes the stack length

TABLE II
SIMULATED GENERATOR DIMENSIONS

Dimension	Value (mm)	Dimension	Value (mm)
τ_p	83.3	h_{BI2}	33.7
h_{MI}	31.0	τ_{MI}	8.9
h_{M2}	20.5	τ_{M2}	41.7
l_s	300	D_{CO}	77.8
h_{BI1}	11.2	D_{CI}	21.1

of the machine, attached to a small scale buoy. The simulation was performed for a monochromatic sea (i.e. single frequency sinusoidal sea waves) with frequency 0.4 Hz and amplitude 0.75 m. The buoy used in this case was an axi-symmetric cylinder of radius 0.5 m with a 1 m draft and a height of 1.5 m. The spring constant was 579 N/mm.

The simulation was performed for 60 seconds of operation starting from rest with the hydrodynamic, electrical and mechanical results shown in Figures 4 to 9; with close up views of the point at which snapping occurs presented in Figure 10. The mean power exported to the grid was calculated as the mean power dissipated in the load resistance during the simulation. This was approximately 360 W over the entire simulation time. However, if only the period after 'snapping' has occurred is considered, i.e. 22-60 seconds, the mean power rises to 866 W. As stated previously, there will be additional losses in a real device not accounted for in this model which would reduce this value.

The total energy extracted during the simulation was 23.5 kJ. The voltages and currents shown in Figures 6 and 7 are for a single coil on an armature made up of six poles. The translator was assumed sufficiently long to accommodate any movement with a full overlap between the armature and translator.

VI. DISCUSSION

One interesting aspect of the system behaviour arising from this dynamic simulation is the effect of the magnetic forces after the snapping action has occurred. When the magnetic attraction forces are exceeded by the wave forces, the armature rapidly accelerates and begins to oscillate; initially at the natural frequency of the mass-spring system, almost completely decoupled from the motion of the translator. This is in contrast to the expectation that the armature and translator would rapidly fall into the stable locked position relative to each other resulting in a series of short jerking movements. The motion instead continues for some time until the momentum of the armature is unable to overcome the magnetic attraction forces. Until this occurs, the forces between the armature and translator due to the interaction of the permanent magnets rapidly flip from positive to negative yielding a net acceleration of approximately zero. The armature still undergoes forces due to the energy extraction of the coils resulting in a damped oscillation. In practice, friction within the machine will provide further damping.

Due to the complex interaction of the system parameters, it is difficult to predict the performance, or general behaviour of the system in random seas more representative of real wave climates. For this reason it is expected that manual design of the device, including the spring, will be difficult and require the use of some computer aided optimization process based on devices scored through simulations in these conditions. A genetic algorithm approach has been identified as a suitable candidate.

The analysis of this WEC implies that this concept is entirely feasible. This will be confirmed when a more fully developed prototype system design has been built and tested in a wave tank. The cost of electricity from this device has not been calculated as the simulation is based on a scaled prototype and therefore can not predict the costs associated with a full scale device. Moreover, the cost reduction from mass manufacturing methods would not be included.

VII. CONCLUSIONS

A combined hydrodynamic, electrical and electromechanical model of a heaving buoy coupled to a novel power take-off method consisting of a direct-drive permanent magnet generator in which the armature is coupled to spring and allowed to move relative to the translator has been presented. The model is based on linear wave theory and the application of standard equations of motion combined with a polynomial approximation of results generated through electromagnetic FEA

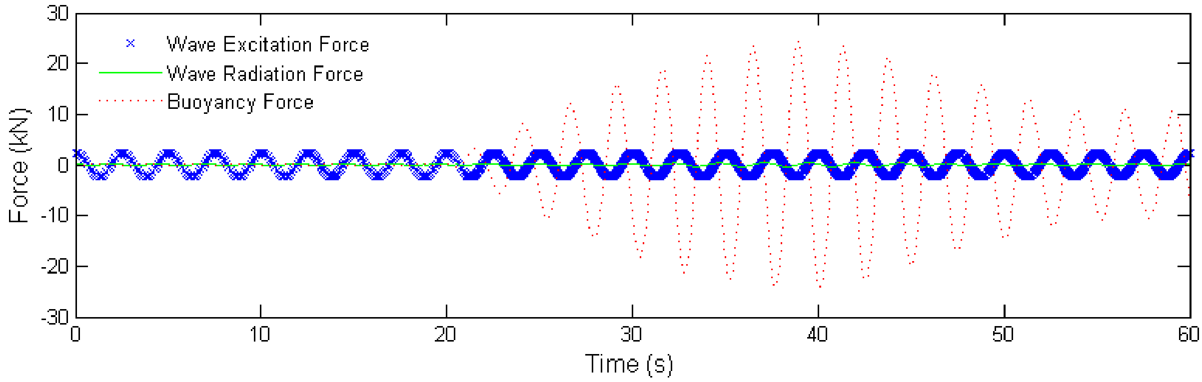

Fig. 4. Wave forces acting on the buoy.

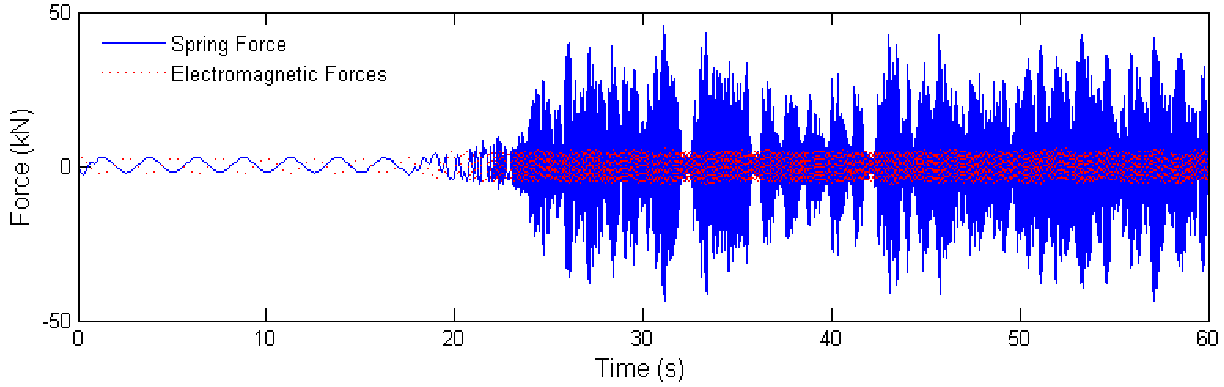

Fig. 5. Forces acting on the armature, the electromagnetic forces and spring force.

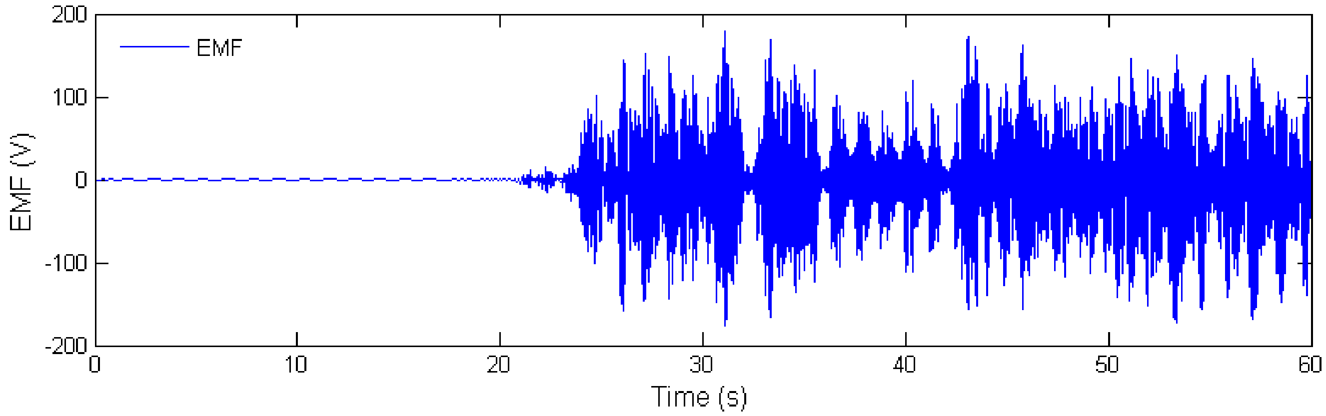

Fig. 6. EMF generated in a single coil of the device.

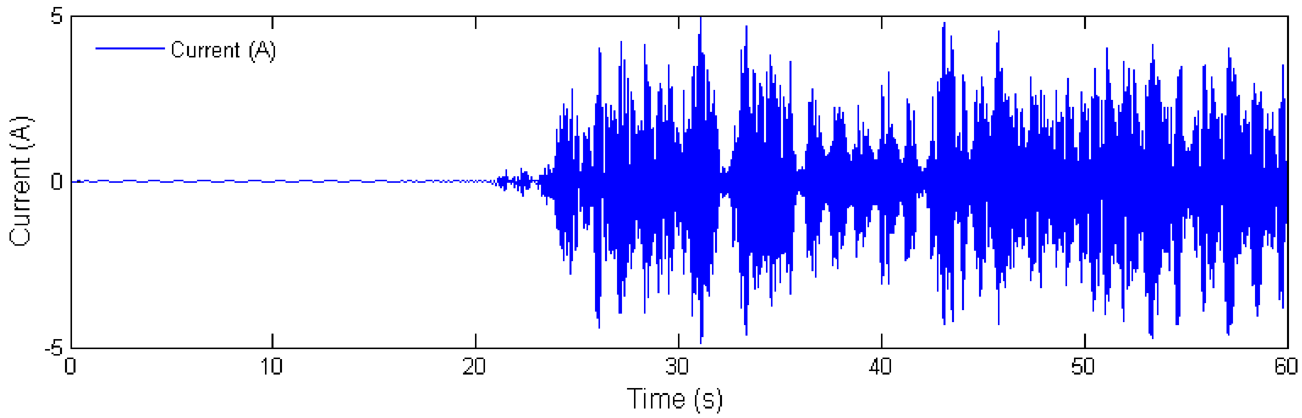

Fig. 7. Current produced due to the applied EMF.

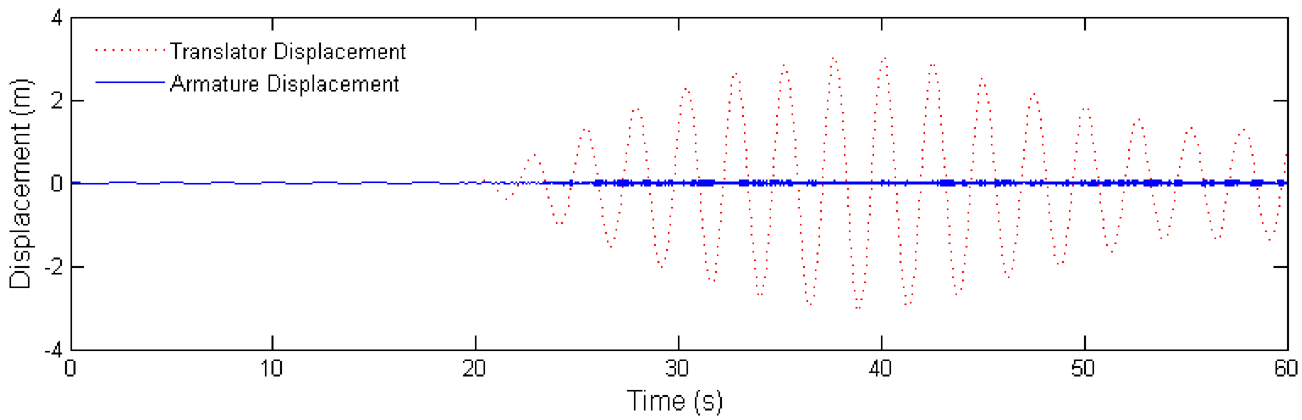

Fig. 8. Armature and translator displacements.

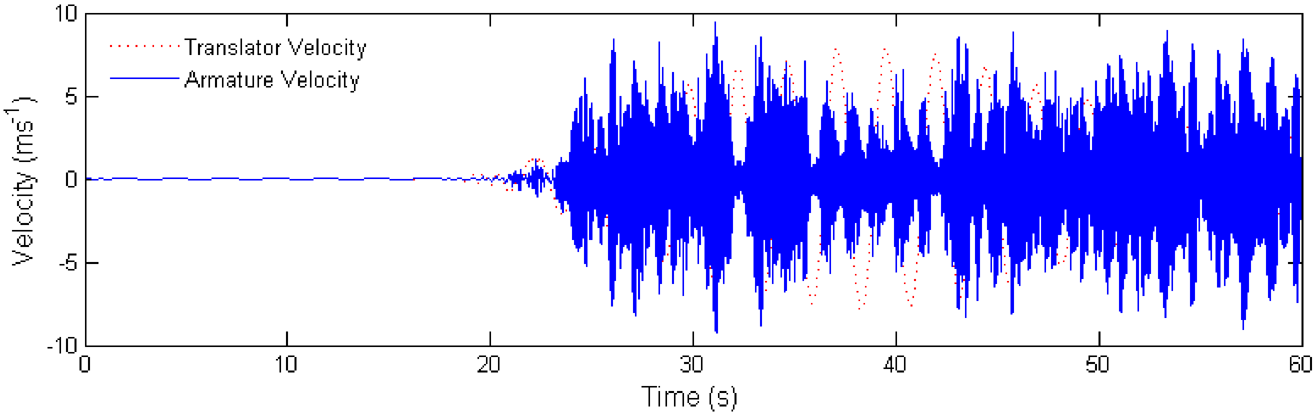

Fig. 9. Armature and translator velocities.

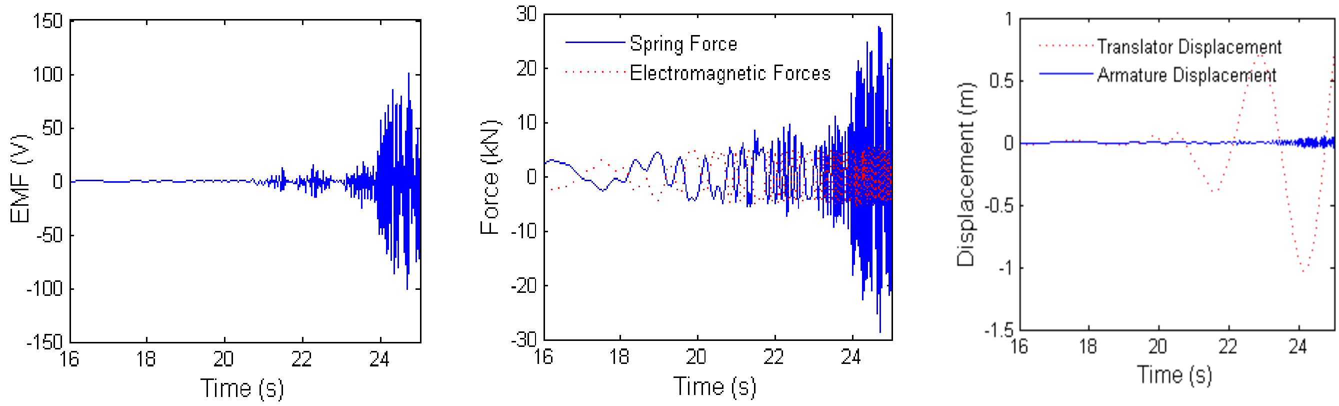

Fig. 10. Zoomed view of EMF, forces and displacement at the point where snapping occurs between 16 and 25 seconds

Results from a simulation of the system for a small-scale prototype device have been demonstrated for monochromatic seas yielding a mean power of 360 W and a total energy extraction of 23.5 kJ. These are maximum values for this prototype setup since they do not include drag and frictional energy losses. The results also indicate that using conventional design techniques to optimise the system may be difficult due to the stochastic nature of both the energy input and resulting dynamic behaviour. One suitable method may be the use of evolutionary computing techniques.

VIII. Acknowledgment

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