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CHARACTERISTICS OF COCKERELL DEVICE FOR EXTRACTING ENERGY FROM WAVES

خصائص وسيلة كوكريل لاستخلاص الطاقة من الامواج

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الخلاصة :

تمثل طاقة الامواج مصدرا عظيما من مصادر الطاقة النظيفة الواعدة . غير ان هذا المصدر ظل لسنوات طويلة بعيدا عن مجال البحث العلمي بالرغم من وجود مئات الابتكارات والاختراعات لاستغلال هذه الطاقة . احدى الطرق المعروفة في هذا المجال هي وسيلة كوكريل والتي تتكون من مجموعة من الهياكل المتصلة مفصليا وتطفو فوق السطح الموجي ونتيجة للحركة الموجية على جوانب وقاع الهياكل فانها تكتسب قدرا من الطاقة يمكن استخلاصه عند المفاصل . وتتميز هذه الطريقة ببساطة التركيب وقلة التكاليف وارتفاع الكفاءة . ولما كانت الدراسات السابقة تنحصر في تجارب معملية وميدانية بغرض رفع الكفاءة . لهذا كان الهدف من هذا البحث القاء مزيد من الضوء على هذا النظام ودراسة العوامل التي تؤثر على الطاقة المستخلصة .

لهذا الغرض تمت دراسة نموذج مبسط يتكون من هيكل واحد ذو وحده عرض واحدة موضوع فوق سطح موجه أحاديه (Solitary Wave) وتستخلص الطاقة من محاور متصلة بمحور الدوران المار بمركز الثقل . وحيث أن الشروط الابتدائية والحدية لسطح الموجة الاحادية معروفة فلقد امكن استنتاج توزيع الضغوط على جوانب وقاع الهيكل وأمكن حساب العزم الناتج من كل منها حول محور الدوران وبحساب السرعة الزاوية لدوران الهيكل نتيجة لتقدم الموجة امكن حساب القدرة المستخلصة عند ازمنة مختلفة يحتل خلالها الهيكل اوضاع مختلفة بالنسبة لقمة الموجة .

ولقد تم عمل برنامج على الحاسب الآلي يسمح بدراسة خصائص الحمل الموجي للموجة الاحادية (عمق الماء قبل حدوث الموجة ورقم فرويد المُحدد لارتفاع الموجة) الى جانب دراسة خصائص الهيكل (طوله وسمكه والوزن النسبي للمادة المصنوع منها) . ولقد أوضحت النتائج ان الطاقة المستخلصة لكل وحدة طول من الهيكل تزداد بزيادة رقم فرويد وبزيادة طول الهيكل وبانخفاض عمق الماء قبل حدوث الموجة وكذلك اوضحت الدراسة ان سمك الهيكل والوزن النسبي للمادة المصنوع منها يمكن اهمال تأثيرها على الطاقة المستخلصة .

ABSTRACT

This paper discusses the characteristics of the Cockerell device for wave power extrsction. A system consists of one pontoon contoured on a solitary wave was considered. The effect of both wave and pontoons characteristics on the extracted power was theoretically investigated. Curves are presented showing the variation of the extracted power with time during wave propagation for various values of Froude number, head of undisturbed flow and pontoons length, thickness and specific gravity. The results show a great dependence of the extracted power on the Froude number, head of undisturbed flow and pontoons length, whils the pontoons thicknesa and material specific gravity have a negligible effect on the extracted power.

INTRODUCTION

Water waves represents a large, pollution-free energy resource. Surprisingly enough this energy potential has, until recently, been neglected in the acientific literature although the patent literature shows hundreds of proposals for extracting energy from waves. However, throughout the last few years several research projecta on large-scale wave-power conversion have been started [1].

The patent literature is full of suggested devices for extracting energy from waves such as floats, ramps, flaps and converging channels. Although very large amounts of power are available in the waves, it is important to consider how much power can be extracted. A few years ago only a few percent efficiency had been achieved. Recently, however, several devices have been studied which have relatively higher efficiencies. Some devices of the highest efficiencies to date have been obtained with the device invented by Salter, which is called Salter's duck [2]. Another system invented by Masuda (1975), uses a bell-shaped chamber filled with air which is pumped through an air-turbine by the rising and falling motion of the water. Glendenning [3] reported that Masuda has conducted a number of experiments to identify the best configuration for a many chambered buoy. Several hundred devices of this sort are in continuous use around the world [3,4].

Tanaka et al [2] tested the wave power absorbed by a rocking body of Salter's duck. They examined the effect of the shape of the front section on the efficiency and also the effect of the load characteristics on the efficiency. Lighthill [5] described analysis relevant to the absorption of wave energy by submerged resonant ducts, which is connected to a submerged device (wells air-turbine) to extract a significant fraction of the incident power. The variation of energy absorption and the amplitude of the duct response with frequency for various depths of submergence were studied by Simon [6] and Thomas [7].

Other devices could have much smaller displacements and hence, possibility, much lower specific costs. An example of these devices is the contouring raft system invented by Cockerell as reported in references [3,4]. He proposed a series of articulated pontoons which would contour to the wave and extract energy from the relative motion of hinges. This system looks very promising and might be improved. Experimental tests were carried out by the British Hovercraft Corporation to confirm the length of each pontoon [3].

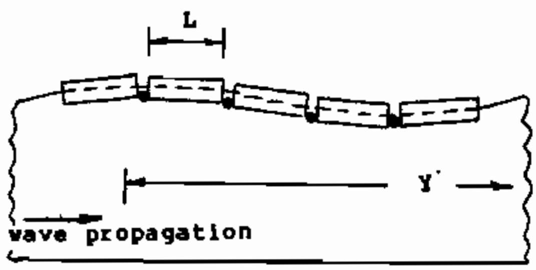

Fig.(1) Wave contouring pontoons suggested by Cockerell

The objective of the present study is to investigate theoretically the effect of load characteristics (wave parameters) as well as the effect of pontoons length, thickness and material specific gravity on the extracted power from the Cockerell device. This can be simplified by studying the forces and moments which cause the relative motion at the pontoons hinges to evaluate the extracted power.

THEORETICAL ANALYSIS

The Cockerell device for extracting power can be treated as a problem of floating body over a wavy surface. Consider an unrestrained floating object that is relatively small compared to the wave length. Since this object displaces its own weight of water, it is clear that the forces on the object are exactly those that would have occurred on the displaced fluid and hence the motion of the object will be the same as that of the displaced fluid. For objects that are restrained or large such that the kinematics change significantly over the object dimension, the situation becomes more complex as the object affects the wave. In the following study the kinematics change over the object dimensions will be considered, while the effect of the object on the wave will be neglected.

Consider the case of a rectangular object (pontoon) contoured on the free surface, which is affected by the propagation of a solitary wave. The pontoon is assumed to have a unit breadth and the wave is considered wide enough and can be treated as a two-dimensional one. Therefore the flow parameters (head, pressure, velocity components) are recommended to be calculated according to the two-dimensional model described in [8,9]. The flow parameters for steep propagating solitary waves were obtained in the following form [8]:

$$\delta = \frac{H}{H_1} = 1 + (\delta_m - 1) . \operatorname{sech}^2 \beta \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\delta_m = \frac{H_m}{H_1} = 1 + \tfrac{1}{2} F^2 [1 - \operatorname{Exp} (-4 \ln F (1 + \frac{3}{2} \ln F))] \qquad \ldots\ldots(2)$$

where; F the Froude Number
H_1 the head of undisturbed flow
H the head at a section of distance x from the wave vertex
H_m maximum head at wave vertex

$$\beta = \frac{x}{H_1} \sqrt{\frac{3}{2} \ln F}$$ is a dimension linear coordinate

The horizontal and vertical components of velocity $\overset{o}{u}_x$ and $\overset{o}{u}_z$ at the free surface were obtained in the following form;

$$\overset{o}{u}_x = \sqrt{g\ H} . \sqrt{F^2 - 2(\delta - 1)} . \frac{1}{\sqrt{1 + M^2 \operatorname{sech}^4 Nx \tanh^2 Nx}} \qquad \ldots\ldots\ldots\ldots(3)$$

$$\overset{o}{u}_z = - \sqrt{g\ h} \sqrt{F^2 - 2\ (\delta - 1)} . \frac{M \operatorname{sech}^2 Nx \tanh Nx}{\sqrt{1 + M^2 \operatorname{sech}^4 Nx \tanh^2 Nx}}$$

where M and N are functions of F as follows;

$$M = (\delta - 1) \sqrt{6 \ln F}$$

$$N = \frac{1}{H_1} \sqrt{\frac{3}{2} \ln F}$$

The potential theory is applicable in most cases and the boundary conditions are well known [11]. Therefore knowing the free-surface boundary conditions as mentioned above and assuming thet the vertical component of velocity changes linearly from bottom to top, the following relatione were obtained for the horizontal and vertical components of velocity at any point in the flow field (u_x, u_z) [8];

$$u_x = u_x^o + (H^2 - z^2) \frac{N}{M\, H\, (1 + (\delta - 1)\, \mathrm{sech}^2\, Nx)} \Bigg[\{ (\delta - 1) \sqrt{gH} \sqrt{F^2 - 2(\delta - 1)} \frac{M^2\, \mathrm{sech}^4\, Nx\, \tanh^2\, Nx}{\sqrt{1 + M^2\, \mathrm{sech}^4\, Nx\, \tanh^2\, Nx}} \} \left(\frac{H}{H_1} + \frac{1}{F^2 - 2(\delta - 1)\, \mathrm{sech}^2\, Nx} \right) + \frac{u_x^o}{2} \left(\frac{1}{\sqrt{1 + M^2\, \mathrm{sech}^4\, Nx\, \tanh^2\, Nx}} \right) (M^2\, \mathrm{sech}^4\, Nx - 2M^2\, \mathrm{sech}^4 Nx\, \tanh^2\, Nx) \Bigg] \quad \text{.............(4)}$$

$$u_z = u_z^o \frac{z}{H} \quad \text{.............(5)}$$

where x and z are the coordinates of the considered point measured from the channel bottom.

Also the pressure at any considered point can be calculated using Bernoulli's equation.

The above relations describe the flow field during the propagation of steep waves in open channels. The numerical solution of these equations gives the longitudinal and vertical components of velocity (u_x, u_z), head (H) and pressure (P) at any point in the flow field.

Consider the rectangular object (pontoon) illustrated in Fig. (2), which is partially immersed in water. The extracted energy is assumed to be taken from rods connected at the middle of the pontoons sides with its axis passing through the center of gravity of the object. The rod axis is situated in the direction about which the pontoons will pitch. The pitch moment about the center of gravity consists of a primary contribution due to pressure on the large horizontal bottom surface and a smaller contribution from the two ends of the object. Referring to Fig. (2) the pitch moment about the center of gravity M_0 can be written as follows;

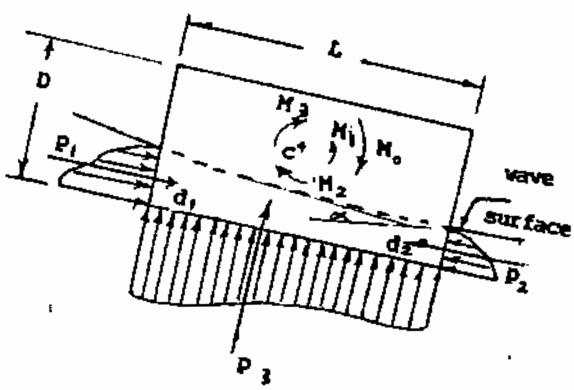

Fig. (2) Sketch of pressure distribution acting on pontoons sides and bottom

$$M_o = M_1 + M_2 + M_3 \qquad (6)$$

where;

$$M_1 = \int_{-B/2}^{+B/2} \int_{-d_1}^{0} (z_1 - z)\, P(x,y,z)\, dz\, dy \qquad (7)$$

$$M_2 = \int_{-B/2}^{+B/2} \int_{-d_2}^{0} (z_1 - z)\, P(x,y,z)\, dz\, dy \qquad (8)$$

$$M_3 = \int_{-B/2}^{+B/2} \int_{-L/2}^{+L/2} (x_1 - x)\, P\,(x,y,z)\, dx\, dy \qquad (9)$$

where; B pontoons breadth;
d_1, d_2. is the depth of the immersed ends of the pontoon;
x,y,z system coordinates;
x_1, z_1 coordinates of the center of gravity of the pontoon;

The first two integrals M_1 and M_2 represent the contribution of the two ends, and the third integral is the moment due to the pressure acting on the bottom of the object.

Knowing the flow parameters (velocity and head) in the undisturbed section, then the pressure distribution on the pontoons can be determined using the above relations. Consequently the force applied on any element and its moment about the center of gravity of the pontoons can be calculated. The integrals (7),(8) and (9) also can be determined numerically and added together to get the resultant applied moment at the considered position of the pontoons with respect to wave vertex.

The pontoon is assumed to be fixed while the wave is propagated. After a small interval of time Δt the pontoon will be subjected to another pressure distribution as the pontoons will occupy another position on the wave surface. During the interval of time Δt the wave slope will be varied by an angle $\Delta \alpha$. Neglecting the inertia forces caused due to the movement of the pontoon, then the change of the angle of inclination of the pontoon can be assumed equals to $\Delta \alpha$. Then the angular velocity of the pontoon ($\Delta \alpha$ / Δ t) can be multiplied by the resultant moment to calculate the extracted power by the pontoon. The above procedure can be repeated at a new position after another interval of time Δ t and so on.

A computer program was constructed following the above mentioned method of solution to study the effect of load characteristics (initial head and Froude number) and also the effect of pontoons shape and material specific gravity on the extracted power.

RESULTS AND DISCUSSIONS

Fig. (3) is presented in dimensionleee form to show the wave profile for different values of Froude number. From this figure it is clear that increasing Froude number increases the wave steepnees. It is known that as the wave steepnese increases the kinematics of the flow change strongly until a certain value after which the wave must be broken [10].

Figs. (4) and (5) show the extracted power from Cockerell device, against the time T. The device is composed of one pontoon floating on a solitary wave at different intervals of time corresponding to different longitudinal distances in the direction of wave propagation. The extracted power is presented in dimensionless form (devided by the kinetic energy of the fluid in the undisturbed region and multiplied by half the wave period). In figure (4) the head in the undisturbed region H_1=3 m., the pontoons length (L) , thicknees (D) and specific gravity ($P_{s.g.}$) are 2 m., 1 m., and 0.5 respectively. Fig. (5) was obtained for H_1 = 4 m., L = 2 m., D = 1 m. and $P_{s.g.}$ = 0.5. The presented extracted power was obtained per meter length of pontoons length for different values of Froude number. From Figs. (4) and (5) it is clear that increasing the Froude number, i.e. increasing wave steepness increases the extracted power. This can be explained due to the increase of wave energy with increasing Froude number [9], which in turn increases the amount of extracted power. One important thing to be noticed is that in both Figures the curves characterizing the relation change drastically when the Froude number reaches a certain value. Of course this is due to increasing wave steepness, which is strongly connected with wave break, since in neture the waves begin to broken when Froude number reaches about 1.2. This velue depends to a great extent on the wave head, which is a function of the head of undisturbed flow H_1 (at F=1.2 and for H_1 = 3 m. the wave head equals about 1.33 m., while for H_1=4 m. the wave head equals about 1.76 m.). Therefore the possibility of wave break can be expected at lower value of Froude number for H_1= 4 m. The total extracted power during the propagation of the wave through a certain fraction of time can be calculated by the numerical integration of the extracted power. This can be done by computing the area under the considered curve. Figure (6) shows the total extracted power through a certain fraction of time (0.88 sec.) versus Froude number. A fair measure of agreement can be noticed between the obtained performance of the Cockerell device and that of Salters device reported in [3]. In both cases the extracted power increasees until it reaches its maximum value at a certain distance from the wave vertex after which it decreases. The position at which the maximum power is obtained occurs at the section where the wave slope changes its direction. This position was deduced by [8] and was found to be equal to $0.537/\sqrt{\ln F}$.

Figure (7) indicates the extracted power against the time T for different values of the head of undisturbed flow H_1. The extracted power increases with the decrsase of H_1. Indeed as H_1 increases to a great extent (i.e. for deep water), the wave has a minor effect on the pressure distribution in the flow domain and the distribution approaches that of the static one. While at lower values of H_1 the pressure distribution takes another distribution with relatively higher values near the free surface of the wave [8]. This can explain why the extracted power increases with increasing H_1. Therefore it is recommended to construct such unites in mild places. The total extracted power through a certain fraction of time (0.88 sec.) against the head H_1 is shown in Fig. (8).

The effect of pontoons length (L) is shown in Fig. (9), where the extracted power is drawn against the time for different values of pontoons length. The presented extracted power was calculated per unit length of the pontoon. From this Figure it can be seen that the extracted power per unit length increases with increasing pontoons length. This result agrees enough with that obtained experimentally by the British Hovercraft Corporation, as reported in [3], where experimental tests were carried out and suggested a series of three pontoons with 30 - 40 m. long at full scale. The total extracted power through a certain fraction of time (0.88 sec.) against the dimensionless pontoons length is illustrated in Fig. (10).

The effect of pontoons thicknees (D) is shown in Fig. (11) and (12). The change of pontoons thickness has a negligible effect on the total extracted power as shown in Fig.(12). Also the specific gravity of the pontoons material has a minor effect on the extracted power as indicated in Fig. (13). This can be explained due to small pressure changes near the free surface of the wave, therefore the change of the pontoons thickness or specific gravity has a minor effect on the extracted energy.

CONCLUSIONS

In this paper a simplified model of Cockerell device for extracting power from waves has been used to study the behavior of the device. Curves of the extracted power against the time during wave propagation were obtained in dimensionless form. The results are summarized as follows:

1) The extracted power increases with the increase of Froude number.

2) The decrease of the head of undisturbed flow increases the extracted power, therefore it is recommended to construct such unites in mild spaces.

3) The increase of the pontoons length increases the extracted power. The limitation of which must be strongly dependent on structural material and design.

4) Both pontoons thickness and material specific gravity have a minor effect on the extracted power.

NOMENCLATURE

B	pontoons breadth
D	pontoons thickness
d_1, d_2	submergence level at pontoons ends
F	Froude number
g	gravitational acceleration
H	head
H_1	head of undisturbed flow
H_m	head at the wave vertex (maximum head)
L	pontoons length
M	function of Froude number
M_o	resultant pitch moment
M_1	moment resulting due to force on the first side
M_2	moment resulting due to force on the second side

M_3	moment resulting due to force on the bottom
M	function of Froude number
P	pressure
$P_{s.g.}$	specific gravity of pontoons material
T	time
u_x	horizontal component of velocity
u_z	vertical component of velocity
$\mathring{u}_x$	horizontal component of velocity at the free surface
$\mathring{u}_z$	vertical component of velocity at the free surface
x,y,z	system coordinates
Y	wave length
z_1	height of the center of gravity above channel bottom
α	angle of inclination of the wave surface
β	dimension linear coordinate
δ	head ratio
δ_m	maximum head ratio

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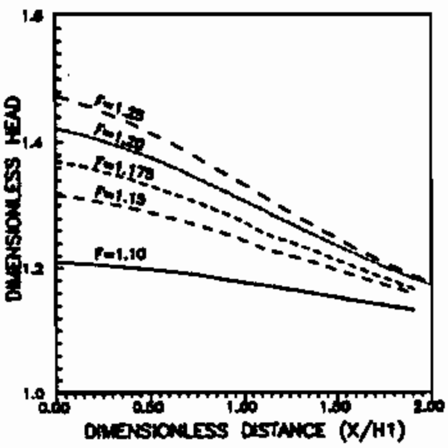

Fig. (3) Wave profile (Dimensionless Head Against Dimensionless Distance)

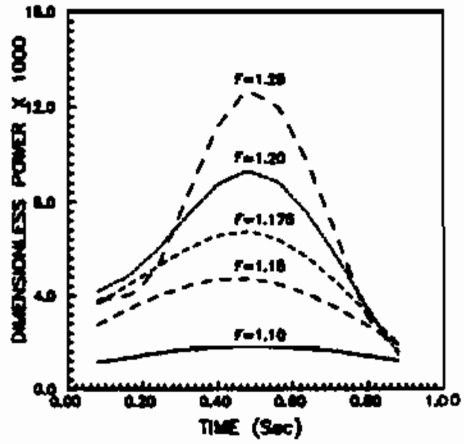

Fig. (4) Extracted Power Versus Time for Different Values of Froude Numbe (H1=3 m., L=2 m., D=1 m., Ps.g.=0.5)

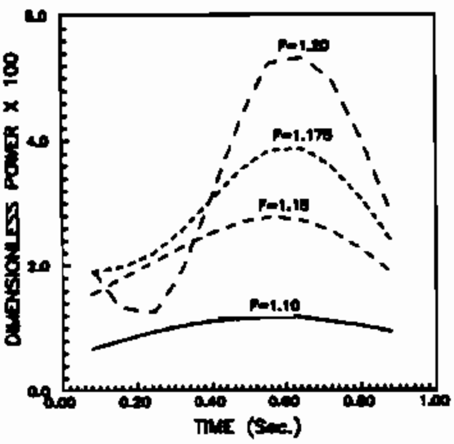

Fig. (5) Extracted Power Versus Time for Different Values of Froude Number (H1=4m., L=2 m., D=1 m., Ps.g.=0.5)

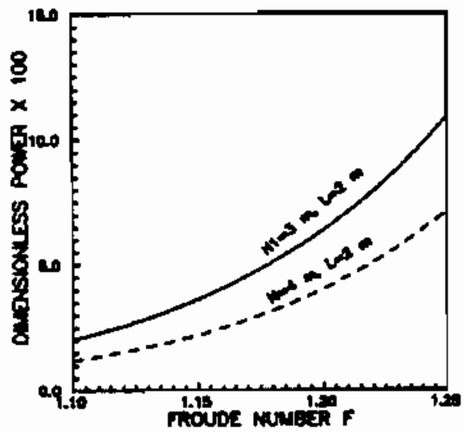

Fig. (6) Total Extracted Power Versus Froude Number for Different Values of H1 and Pontoons Length (D=1 m., Ps.g.0.5)

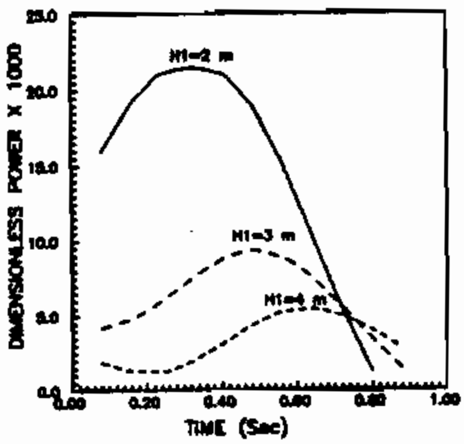

Fig. (7) Extracted Power Against Time for Different Values of H1 (F=1.2, L=2 m., D=1 m., Ps.g.=0.5)

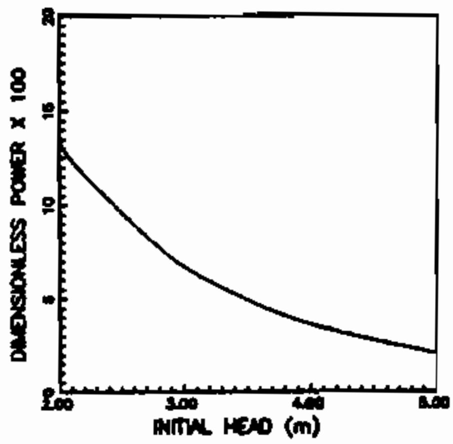

Fig.(8) Total Extracted Power Against the Head of Undisturbed Flow H1 (F=1.2, L=2 m., D=1 m., Ps.g.= 0.5)

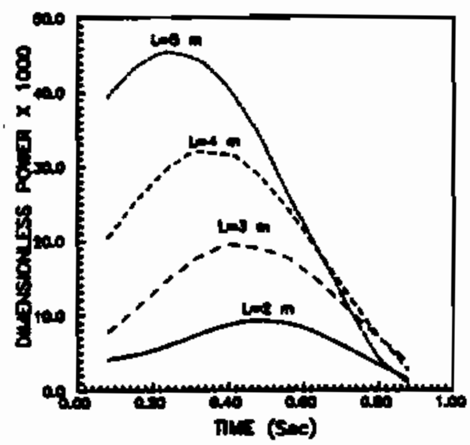

Fig. (9) Extracted Power Versus Dimensionless Power for Different values of Potoons Length L (F=1.2, H1= 3 m., D=1 m., Ps.g.=0.5)

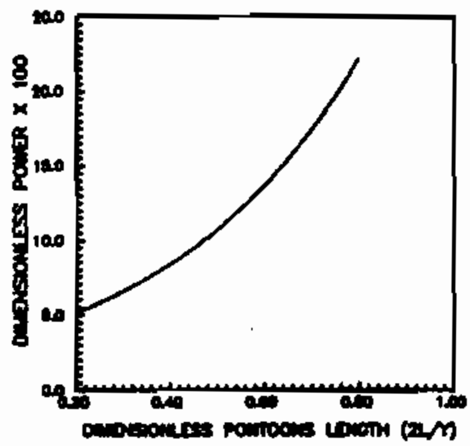

Fig. (10) Total Extracted Power Against Dimensionless Potoons Length L (F=1.2, H1=3 m., D=1 m., Ps.g.=0.5)

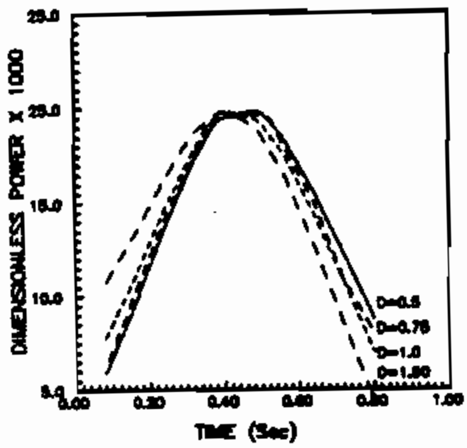

Fig. (11) Extracted Power Versus Time for Different Values of Pontoons Thickness (F=1.2, H1=3 m., L=3 m., Ps.g.=0.5)

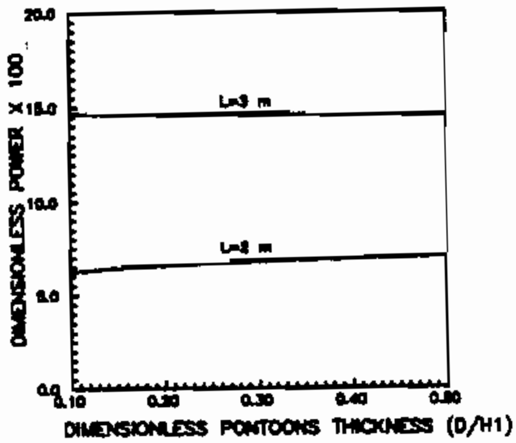

Fig. (12) Total Extracted Power Against Dimensionless Pontoons Thickness (F=1.2, H1=3 m.,Ps.g.=0.5)

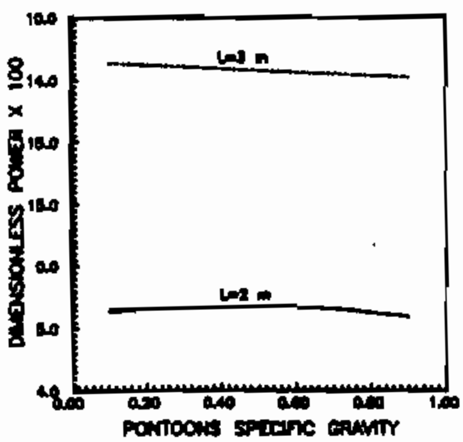

Fig. (13) Total Extracted Power Against Pontoons Specific Gravity Ps.g. (F=1.2, H1=3 m., L= 2 m., D=1 m)