Experimental investigation of the interaction between a vertical flexible seawall and random sea waves

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Abstract: Seawalls are sheltering structures used for protecting the coastal regions against wave induced forces. Because of random nature of the wave behavior, application of physical models for the study of wave-structure interaction can be quite efficient. In the present research, physical models of thin flexible walls were constructed and tested in a wave flume subject to generated random waves. The water surface variations and the strains at the base of the wall were recorded using sensors; and the relationship between the strain and the wave height was obtained using the zero up-crossing method. The results indicate that the strain-wave height relationship is linear. Since the behavior of the wall is within the elastic region, the relationship between the strain and the flexural moment at the base of the wall follows the Hook's Law; and accordingly the relationship between the wave height and flexural moment at the base of the wall was obtained.

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Key Word: Seawall, Random waves, Strain, Wave height, Flexural moment.

1. Introduction

Because of vast coastal lines and country's population in coastal areas and damage caused by storm waves, check resistant structures against stormy waves have become one of the basic needs in our country.

The seawalls are one of the important structures which have basic role in protection coasts .The seawalls in addition to bear on the random waves induced forces , due to environmental condition must be endure induced forces such as earthquakes, ocean currents, wind and impact buoys ,also. One of the most important tools for study the interactions is the physical models that recently have been used by researchers and engineers widely. The theoretical basis of these models established in the fifteenth century by Leonardo Davinchy then presented by Isaac Newton in the 17th century comprehensively. A comprehensive laboratory study only is not limit to data correct collection consistent with the problem physical conditions rather must use the information collected eventually. Accordingly, this data have utmost importance. Today, the appropriate tools are available to researchers in this field. Numerical methods and signal processing as a powerful technique for data processing are widely used. Despite the findings of researches on the interaction between seawall and sea random waves, a lot of studies have not been on relationship between the wave and exerted forces on wall. In this study, the strain on the wall when encountered with sea random wave, strain and flexural moment measured and relation between them has been determined using an in vitro model (Cheghini, 1998).

2. The works done in this area

Senfelo in 1928 is one of the first researchers that is presented a way to determinate the pressure resulting of non-breaking wave induced forces. The advantage of his approach is its easy use. Using this method can be estimated the pressure distribution by a straight line roughly (Quoted in 1) .Rundgrin in 1958, with a laboratory work indicated that Senfelo method show non-breaking wave induced forces more than real values (Rundgren, 1958). Minikin theory has been presented based on empirical observations on the large-scale wall which affected regular break waves in 1963. In fact Minikin work was the first laboratory works to examine the scale impact on his studies comprehensively (Minikin, 1963). Most important studies have been conducted about wave induced forces on seawall and vertical foreshore are Gouda works in 1974 which are used by many engineers in design and have been used in many articles and books as reference (Yung Fang et al., 2007). Vigaya Karisma and et.al are studied the regular wave induced wall dynamic response analysis on energy absorbing structure based on scale of 1 to 20 in 2004 as an experimental research (Vijayakrishnaet al., 2004). Hugh in 2004 has investigated wave induced flexural moment which created in coastal structure (Hughes, 2004). Nilamani and et.al checkered roughness effects on seawall which are considered as both come before and after block on wall in the laboratory also, they had been investigated the waves upward and downward currents and their effect on wave induced forces . Advantage their work is use from random waves and steep wall with different slopes (Hughes, 2004). Como and et.al studied in 2010, the Froude number similarity between model and prototype on seawall against breaking waves. Their results showed that the amount induced pressure on seawalls which is obtained from dimensional analysis to prototype is more than true value that likely occur in nature. This is because entering the air phase when exerted wave which can be considered as a factor to reduce the force while this effect is negligible in the laboratory. He considered force value and breaking waves induced moment on the wall using pressure numerical integration on the wall then measured the pressure using wave generator 100-meter flume at different height of the wall. Barometers value in his experiment was number 8 at wall height; also wall width which was equal with the flume width was 3 m (Cumo et al., 2010).

3. Interaction between waves and seawalls

In figures 1 and 2, thick and thin walls and their failure mechanisms are shown. In thick walls hydrostatic and hydrodynamic forces induced stimulus moment which causes collapse wall are around base of the wall and as a persistent moment must be more than induced moment around wall base to prevent collapse the wall. Also wall weigh and contact the surfaces with floor must generate frictional force more than the force required to produce waves to prevent slipping.

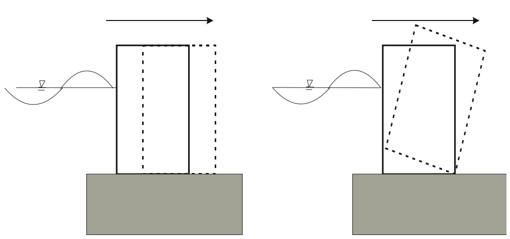

Figure 1: slip and collapse in thick walls

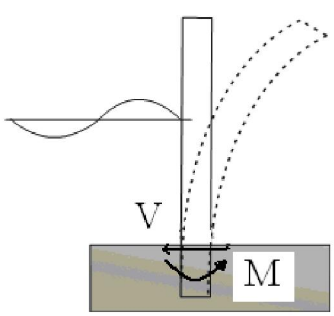

Figure 2: internal forces in the thin wall

In thin walls, stability mechanism is between the floor and the walls which can be meeting by considering a sufficient length to penetrate the walls in the floor. Wall base flexure moment (M) which cause flexure stresses and wall base shear (V) led to create base shear stresses. The study is used physical model of the thin walls. Note that the walls are built along the coast therefore, wall length is much larger than section dimensions. Thus the wall behavior against wave force would be a flat strain (Vafaiepour Sorkhabi et al., 2011). So it can be review with regard to the wall length and section dimensions and height based on the Froude number similarity. In this regard, determine flexural moment and shear forces would be more important than rest of the parameters to investigate wall structural behavior. Note that wave induced forces effect near the water surface so; base flexural moment will be more decisive by increase wall height. In physical models, can be used barometric and strain metric methods to determine the moment and shear. In barometric method, pressure values at regular points of the wall height are determined using a set of sensors or sensitive Pyrometer to pressure then are obtained by equations 1 and 2 based on the surface bellow pressure chart, moment and shear (Strain, 2009).

$$V_t = \sum_{k=1}^{k=n} P_{kt} .\Delta z$$

$$M_t = \sum_{k=1}^{k=n} P_{kt} .\Delta z . z_k$$

Pkt value is the pressure measured by the k nd barometer on the wall in t pitch, Δz distance between barometers; z_k distance M nd barometer from bottom of the channel, V_t the base shear value and M_t is flexural moment value at wall base. During radiation, moment wave and shear will be having history like each other (Cumo et al., 2010). In strain gauge method, flexural strain and base shear are meeting using strain gauge sensors directly. Strain gauges install at wall base to measure bending on wall , then the strains are read in accordance with figure 3 also flexural moment obtain by (3) to (6) equations (SPM, 1984).

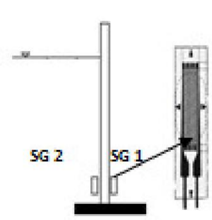

Figure 3: How flexural strain gauge is placement on the wall

$$|\varepsilon_{1t}| \# |\varepsilon_{2t}|$$

$$\bar{\varepsilon}_t = \frac{|\varepsilon_{1t}| + |\varepsilon_{2t}|}{2}$$

$$\sigma_t = E.\bar{\varepsilon}_t$$

$$M_t = \sigma_t.W$$

In above equations ε $_{1t}$ and ε $_{2t}$ are measured strains in t pitch ,E elasticity module ,σ_t flexural stress and W section base at the location of install strain gauges. We should consider that above relations are valid in linear range of the stress-strain.

Thus the wall sections should be chosen so that the stress does not exceed this limit. Shear strain gauges are installed in accordance with Figure 4 and base shear value are obtained from the 7 to 9 relations.

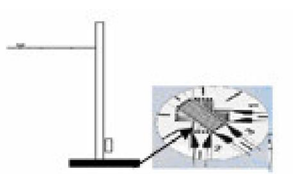

Figure 4: How shear strain gauge are placement on the wall

$$\gamma_{\max t} = \sqrt{2[(\varepsilon_{1t} - \varepsilon_{3t})^2 + (\varepsilon_{2t} - \varepsilon_{3t})^2]}$$

$$\tau_{\max t} = \frac{E}{2(1+\nu)} \gamma_{\max t}$$

$$V_t = \frac{\tau_{\max t}.I.T}{Q}$$

In the above equations, ε $_{1t}$ and ε $_{2t}$ and ε $_{3t}$ are the strains readings from strain gauges 1, 2 and 3, γ_{max} shear strain, ν Poisson's ratio, τ_{max} section shear stress , I section inertia moment and Q is section half static torque relation to inter fiber (Cumo et al., 2010).

4. Random Waves

In general, waves are classified into two categories; regular and random waves. Random waves can be defined by a combination of regular waves. Sea waves in stormy condition are kind of random waves and water level is non-regulated. In the laboratory and the field findings, waves have random nonlinear wave mode. In this mode, all of the waves must be considered as a wave by wave. In this case the wave hydrodynamic properties are considered by zero up-crossing or zero downward crossing method. Upward zero crossings method is a more conventional method and in this study has been used of it.

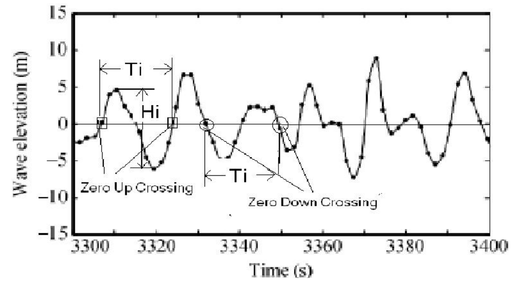

Figure 5: Non-linear random waves (field and laboratory waves)

4.1. Analysis the wave spectra

Random waves can be studied using spectral analysis of waves was recorded. Therefore the waves in sea conditions can be stated by spectral density comprehensively (SPM, 1984). Accordingly various spectrums like as Bretschnider spectrum in 1959, P-M in 1964, TMA in 1985 and Jonswap spectrum in 1974 are defined based on the recorded data. Sorensen has defined Jonswap spectrum as one of the most spectrums with widely application for the coastal structures design (Sorensen, 1993). New researches have been done about construct an appropriate spectrum with climate condition of Iran. But can be used from the spectrums in case lack of the spectrum. In this research was used from Jonswap spectrum. Equation 10 shows energy density during use Jonswap spectrum and figure 6 shows the Jonswap spectrum.

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-1.25\left(f_p/f\right)^4} \gamma^a$$

In this spectrum, γ coefficient is values between 1/6 to 6 but number 3/3 is recommended. γ coefficient is density ratio to in maximum frequency on the spectrum Johnson to P-M spectrum [8] in equation 10.

$$a = e^{-\left[(f - f_p)/(2\sigma^2 f_p^2)\right]} \text{ ، } \alpha = 0.076\left(\frac{gF}{W^2}\right)^{-0.22}$$

$$f_p = \frac{3.5g}{W}\left(\frac{gF}{W^2}\right)^{-0.33}$$

In the above equations, F is wave location length, W wind speed, f frequency and fp is wave peak frequency (Regulation of design and offshore structures ports of Iran, 2006).

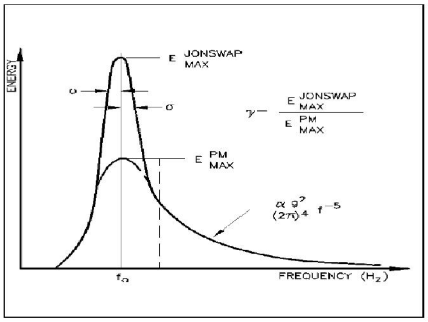

Figure 6: Jonswap wave spectrum

5. Physical model and tests

In order to conduct research experiments, the wave flume was designed and built at marine structure laboratory of Tabriz University. Profile used for the test is as follows (Figure 7):

- Flume length: 12/5 m
-Flume width: 1/15m
-Flume floor height above ground level75: cm
-Flume inters portion height: 1/05 m
-Water deep (d):60 cm
-Generated wave type: hinged
-Type of wall: Metal, impenetrable, without overflow wave, tangy on the floor, open in sides
- Wave used: random wave under Johnson spectrum.
-Sampling frequency of water surface: about 10 Hz
- Sampling frequency of wall strain: about 50 Hz

Figure 7: Overview of the hydraulic laboratory wave flume of Tabriz University

6. Produce and use of wave

Input data according to Jonswap wave spectrum enter into generator wave system software by an input file waves then the pedals began to move based on the given data and wave generation process is summarized in three steps (Figures 8, 9).

-Wave initial production based on DSA numerical model and getting the obtained wave from data takes off from sensor 1 (MOD0).
-Correct spectra obtained from step 1 due to the theoretical spectrum (MOD1).
-Repeat step 2 to reduce difference between the spectra obtained and theoretical spectra (MOD2, 3...).

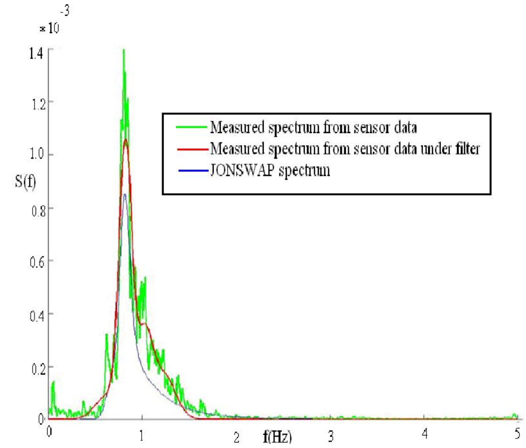

Figure 8: The initial spectrum (measured, filtered and theoretical)

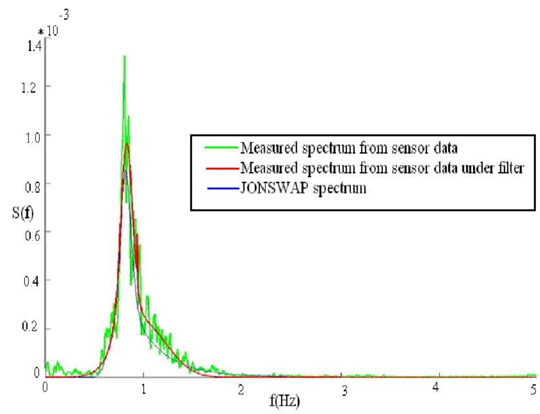

Figure 9: Corrected spectra (measured, filtered and theoretical)

7. Strain used

Strains applied are kind of TML Metal Pam E-101R which used to measure the flexural moment as half-bridge. Sampling range of the strain gauge is from zero to 100 Hz. Because of wall vibration is faster than sea level variations so must be careful in selecting the sampling frequency of the wall response to prevent of come with Aliasing problem undesirable. In the present study, strain sampling frequency is 50 Hz. How the half-bridge is connected and connect details strain gauges are shown in figure 10.

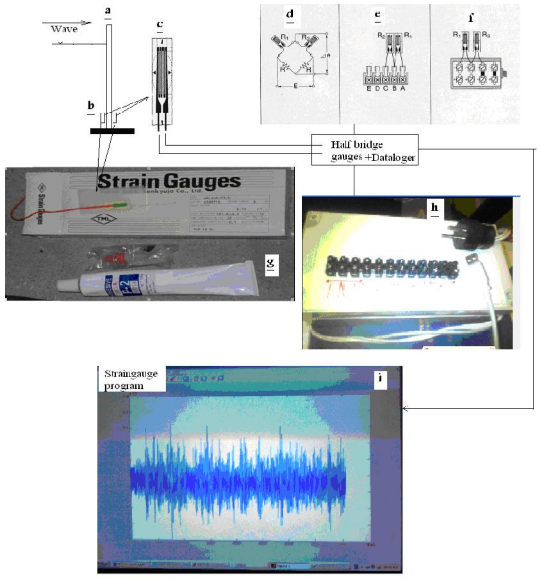

Figure 10: Take off strain on the wall (a: wall, b: place a strain gauge mounted on the wall, c: strain gauge schematic figure, d: half-bridge circuit, e: Strain gauges connected to a data single-way data logger, f: connect the strain gauge to two-way data logger, g: strain gauge real picture with a special glue, h: data logger, i: data taken off image of the strain gauges).

8. Tests conducted

Experiments conducted are presented in table 1. Changes of the effective height, H_s from 3/9 to 9/2 cm and peak frequency from 0/8 to 1/24 Hz are presented in table 1.

Table 1: Characteristics of generated randomly wave with Johnson spectrum based on effective height and peak frequency.

Experiments number	H_s	f_p
1	5	0/8
2	5/2	1/24
3	5	1
4	5/6	1/23
5	7/3	1/22
6	3/9	1/23
7	5/4	1
8	5/4	1/2
9	4/3	1/23
10	7/7	1/21
11	6	1/23
12	7/5	1/23
13	9/2	1/23
14	5/6	1/24
15	7/5	1/21

The taking off data are used to determine wave on the determinant sensors of water level while number of them is 5 and they used for each of 15 defined waves in table 1. For example, in Table 8, the tests are in water level for the wave number 8 with height of 5/4 cm and the peak frequency is 1/2 Hz. In order to exact determine the water level in each experiment a study is conducted on the surface water and obtained data stored in a separate file. The resulting file will have the time series.

Table 2: Studies performed to determine the wave by determinant sensors of water level

	WP1 sensor	WP2	WP3	WP4	WP5
Name of water level	W1	W2	W3	W4	W5
Name of water static level	W001	W002	W003	W004	W005

Take off strain is done with water level at same time. In order to determine the net strain for wave, take off work is done in wall static mode. So taking off strain in table 3 is done accordance to taking off work in table 2 on the wave number 8. Given that only one strain gauge mounted on the wall so there will be only one file of strain time series.

Table 3: Take off is done to determine strain based on the strain gauge mounted on the wall

	SG1
Strain file name	E1
Name of strain file for wall static mode	E001

9. Analysis results

Statistical analysis are done wave by wave to obtain many parameters such as wave height, wave length and wave statistical properties. As well as to study the interaction between the wall and waves, wave by wave analysis will be necessary to strain. Also, in design is necessary determine more influence on the strain per each wave passing while it occurs with compares impact peak of each wave on the strain volatility. To investigate the relationship between time histories of the strain (E) and water level (W), the data has isolated by wave by wave method (according to cross upward zero method) and for each wave, maximum positive amplitude (above water zero level) and the maximum negative amplitude (below water zero level) are obtained separately. In this case, the wave height can be obtained from the following equation:

$H_k = \max\left(|(a_{max}^{+})_k + |(a_{max}^{-})_k|\right)$

In strain analysis the strain value in k nd wave is obtained from the following equation:

$\varepsilon_k = \max\left(|(\varepsilon_{max}^{+})_k|, |((\varepsilon_{max}^{-})_k|\right)$

In above equation $(\varepsilon_{max}^{+})_k$ is maximum flexural strain on the wall in direction of the wave influence and $(\varepsilon_{max}^{-})_k$ is maximum flexural strain on the wall in opposition direction of the wave influence . So the strain such as H_k height will be ε_k. Therefore, a program under name wavebywavevafaei.m is written in MATLAB software that can be detect waves by upward zero crossing and the downward zero crossing separately then investigate them wave by wave and obtain for each of them maximum positive range (above water zero level) and maximum negative amplitude (below water zero level), maximum wave height, wave length and period. To isolate each wave, at the beginning of work, final data from before wave connect to the first data and equation of a line passing through this point cut off in the static water surface which represents the point as starting point and the end point of the wave to the end of the first data of the next wave and the line passing through this point in the surface water has been cut off which represents the point as final point. Figure 11 show properties of a wave that have maximum height and obtained from analysis wave by wave of time history of water level .The wave is obtained per the No. 65 wave and the total number of waves are 228.

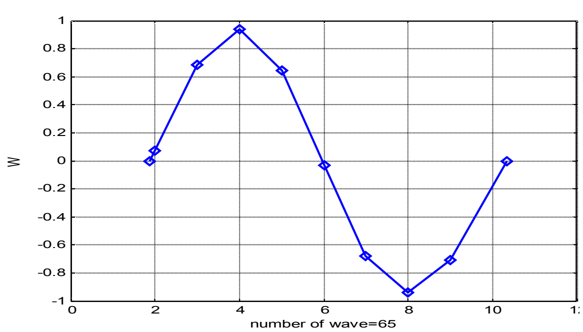

Figure 11: No. 65 wave is obtained of analysis wave to wave of time history of water level.

The maximum wave is obtained in figure 11 is achieved of normalized time history of water level. The positive amplitude of this wave is $(a_{max})_{norm}$ =0/9404 and its negative amplitude is $(a_{min})_{norm}$ =-0/9601 ,as well as wave height is $(H_{max})_{norm}$ =1/8809. To obtain actual values must be multiplied these numbers to reverse the number were normalize. In this case, a_{max}= 6/300 cm, a_{min} =-5/600 cm, H_{max}=|6/300|+|-5/600|=11/9 and maximum wavelength will be L_{max} =84/698 cm. Due to the water depth ratio to wave length is

$\frac{d}{L}$=0/710> 0/5 water depth value will be correct. For all waves, on the time history can be achieved these parameters. Figure 12 show wave height diagram based on wave number.

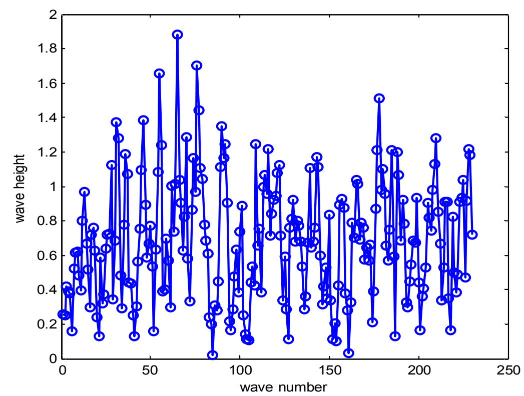

Figure 12: Diagram of wave's height for a water level.

If the waves height are arranged in order from large to small, middle wave height H_{ave} =4/49 cm , wave height of one third largest waves , $H_{1/3}$ =5/79 CM ,root mean square wave height, H_{rms} =5/15 cm will be obtained. When produce of this wave value of effect height of wave is considered 5/89 cm. Due to obtained results the error of 9% seems to be acceptable. In the analysis of wave by wave the maximum strain was in dynamic state ε_{dyn}=2/2017*10 $^{-4}$ and in this case flexural moment value in dynamic mode will be :

$$M_{dyn} = E\varepsilon_{dyn}.W = 2*10^{6}*2.2017$$
$$*10^{-4}*21.33 = 9386\ kg.cm = 94\ kg.m$$

It should be noted that the moment has been obtained in 10 cm level from floor and install place of the strain gauge and because of the wall is placement on two bases, it show half wall dynamic moment. Per wave height, a strain like it obtains. Therefore can be predicate the strain based on wave height. Figure 13 diagram shows the strain values at the corresponding height. These graphs provided appropriate linear behavior. R2 values in these graphs are 0/8434 and very few points placed out of bands range 95%. As can be seen in Figure 13, the relationship between wave height and strain 11 is established. This equation is written in dimensionless form:

$$\frac{\varepsilon_i}{\varepsilon_{\max}} = 0.8241\frac{H_i}{H_{\max}} + 0.09677$$

In this equation H_i is wave height, H_{max} maximum wave height in time history, ε_i is a strain like as H_i, and ε_{max} is considered maximum strain in the history. In the wall H_{max} =11/813 cm,
ε_{max} = 2/2017*10^{-4} that it is strain in dynamic state resulting of wave rate but static content is not included. Due to the relation $M_{dyn} = E\varepsilon_{dyn} .W$, relationship between wall base moment in dynamic state and wave height would be as equation 12:
M=625.48H+ 867.63

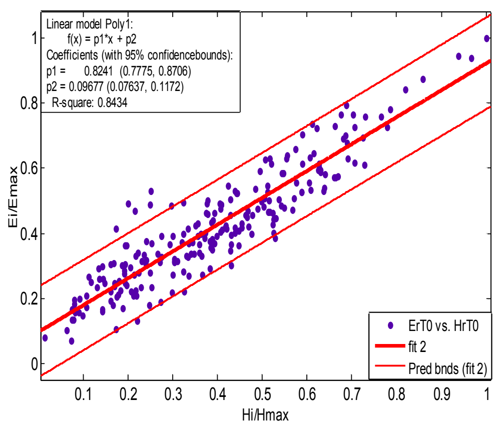

Figure 13: base wall strain chart against wave height

In Figure 14 water level spectrum and in figure 15 the random wave induced strain range in the wall is shown. As can be seen in both spectra peak frequencies are close together and frequency energy of strain range is more than 17 percent of the water level energy.

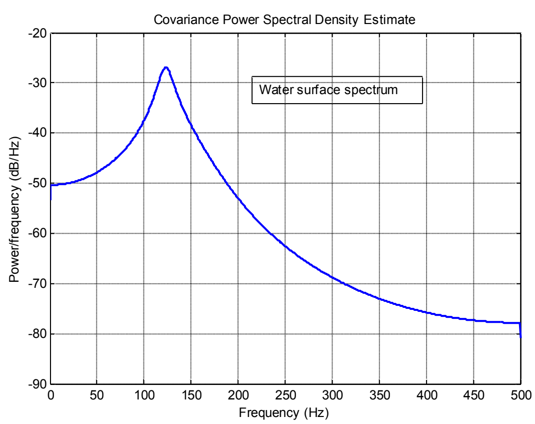

Figure 14: The water level spectrum

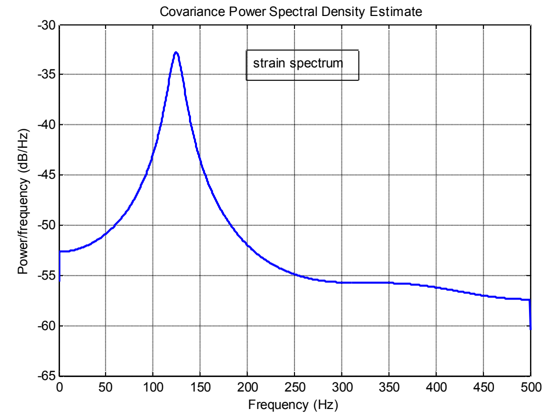

Figure 15: Strain range

According to the same spectrums figure and frequency range governing them can be concluded that relationship between changes in strain with water level is fairly linear. This case is visible in analysis of the time series, also (Figure 13).

10. Conclusions

- The strain behavior and fairly linear wave height with determinant coefficient is about 85 percent.
- assume generating wave in deep water for hinged wave generator pedal are confirmed based on the results obtained from wave by wave approaches on the zero up crossing method ($\frac{d}{L}$= 0.710>0.5).
-In reform process of produced wave in flume after steps 2 or 3 can be usually get an appropriate answer. But at higher step despite improve compliance in spectrum peak may be produce more deviations in the high-frequency part of the spectrum.
- Frequency peak of water level spectrum is roughly equivalent with strain range.
-Linear relationship between strain and water level can be observed by time-series analysis and comparison of the spectrums.

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