Displacement Analysis of Turbo-generator's raft foundations resting on Friction Piles

A.T. Kassem

Assistant Professor, Civil Engineering Department, Faculty of Engineering, Beni-Suef University, Egypt
Abdelraouf_kassem@yahoo.com

Abstract: Turbo-generators represent large, axis-rotating mass machines, supported mostly by deep foundations; to control deformations. Turbo-generators foundations are usually designed using both static and dynamic load patterns. Dynamic loads, resulting from un-symmetric masses are usually evaluated using turbine manufacturer catalogues, based on prototype physical models; that mostly consider foundations as a fixed platform. Neglecting foundations vertical and horizontal stiffness, arising from foundation configuration and soil conditions, results in an uneconomic structural design. This paper presents a mathematical model, based on energy principles, and considering foundation stiffness to evaluate turbine raft foundation displacements. An actual turbo-generator foundation has been presented, as a case study. Finally a parametric study, has been performed to figure out effects of foundation geometric and structural parameters on its behavior, when subjected to turbine dynamic loads.
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Key words: Turbine foundation, dynamic analysis, elastic response

1. Introduction

Turbo-generators as, combined cycle gas turbines [CCGT] are large axis-rotating machines, as shown in figure (1).

Figure 1. Installed CCGT[6]

They usually operate at a large frequency (>3000 rpm)[1]. Analysis of CCGT requires studying their special operational, emergency, and accidental cases of loading. Operation in a perfect environment, where all the kinetic energy resulting from the rotating shaft is balanced; does not require any special analysis. A perfect balanced case could be treated as a static case, where dead load only is to be considered. The perfect balanced case does not take place in real operation; because shaft blades do not represent a continuous function along the shaft circumference, as shown in figure (2).

In addition during operation some blades get broken, increasing the discontinuity of blades and resulting in more un-balanced energy. Moreover in case of a short circuit a sudden stop takes place, resulting in a high un-balanced energy; that transforms to a form of strain energy, affecting CCGT foundations. Broken blades and short circuits are two load case, requiring dynamic analysis.

Figure 2. CCGT Shaft Blades[6]

Displacements have been chosen as a main studied parameter in this research, because of their significance in structural design process. The nature of CCGT foundation problem implies a lot of precautions regarding deformations and displacements, to ensure mechanical installations will not be affected by any relative motion within the foundation mass. Raft is always designed as a rigid plate to ensure internal deformation are of a negligible order. That is why mostly CCGT rafts are supported by piles. On the other hand external displacements of the concrete foundation mass are still representing a source of risk for mechanical installations interconnected with CCGT body, because above range displacements will cause a system breakdown or undesirable leakage out of pressurized steam pipes.

Ming et al[1], have investigated dynamic analysis of turbine foundations considering soil structure interaction [SSI]. They found that considering SSI results in a significant effect in evaluation of foundation displacements and internal forces. They[1] prepared a three dimensional viscous spring boundary elements model, for a deck type turbine foundation. Their[1] study considered the standard eccentricity of 0.05 mm at an operation of 50 Hz, for both case of rigid and flexible foundations. Ming[1] found that turbine foundation could be considered a rigid body compared with the surrounding soil medium.

Livshits[2] used the finite element program [ANSYS] by the Civil FEM compiler to model a turbine raft foundation resting on end bearing piles. Modal analysis, up to 40 modes have been investigated.

Jayarajan et al[3] studied on deck turbines, using SAP2000 and highlighted various points regarding modelling of turbines and surrounding soil for the dynamic analysis of foundation systems.

Naik and Tande[4] used the finite element software [STAAD] to study dynamic analysis of deck type turbines. They could define turbine foundations natural frequency in three perpendicular directions. Moreover they could determine foundation vibration amplitude in three perpendicular directions. Checks have been performed to ensure frequency and vibrations are within the accepted limits of the turbine manufacturer.

Thakare and Rangari[5] studied effects of seismic parameters and structural configuration on natural frequencies. They found that change in seismic Zone parameters is insignificant regarding foundations natural frequencies whereas horizontal. Moreover change in supporting condition from fixed to hinged results in insignificant change in vertical frequencies and significant changes in horizontal ones.

This research considered the interaction of four main components inside one system. These components are a turbine, rigid raft, friction piles, and enclosing soil. Figure (3) clarifies the problem physical form via a vertical section.

This paper introduces a simplified closed form formulation for evaluating CCGT raft displacement, in case of resting on friction type piles. The mathematical formulation has been evaluated by comparing its outputs with finite element modelling prepared by the software "Robot". A parametric study has been conducted to figure out the significance of some structural parameters on CCGT raft displacements. Moreover a case study of an actual CCGT project has been used as a guideline in estimating practical ranges of various structural parameters.

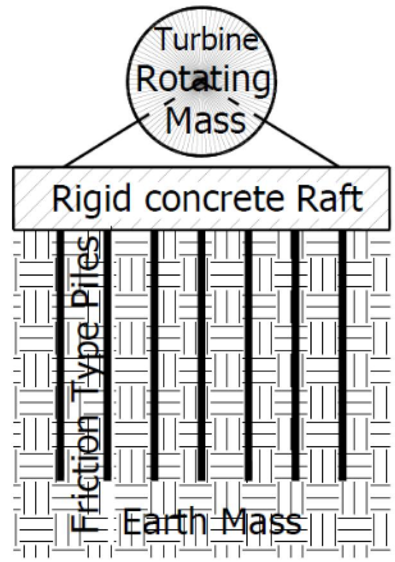

Figure 3. Turbine and Foundation Section

2. Mathematical Formulation

The introduced mathematical formulation for evaluation of CCGT raft displacements has been prepared based upon equalizing the un-balanced energy rising out of the turbine, resulting from un-balance loads, as shown in figure (4); with strain energy of turbine foundations.

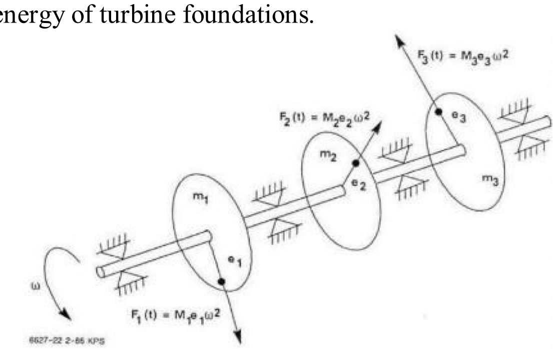

Figure 4. Scheme of un-balanced loads[3]

Strain energy of turbine foundations results from two main sources. The first is deformations of the CCGT raft; which could be neglected, as the raft is always designed as a rigid platform to enable CCGT installation. The second source is vertical and lateral displacements, main concern of this research. Figure (5) shows CCGT system geometric parameters and displacements.

Equations (1) up to (13) summarize the mathematical formulation beginning by equalizing energies till evaluating displacements.

Since the rotation of turbine is axisymmetric with its supporting raft, then for a rigid platform assumption and considering piles below raft are forming a uniform supporting condition; then for a unit length along centerline the physical model shown in figure (6) could be adopted.

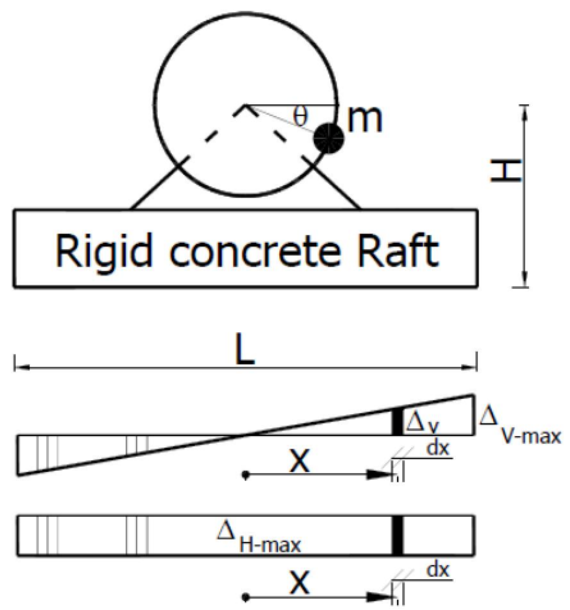

Figure 5. Rigid Platform Parameters and Displacements

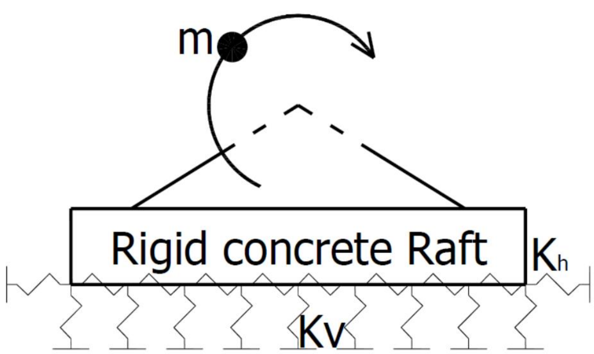

Figure 6. Turbine Foundation Physical Model

Foundation physical model has been considered for both mathematical formulation and finite element modelling. Regarding mathematical formulation, total strain energy could be evaluated by adding strain energy arising from vertical displacement to that arising from horizontal displacement. The general equation for strain energy in case of representing stiffness by springs is introduced in equation (1).

$$E = \int \frac{1}{2} K \Delta^2 \quad (1)$$

Where

E is the strain energy

K is the considered stiffness

is the considered displacement

Applying the general energy equation on the two displacement components results in equation (2).

$$E = 2\int_0^{\frac{L}{2}} \left(\frac{1}{2} K_v \Delta_v^2 dx + \frac{1}{2} K_h \Delta_h^2 dx \right) \quad (2)$$

Since

$$\frac{\Delta_v}{x} = \frac{2\Delta_{v-\max}}{L} \quad (3)$$

Then total strain energy could be formulated as a function of maximum displacement as shown in equation (4).

$$E = \frac{4K_v \Delta_{v-\max}^2}{L^2} \int_0^{\frac{L}{2}} x^2 dx + K_h \Delta_h^2 \int_0^{\frac{L}{2}} dx \quad (4)$$

By closed integration

$$E = \frac{K_v \Delta_{v-\max}^2 L}{6} + \frac{K_h \Delta_h^2 L}{2} \quad (5)$$

Since the same centrifugal force is the main cause of vertical and horizontal displacements, based on force orientation according to rotation angle; then a relation could be inducted between vertical and horizontal displacement, based on geometric and structural parameters shown in figures (4) and (5). Theoretical normal stresses beneath rigid platform for a unit length along centerline could be formulated using plane stress hypothesis as shown in equation (6).

$$\sigma = \frac{f \sin\theta}{L} + \frac{6Hf \cos\theta}{L^2} \quad (6)$$

While theoretical shear stresses could be formulated, as shown in equation (7).

$$\tau = \frac{f \cos\theta}{L} \quad (7)$$

Known that by definition

Stress = displacement x soil subgrade reaction (8)

Consequently vertical and horizontal displacements could be expressed as functions of stresses

$$\Delta_v K_v = f\left(\frac{\sin\theta}{L} + \frac{6H \cos\theta}{L^2} \right) \quad (9)$$

$$\Delta_h K_h = f \frac{\cos\theta}{L} \quad (10)$$

Then a relation between horizontal displacement and maximum vertical displacement could be introduced as.

$$\frac{\Delta_h}{\Delta_v} = \frac{K_v \cos\theta}{K_h\left(\sin\theta + \frac{6H}{L}\cos\theta\right)} \tag{11}$$

Substituting from equation (11) into equation (5), formulae for vertical and horizontal displacements could be expresses as in equations (12) and (13).

$$\Delta_v = \sqrt{\frac{2E}{K_v L\left[\frac{1}{3} + \frac{K_v}{K_h}\frac{\cos^2\theta}{\left(\sin\theta + \frac{6H}{L}\cos\theta\right)^2}\right]}} \tag{12}$$

$$\Delta_h = \sqrt{\frac{2E}{K_h L\left[\frac{1}{3}\frac{K_h}{K_v}\frac{\left(\sin\theta + \frac{6H}{L}\cos\theta\right)^2}{\cos^2\theta} + 1\right]}} \tag{13}$$

Since equations (12) and (13) are mathematically inducted, then they need no verification. Even actual turbines are more complicated than a simple rotating mass supported by a platform, but the derived equations could be used as a guide to judge the significance of modelling outputs.

3. Abu Qir case Study CCGT

A case study has been introduced foran already designed CCGT project, in Abu Qir, Alex. Egypt. Turbine foundations composed of a raft [6.2 m x 45 m], with an average thickness of 1.8 m, resting on 45 piles of 0.6 m diameter and 20 meters depth, as shown in figures (7.a, and 7.b).

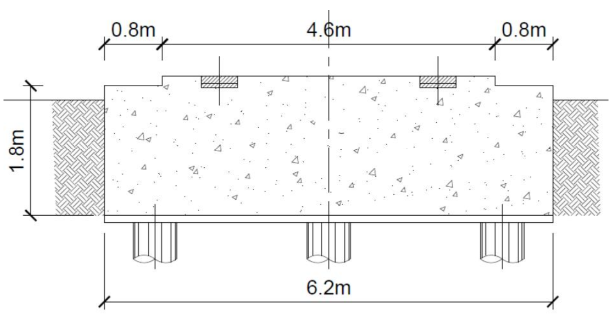

Figure 7a. Abu Qir CCGT foundation cross section

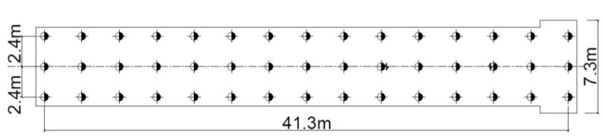

Figure 7b. Abu Qir CCGT foundation Plan

The same physical model, previously presented in figure (6) has been used for preparing the detailed finite element model, shown in figure (8).

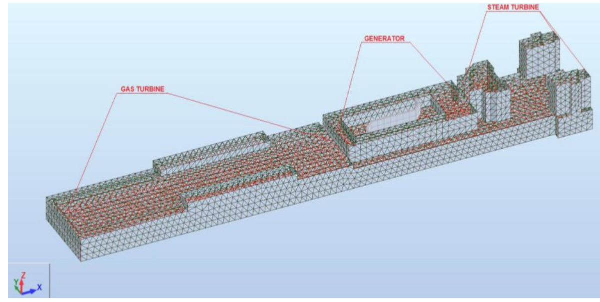

Figure 8. Abu Qir CCGT Robot F.E. Model

Outputs of cases of short circuit and blade failure have been considered for the analysis, based on the load patterns proposed by the turbine manufacturer, as shown in figures (9) and (10). It could be notice that manufacturer recommendations for envelope loads assigned short circuit loads at the generator location, while blade failure loads at the turbine location.

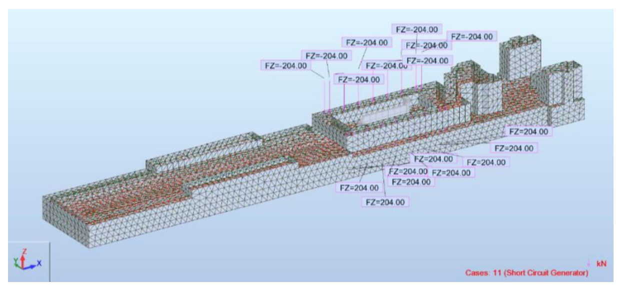

Figure 9. Abu Qir CCGT Short Circuit Load Case

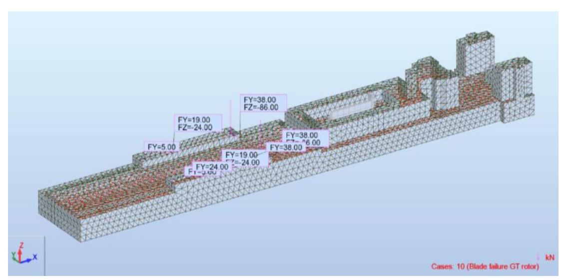

Figure 10. Abu Qir CCGT Blade Failure Load Case

On the other hand it should be noted that supports springs should fulfill minimum dynamic stiffness[7 & 8], specified by turbine manufacturer to ensure that during the beginning of operation, while frequency is increasing till reaching operation frequency; it will not pass by foundation natural frequency. This condition avoids resonance between turbine and its foundations. Dynamic stiffness is a geotechnical analysis output dependent on pile support layout, configuration and soil formation. Figure (11) shows both vertical and horizontal dynamic stiffness for Abu Qir foundation raft.

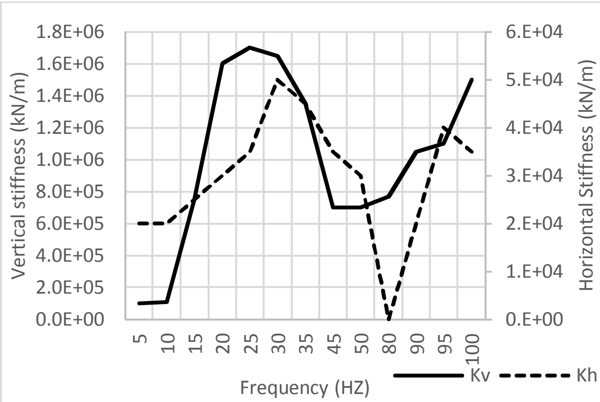

Figure 11. Pile Dynamic Stiffness [15x3] Piles Layout

According to manufacturer recommendations regarding turbine frequency dynamic values of vertical and horizontal stiffness have been assigned as:

K_v= 700000 kN/m K_h = 30000 kN/m

Outputs of finite element analysis, based on equivalent static loads suggested by the manufacturer (on the turbine segment separately); resulted in maximum vertical displacement of 2.3 mm, while the proposed mathematical formulation resulted in 1.9 mm (18% reduction in displacement). Figure (12) plots both outputs on the same graph.

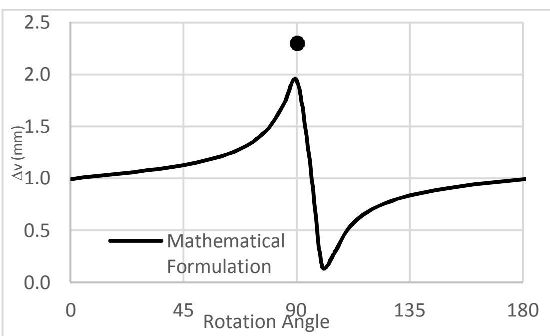

Figure 12. Vertical Displacement Verification (mm)

4. Parametric Study

The derivation of formulae for vertical and horizontal displacements, resulting from un-balanced rotating mass, allowed performing a detailed parametric study to figure out the significance of various structural parameters on foundation displacements. The main studied parameters are relative turbine height to raft width [H/L] and relative vertical to horizontal stiffness [K_v/K_h]. Figures (13) displays the maximum vertical displacement relative to raft width for various [H/L] values, while figure (14) displays horizontal displacement relative to raft width for the same [H/L] values.

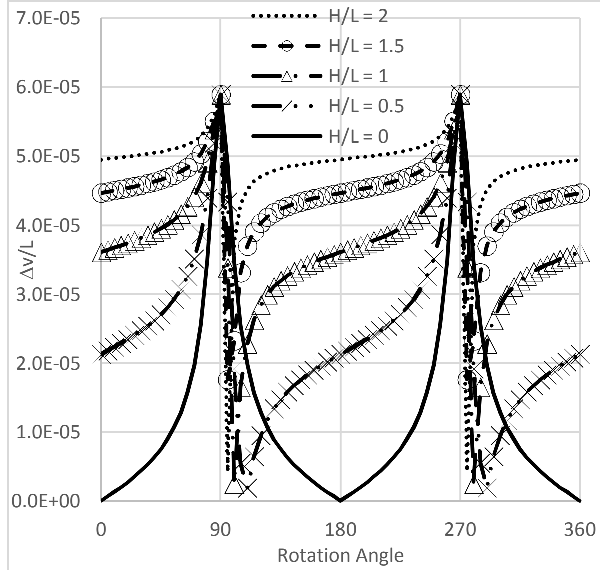

Figure 13. Maximum Vertical Relative Displacement for various [H/L] values

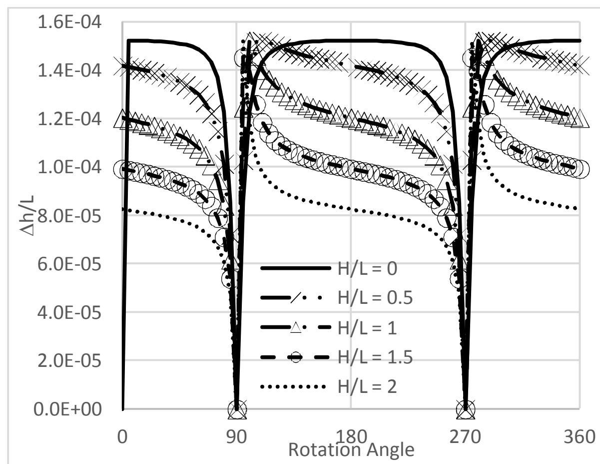

Figure 14. Horizontal Relative Displacement for various [H/L] values

It could be noticed that in case of aligning the turbine center with foundation surface vertical displacement drops to zero at angles of horizontally aligned masses (nπ). Other than the previously stated case vertical displacement resulting from un-balanced rotating mass never drops to zero. Moreover maximum vertical displacement reaches it maximum while horizontal displacement drops to zero. In addition it is shown clearly that rate of change in vertical displacement with respect to angle of rotation is steeper for vertical than horizontal displacement.

Figures (15, 16, and 17) display the maximum vertical relative displacement for various values of foundation relative vertical to horizontal stiffness and turbine height to raft width ratios.

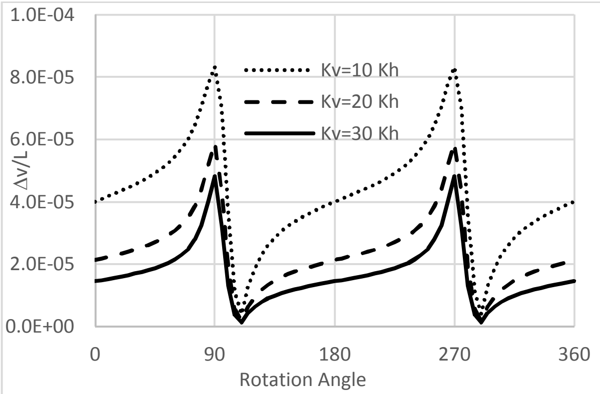

Figure 15. Maximum Vertical Relative Displacement [H/L=0.5]

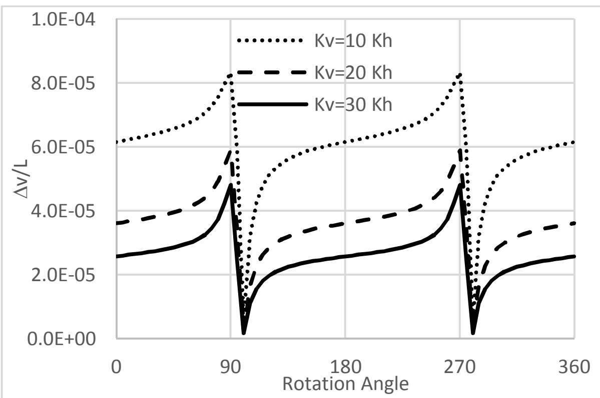

Figure 16. Maximum Vertical Relative Displacement [H/L=1]

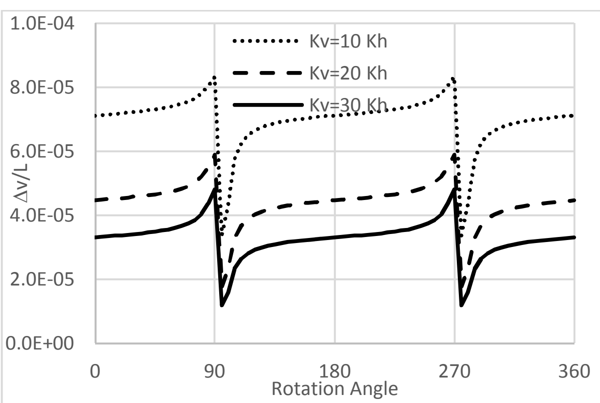

Figure 17. Maximum Vertical Relative Displacement [H/L=1.5]

Studying figures (15, 16, and 17) clarified the increasing rate of increase in maximum vertical displacement by the decrease in vertical stiffness, for the same un-balanced energy. Figures (18, 19, and 20) display horizontal relative displacement for various values of foundation relative vertical to horizontal stiffness and turbine height to raft width ratios.

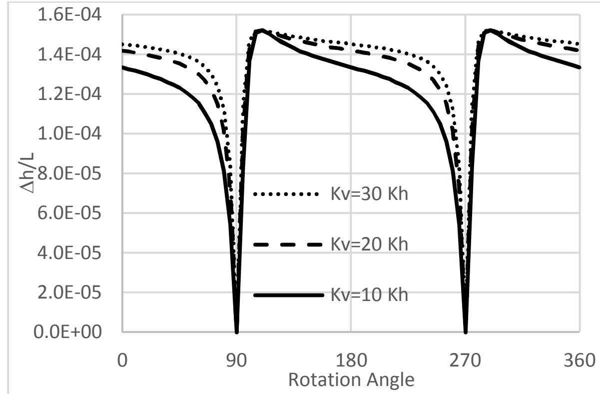

Figure 18. Horizontal Relative Displacement [H/L=0.5]

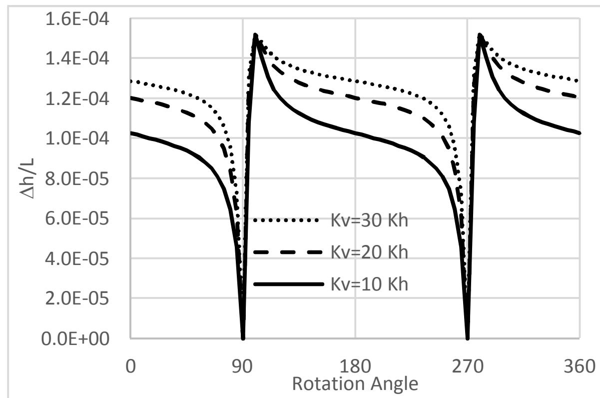

Figure 19. Horizontal Relative Displacement [H/L=1]

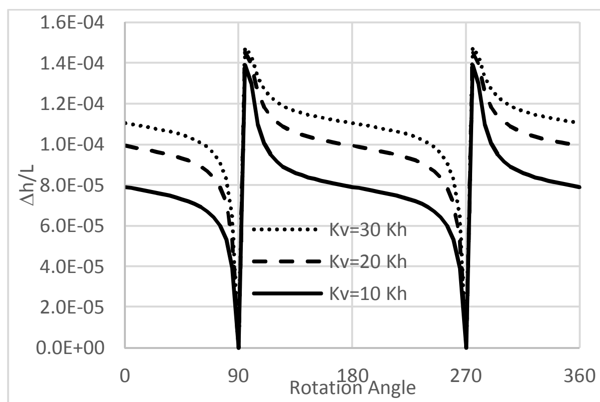

Figure 20. Horizontal Relative Displacement [H/L=1.5]

It could be noticed that the more the turbine height to raft width ratio the more the significance of foundation relative vertical to horizontal stiffness regarding horizontal displacement.

5. Conclusions

Analysis of research outputs have arisen a number of conclusions as shown hereinafter:

1- The proposed mathematical formulation showed reliable outputs, regarding evaluation of turbo-generators raft foundation displacements.

2- The more the generator's height the more the maximum vertical displacement, and the less the rate of its increase.

3- The more the generator's height the less the horizontal displacement.

4- The more the rafts vertical to horizontal stiffness the less the maximum vertical displacement, and the less the decreasing rate.

5- The more the rafts vertical to horizontal stiffness the more the horizontal displacement, and the less the increasing rate.

6- Generators located at foundation level suffer steep changes in vertical displacement, while consistent horizontal displacement, except at vertical rotating mass orientation.

7- Peak vertical displacement is more vulnerable to vertical to horizontal stiffness than peak horizontal displacement.

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