Fluid-Soil-Structure Interaction Impacting the Stability of the Pump Station Building

Hendri Hermawan [a,1,*]
[a] Civil Engineering Department, Universitas Muhammadiyah Sidoarjo, Sidoarjo, Indonesia
[1] hendri.hermawan@umsida.ac.id *
* Corresponding Author

ABSTRACT

Within the first year after construction, there was excitation at a low-rise reinforced concrete building. It has been discovered that the structures perform up to 4 kPa of water transport activity while lying on a thick soil layer. To explore the dynamic behavior and interactions of the phenomena known as fluid-soil-structure interaction, three techniques have been used. Applying finite element computing, the dynamic of the soil-fluid and structure is represented, and the models of the actual and ideal-fixed base conditions are compared. According to research, the rigidity of the foundation and the volume of fluid moving through the pump station have a significant impact on the structure's modes frequencies. The vibration does occur and tends to enlarged over time, according to a time history string of displacements at an arbitrarily chosen position.

KEYWORDS
Excitation
Coupled
Interaction
Frequency
Finite element
Dynamic

1. Introduction

Rapid development of numerical methods in the past decades retrieved new possibilities to conduct sophisticated structural, soil and fluid dynamics simulations. Complex industrial problems will demand simultaneous solver also, such as fluid-structure and soil-structure interaction phenomenon. Principle approaches used to study the phenomenon such Flow Induced Vibration (FIV) for fluid, Finite Element Analysis (FEA) for building/structure, and for the soil model will use K-spring approach in each vertical and horizontally direction. The dynamic properties of fluid-soil and how it affects the dynamic behavior of the structure as a whole is the main objectives of this research.

1.1. Soil Spring

The concept of spring constant was first introduced by [1]. He modeled flexible foundation, such as raft, to stand on independent discreet spring elements or supports. [2] Proposed a method to estimate the magnitude of the spring constants. His approach, also known as subgrade reaction model, then became popular and commonly used in the design of raft foundation. Looking back into the origin of this concept the modulus or the coefficient of subgrade reaction, $K_s(x)$, is defined as the foundation pressure, p(x), divided by the corresponding settlement of the underlying soil, d(x), i.e.:

$$K_s(x) = \frac{p(x)}{d(x)} \tag{1}$$

Assuming the soils inside the bulb pressure zone possess are homogeneous, [3] expanded the Wrinkler model into an elastic model and developed the following equation:

$$K_s = \frac{E_s}{B.I_p(1-\upsilon_s^2)} \tag{2}$$

Where,

B : width of the foundation

E_s : elastic parameters of soils

I_p : the shape factor of the foundation

υ_s : poisson ratio

[4] Suggested providing higher K_s at the edges of the raft and smaller K_s at the center position. The interpretation of an existing soil layer data is refers to origin data by IPAM-Karang Pilang.

1.2. Structure Dynamic

Most structures are exposed to dynamic loading during their lifetime. This dynamic load can, for instance, be caused by storms, fluids, earthquakes or rotating types of machinery. The structural response for such a load can be described by the equation of motion called Forced Vibration Damped System [5]. Hence the fundamental equation for forced vibration is:

$$m\{\ddot{u}\} + c\{\dot{u}\} + k\{u\} = F_0 . \sin \omega_n t \quad (3)$$

Where,
$\{\ddot{u}\}$ is acceleration vector

$\{\dot{u}\}$ is velocity vector

$\{u\}$ is translation vector

F_o is load amplitude

ω_n is load frequency

t is time.

To model the structural parts, an extensive communication had been conducted from formal meeting with IPAM Karang Pilang as well as on a site survey, in order to get the furthest approach to as-built drawings. Consecutive re-drafting the existing building has been done with Solidworks 2017 to get 3D images and to have simulation using solids model. Solidworks is based on finite element method (FEM) and also able to perform dynamic analysis for both linear and non-linear behavior of structures.

The model contains all elements that are considered to affect the structural behavior, reinforced concrete walls, roof, beams and slabs. The non-concrete roof structure is considered to have no contribution to the overall stiffness of the building and is therefore omitted, except as mass. In the modelling process, boundary conditions at the building supports use elastic support which allows rotation and translation in certain value.

1.3. Flow Induced Vibration

The initial study of the experiment of vibrations by giving a certain force (in this case fluid) starting from [6] and experiments on free vibrations from [7] determined the viewpoint that the cylindrical shape experienced significant vibrations only when frequency characteristic shedding resonated with frequency natural structural, hereinafter referred to as "lock-in". The experimental results from [8] presented significant examples of static flow-induced vibration without "lock-in". These results indicate that the "lock-in" framework does not accurately describe the overall dynamic behavior, especially when the ratio between cylinders vs fluid masses becomes relatively small.

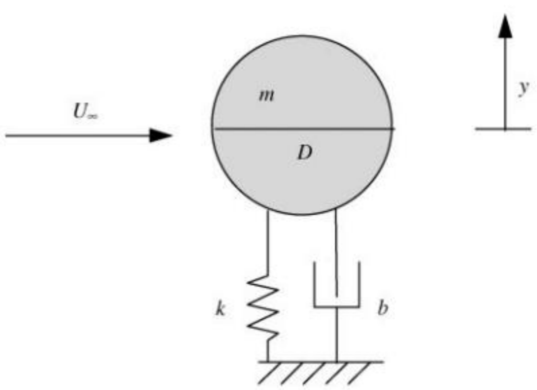


Fig. 1. Idealized Flow-Induced Vibration

1.4. Coupled-Field Analysis

A coupled-field analysis is an analysis that takes into account the interaction (coupling) between two or more disciplines (fields) of engineering. The procedure for a coupled-field analysis may divided into two distinct methods sequential and direct, this paper closely using sequential method. Which described as two or more sequential analyses to a different engineering field.

In the simplest understanding is to apply results from the first analysis as loads for the second analysis. However, for coupling situations which do not exhibit a high degree of nonlinear interaction, the sequential method is more efficient and flexible. It is known that performing the two analyses independently of each other is reliable also [9].

1.5. Coupled Soil-Structure

The classical analysis of soil-structure interaction aims at replacing the actual structure by an equivalent simple oscillator supported on a set of frequency-dependent springs and dashpots accounting for the stiffness and damping of the soil [10].

The system studied is shown in Figure 2 it involves a simple oscillator on a flexible base representing a single story structure, or a multi-story structure after a pertinent reduction of its degrees-of-freedom. A number of different approaches are available to formulate and solve the equations of motion for a soil-structure interacting system. The improvement by [11] is described as the basic equations in solving the horizontal rocking vibration problem of a building-foundation system.

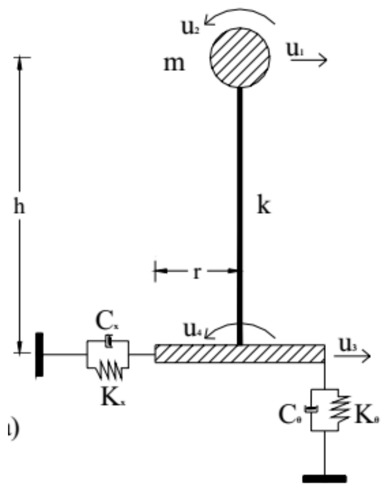


Fig. 2. Idealized Soil-Structure Interaction

1.6. Coupled Fluid-Structure

The distress of a concrete building is affected by several parameters, such as the compressibility, water hammer of the water and lead to various rotor yet fluid dynamic interactions which can be incorporated in the general term “fluid-structure interaction”, the possible existence of effect of surface (sloshing) waves, and the selection of an appropriate upstream boundary condition to represent the infinite extent of the reservoir in the upstream direction. The impact of these factors has been investigated in the past [12] analytically, numerically, or even experimentally as it will be briefly discussed in the sequence.

In order to cope with fluid-structure interaction problems, two approaches have been developed; the Eulerian approach and the Lagrangian approach. The Eulerian element formulation allows analysis of a medium which undergoes major deformation by mesh distortion techniques. The Eulerian-Lagrangian interaction formulation allows the eulerian material model to be analyzed through a Lagrangian, such as capturing the phenomenon of extreme deformation of fluid flow. As is seen on Figure 3, the short brief of Lagrangian Mesh are brought below:

a. Nodal coordinates of the Lagrangian move according to the material.
b. The material coordinates of the material point are not changing with time.

Vol. 1, No. 1, 2023
ISSN: 2987-3932
https://pubs.ast-ptm.or.id/index.php/eat

c. There is no material that moves through/between elements.
d. 4 quadratic points of the element remain to coincide with the points of the material.
e. The capital limit remains on the boundary when initial defining. Therefore, boundary conditions and interface conditions are easy to apply.
f. Extreme mesh distortion can occur because the mesh deforms together with the material.

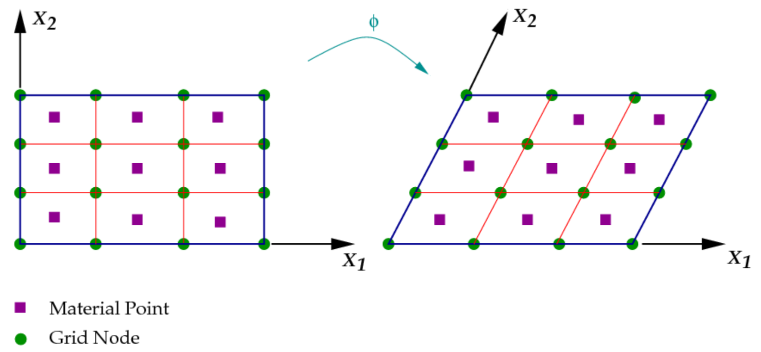


Fig. 3. Approach drawing of Lagrangian Mesh

As is seen on figure 2.7, the short brief of Eulerian Mesh are brought below:

a. Nodal coordinates of Eulerian fix / fixed and coincide with spatial points. The spatial coordinates of material points vary over time.
b. Material flows through/between mesh.
c. The point of the material at the 4 quadratic points of the element changes over time. This makes it more difficult because of dealing with material that depends on the order of time.
d. The material limits and limits allow it not to coincide. Therefore, boundary conditions and interface conditions are difficult to implement.
e. There is no mesh distortion because the mesh remains in space. However, the domain that needs to be modeled is bigger because we don't want the mesh body to leave the domain.

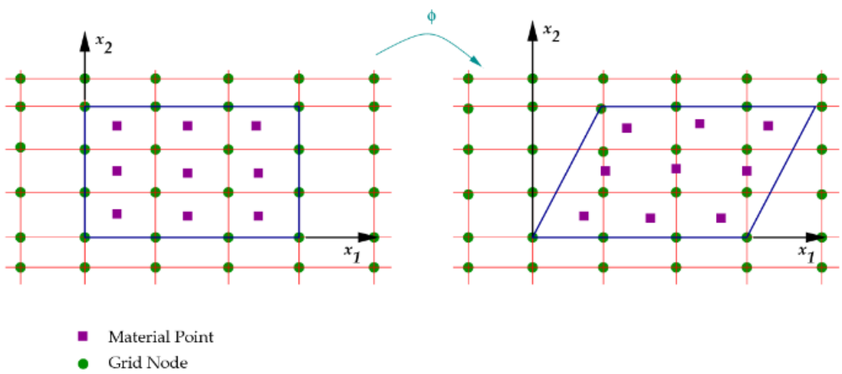


Fig. 4. Approach drawing of Eulerian Mesh

1.7. Rotor Dynamics

A very small amount of unbalance may cause severe problem in high speed rotating machines. The vibration signature of the overhung rotor (as discussed in this paper) is totally different from the center hung rotors. Rotor unbalance is the mostly common reason in machine vibrations [13], the vibration caused by unbalance actually destroy critical parts of the machine, such as bearings, seals, gears and couplings.

Rotor unbalance is a condition in which the center of mass of a rotating assembly, typically the shaft and its fixed components like disks and blades etc. is not coincident with the center of rotation. In practice, rotors can never be perfectly balanced because of manufacturing errors such as porosity in casting, non-uniform density of material, manufacturing tolerances and gain or loss of material during operation. As a result of mass unbalance, a centrifugal force is generated and must be reacted against by bearing and support structures [14].

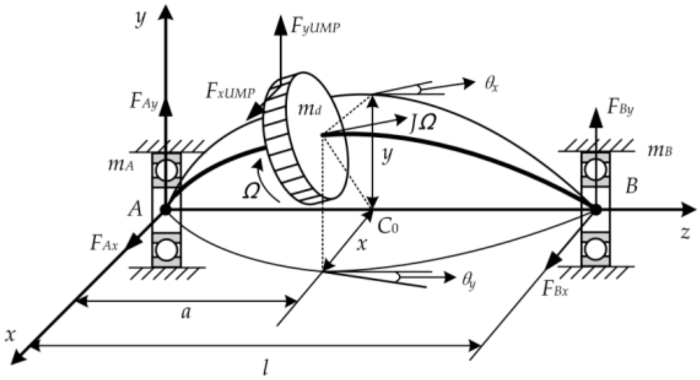


Fig. 5. Vibration model of the shaft element [15]

Based on Newton's second law, the equations of motion (3) can be derived into rotor bearing system as below [15]:

$$M\ddot{u}^T + (\Omega J + C)\dot{u}^T + Ku^T = F \tag{4}$$

Where M is the mass matrix, J is the gyroscopic matrix, K is the stiffness matrix, and C is the damping matrix. Finally proceed to defining F is the sum of the unbalance-mass F1 and ball-bearing force F2.

$$F_1 = \begin{bmatrix} m_d e_0 \Omega^2 \cos \Omega t \\ 0 \\ 0 \\ 0 \\ m_d e_0 \Omega^2 \sin \Omega t \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$F_2 = \begin{bmatrix} 0 \\ 0 \\ F_{AX} \\ F_{BX} \\ 0 \\ 0 \\ F_{AY} \\ F_{BY} \end{bmatrix}$$

Here some brief explanation of the Figure 5. and equation (4):

m_A and m_B : mass of the bearings
m_d is the mass of the rotor
a : distance between the rotor and the left bearing.
l for length of the shaft
x, *y* is the position of rotor in coordinate system
θx, θy is the rotational angles of rotor
And then e_0 is the mass eccentricity of rotor
Ω is the rotating speed of the rotor
J_d is the moment of inertia of rotor
J_p polar moment of inertia of rotor
E is the Young's modulus of the shaft
I is the moment of inertia of shaft
c is the damping of rotor
c_b is the damping of bearings

Vol. 1, No. 1, 2023
ISSN: 2987-3932
https://pubs.ast-ptm.or.id/index.php/eat

2. Method

This vibration phenomena retrieve an engineering intuitive prediction for the root-cause of it, and it is widely known that every rotating equipment ideally creates sinusoidal wave. And particularly these rotating equipment are transferring massive fluids with certain range of pressure value. For the soil-structure interaction, it is concluded (and refer to existing drawing) that the building sub-structure system does not use piling material. Hence it is permissible to assume that the structure is stand on foundation with non-linear rigidity aspect.

Herewith below are quick recap of how the methodology will flow:

1. Static and Modal analysis: using specimens of 1 pcs fixed-base building and 7 pcs spring-base buildings.
2. Computational Fluid Dynamics analysis: using 4 specimens of different pressure bar, 1 to 4 kpa.
3. Operational Deflected Shape analysis: using 8 specimens of deflected shape (from step 1) and each will rotate within different frequencies (from step 2).
4. Non-Linear Time History analysis: using 1 specimen of 3D concrete building model which will be loaded with un-balanced force from step 3.

The representation of the building can be seen at Figure 4, it is the 3D isometric-view for pre-analysis phase.

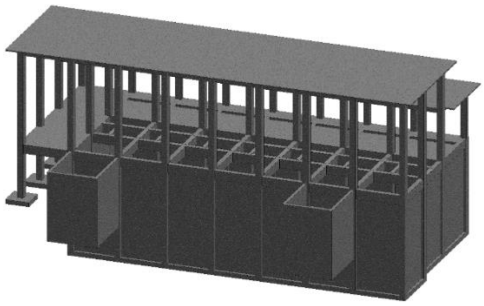


Fig. 6. 3D isometric view of pump station

2.1. Static and Modal Analysis

This analysis holds basic purpose to determine the alternating of the geometry of the building. Static analysis (calculated in different spring condition) will producing a graph relationship between soil spring values with the rotation of the vertical pump's geometry. Table 1 show the definition of concrete modeling value, while table 2 describe hand-calculation of Kspring value at depth of 10m according existing condition.

Table 1. Initial properties of the concrete elements

Mass Density	2400 kg/m3
Poisson's Ratio	0.205
Concrete Strength	40 Mpa.
Elastic Modulus	2.3e10 Mpa

Table 2. Initial properties of the soil for modeling

Depth (m)	N	Soil Type	k_V (kN/m)	k_H (kN/m)
0	0	silty	0.0	0.0
-2	4	silty	20734.5	13200.0
-4	4	silty	20734.5	14520.0
-6	7	silty	26954.9	17160.0
-8	8	silty	29028.3	19800.0
-10	12	silty	37322.1	17820.0

2.2. Computational Fluid Dynamics (CFD) Analysis

CFD analysis is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyze problems that involve fluid flows are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. Figure 7 viewing the boundary environment used in this paper.

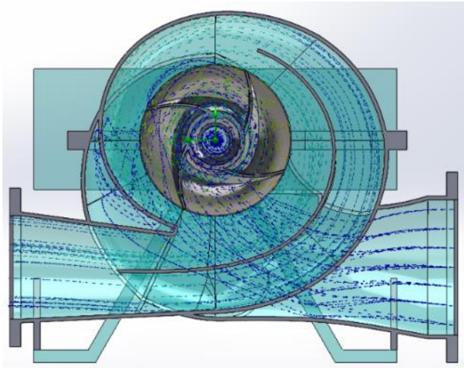


Fig. 7. CFD analysis on centrifugal pump

Table 3. Parameters for Fluid at 300oC

Density	995,77 kg/m3
Visc. Dynamic	7,91 x 10-4 kg/sec-m
Bulk Modulus	215013,5

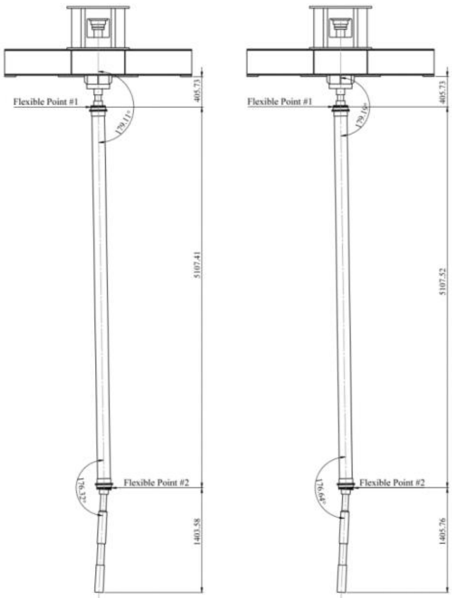


Fig. 8. Deflected shape of vertical pump

2.3. Operational Deflected Shape (ODS) Analysis

This ODS analysis is the continuity from the output shape of static analysis. Every geometric rotational value results from the static analysis shall be correspondent to this analysis, applied as the vertical pump's misalignment. The output of this analysis will be considered as the vibrational force wave-like. Which will be the main external force for next harmonic loading at dynamic analysis. Figure 8 revealed how the parts of vertical pump deflected each to one another, and this shape will be the initial setup for the motion analysis in Solidworks 2017.

2.4. Non-Linear Time History (NLTH) Analysis

This NLTH analysis will take the ODS analysis output as string data force within specific windowing time. This analysis will conducted using FEM software SAP2000 (compacted in Table 4), particularly focused on the performance of NLTH Analysis at the pump station building. The desired outcome from ODS analysis will be take on both conditions fixed and spring base, each conditions shall be represented by force-time graph relations.

Table 4. NLTH analysis setup

Analysis type	Non-Linear TH
Integration	Direct – Hilber Hughes
Initial Cond.	Cont. from NL static
TH Motion type	Transient
Damping Prop.	Proportional
Time Step	4 s
Fixture	Fixed and Spring
Rotation Freq	19, 17, 16, 14 Hz

3. Results and Discussion

The result in Figure 9 describes how the building response within fixed base, it is shown that mass cumulative participation is considered low or far below 80%. It means that the natural frequencies of the building unlikely, not excited by any forced wave frequencies. However the appearance of graph from Figure 10, can be seen that the mass cumulative participation reach above 80% in all direction with different frequency value.

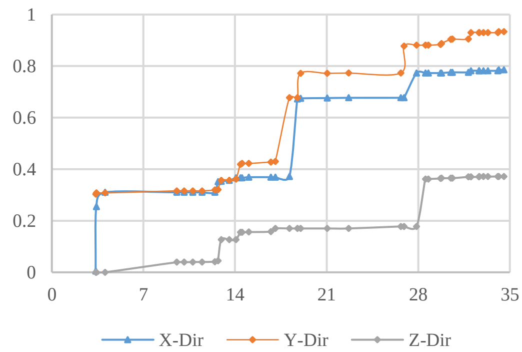


Fig. 9. Frequency (Hz) vs Mass Participation (%) of Fully Fixed base building

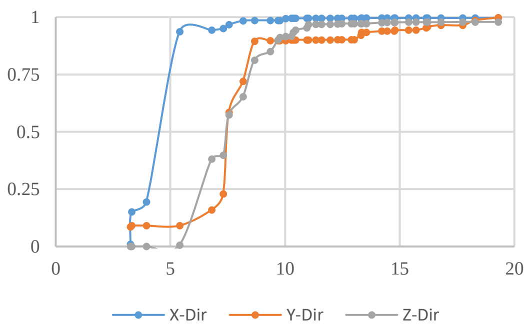


Fig. 10. Frequency (Hz) vs Mass Participation (%) of spring base building

Next result is the static analysis, which intended to find how the building response in ideal condition, and comparing the result of it into another elastic base conditions. This means to produce nondimensional value relationship with of other modal analysis results. Table 5 shows the vertical pump center line's rotation at various vertical pump adjacent each other.

Table 5. Nodal rotation (rad) between beam and floor

Node	Rotation	
1	2.923E-06	Rad
2	1.236E-05	Rad
3	7.695E-06	Rad
4	7.314E-06	Rad
5	8.386E-06	Rad
6	1.134E-05	Rad
7	1.18E-05	Rad
8	5.688E-06	Rad

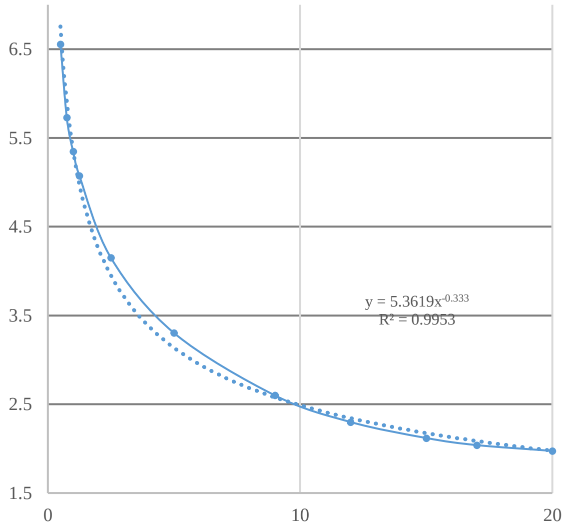
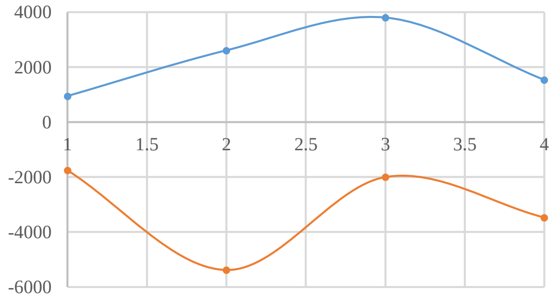


Fig. 11. Magnitude of Kspring vs Rotational magnitude of the shaft

For clearer understanding about the building's rigidity, Figure 11 viewing a graphical interpretation of structure rigidity on other spring-base value. It is founded that the structure would experience five times rotation generated from the same structure if it on a fixed-base footings.

This next analysis mainly as an expansion of Euler-Lagrangian approach, in Solidworks the approach algorithm is already built in within the Computational Fluid Dynamics (CFD) analysis feature. It is found that the fact of the fluid flow dynamics affected at impeller's force. To produce the effect of fluid dynamics at impeller force, several analysis conducted to describe a wider range of possibilities might occur at actual conditions.



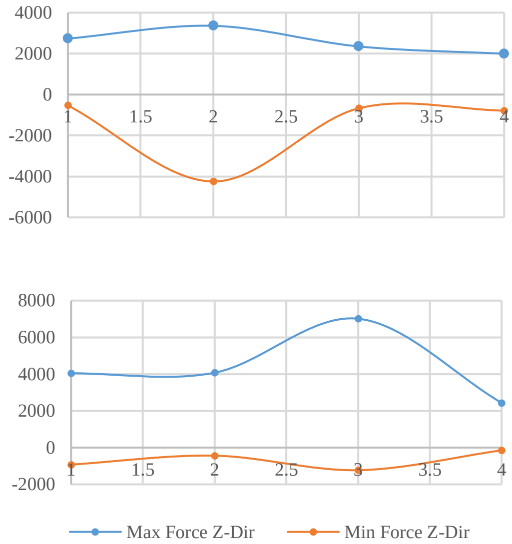


Fig. 12. Fluid Pressure (Bar) vs Force (N) on Centrifugal Pump

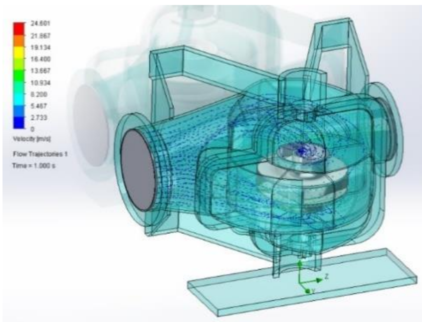


Fig. 13. Fluid flow visualization from CFD analysis

From the Figure 12 and Figure 13, it can be concluded the actual rotation frequency acting on the vertical pump's is ranged between 88 rad/s to 120 rad/s, or it is 14 Hz to 19 Hz. These information significantly important for comparing the force intensity with buildings resonate frequency. Hence the collectible information of the geometric changing (Table 5) and the rotational frequencies (Figure 12 and Figure 13) it is possible to conduct the ODS simulation by using the information as an input load and initial geometric unbalanced, and harnessing the result from it. All ODS analysis then recorded at the place where the forces act (at the concrete overhunged beam). The Figure 14 viewing every fluctuate force (x-direction) in each pressure value (which corresponded to rotation frequency), and Figure 15 viewing the y-direction of fluctuate forces.

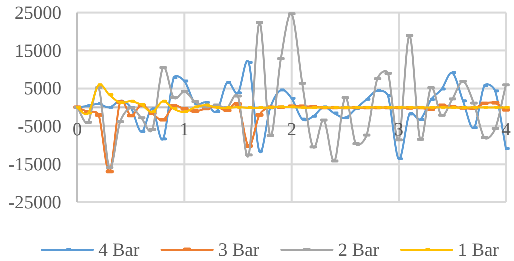


Fig. 14. Time (s) vs Force Resultant (N) affect by the Unbalance rotation

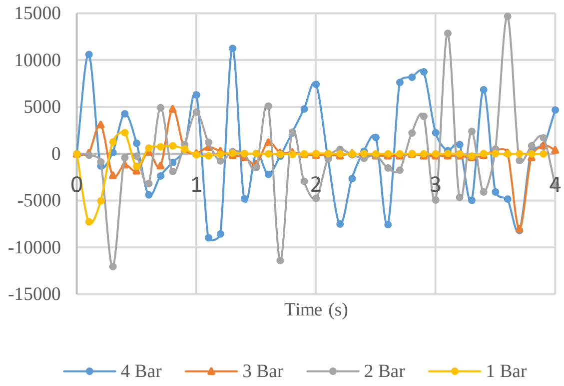


Fig. 15. Time (s) vs Force Resultant (N) affect by the Unbalance rotation

This final section shall discuss about NLTH analysis output, which came from the arbitrary loading data from Figure 12. Since the output is understand-able sinusoidal wave, hence the NLTH approach using feature from SAP2000 is considered reliable enough.

With the comparison of fixed and spring conditions, the difference of both (beam) displacement value are displayed in graphical results below to see the behavior. At Figure 16, the displacement (x-direct.) from unbalance force (spring base), creates arbitrary wave with high-dense fluctuates value alternating at ±0.8mm. And for the displacement from steady force (fixed base), it has value ±0.06mm with near-zero excitation on it. This waves also seen at Figure 17 (y-direct. deflection) with another high-dense fluctuates at value ±0.2mm

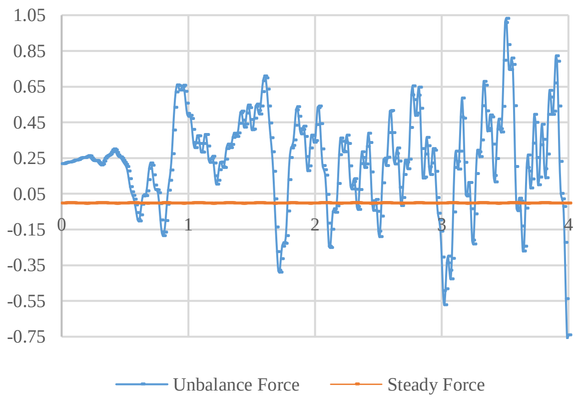


Fig. 16. Time (s) vs Beam X-deflection (mm) affect by the Unbalance rotation

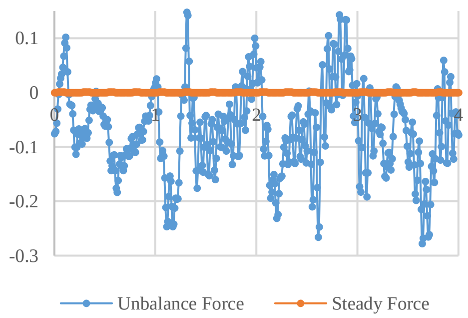


Fig. 17. Time (s) vs Beam Y-deflection (mm) affect by the Unbalance rotation

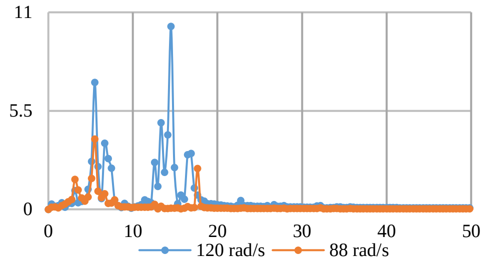


Fig. 18. Frequency (Hz) vs Beam deflection (mm) analyzed using Fourier analysis

From the analysis output, hence some parametric study are conducted, and the following summary can be drawn:

- Geometric changing in structural element of the building primary caused by the base rigidity. In this paper, the spring-base building experiencing nodal rotation 5 times larger than fixed-base building.
- Alternating in fluid pressure will significantly varying the rotation of the impeller, which affects the frequency state of the forces. This range of angular speed need to be mapped before designing the building, since from the Figure 18 shown that resonance occur at 14,5 Hertz.
- Vibration phenomena occurrence at the building shall considered 'small' due to its comparisons with building's nominal strength, but in the perspective of mechanical parts this phenomena needs to have more attention since the concept of the building is 'non-stop' public civil service.

The author hopes the continuation of this study in order to eliminate most of the aforementioned limitations and model the problem in a more accurate manner. More cases of fairings and splitter plates will also be considered for the analysis at a later stage to better understand the FIV suppressing capabilities of different devices. From the above conclusions, the following recommendation can be drawn:

- The pump station building need to be designed with higher range of natural frequencies. Since the geometric factor in structural response of the building takes significant account onto vibration phenomena.
- Base rigidity holds siginificant factor to retain the geometric displacements, hence the installation of structural piles is mandatory since it will increase to a larger value of base rigidity.
- The design phylosophy of the vertical pump are likely needs to be re-considered, eventhough it's well designed already. It is suggested to lowering the distance between pump and electric motor as Figure 19.
- The codes of structural design needs to consider the modal analysis into more specific tresholds. Especially if the building's structure is attached with machineries.

Further studies on the fluid-soil-structure interaction needed to dive deeper onto the magnification value of fluid and soil non-linearity.

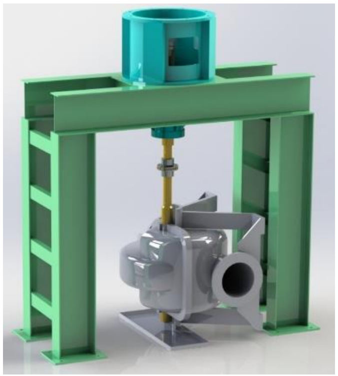


Fig. 19. Recommendation to modify the configuration of vertical pump

References

[1] E. Wrinkler, "Die Lehre Von Elasticitaet Und Festigkeit", 1st ed., Prague: H-Dominicus, 1867.

[2] K. Terzhagi, "Evaluation of coefficients of subgrade reaction," Géotechnique, Volume 5, Issue 4, pp. 297-326, 1955.

[3] A.B. Vesic, "Beams on Elastic Subgrade and Winkler's Hypothesis," Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, pp. 845-850, 1961.

[4] J.E. Bowles, "Foundation Analysis and Design", 5th ed., New York: McGraw-Hill, 1997, pp. 15–64.

[5] A.K. Chopra, "Dynamics of Structures: Theory and Applications to Earthquake Engineering", 3rd ed., Singapore: McGraw-Hill, 2006, pp. 15–64.

[6] G.H. Koopman, "The vortex wakes of vibrating cylinders at low Reynolds numbers," Journal of Fluid Mechanics 28, pp. 501-512, 1967.

[7] C.C. Feng, "The measurement of vortex-induced effects in flow past stationary and oscillating circulator and D-section cylinder," M.Sc. Thesis, University of British Columbia, Vancouver, B.C., Canada.

[8] A. Leonard, "Aspects of Flow-Induced Vibration," Journal of Fluid and Structures 15, pp. 415-425, 2001.

[9] Y.U. Haiping et al, "Sequential coupling simulation for electromagnetic–mechanical tube compression by finite element analysis," Journal of materials processing technology 209, pp. 707–713, 2009.

[10] Z. Benadla, "Influence of the soil-structure interaction on the seismic behavior of buildings on shallow foundations," International Journal of GEOMATE vol.6, pp. 811-816, 2014.

[11] J. Liang et al, "Soil–structure interaction for a SDOF oscillator supported by a flexible foundation embedded in a half-space: Closed-form solution for incident plane SH-waves," Soil Dynamics and Earthquake Engineering 90, pp.287–298, 2016

[12] G. Papazafeiropoulos et al, "Dynamic Interaction of Concrete Dam-Reservoir-Foundation: Analytical and Numerical Solutions," Soil Dynamics and Earthquake Engineering 90, pp.455-488, 2010.

[13] B.K. Kumar et al, "Determination of Unbalance in Rotating Machine Using Vibration Signature Analysis," International Journal of Modern Engineering Research 2, pp. 3415-3421, 2012.

[14] M.A. Saleem, "Detection of Unbalance in Rotating Machines Using Shaft Deflection Measurement during Its Operation," IOSR Journal of Mechanical and Civil Engineering-Volume 3, pp. 08-20, 2012.

[15] A. Zhang et al, "Analysis of Nonlinear Vibration in Permanent Magnet Synchronous Motors under Unbalanced Magnetic Pull," Journal Applied Science-MDPI Vol.8, Issue 1, pp. 113-132, 2018.