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Vibration Analysis of Pump Shaft Using Finite Element Analysis Software: A Review

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Abstract
Rotating shaft and other components in pump system revolving at a speed close to the natural frequency of the system are unsafe because at natural frequency, the amplitude of vibration is highest and it generates the excessive stresses which can cause rotating components' failure. The objective of the review paper is to study the vibration characteristics of pump shaft system of finite element method in software module. The knowledge about the natural frequencies for rotating component in pump system can help to avoid system failure by giving the safe operating speed range and condition monitoring of actual running condition. In the present work, finite element method has been used in vibration analysis of pump system.

***Keywords**: Vibration, vertical pump shaft, FEM, natural frequency, ANSYS*

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INTRODUCTION

A vertical pump converts the input power to kinetic energy in the liquid by accelerating the liquid with an impeller. The energy used by the pump is kinetic energy formulated by the Bernoulli Equation. Fluid goes into the pump from side of the eye of the impeller which is spinning at high speed. The fluid increases speed radially outward from the pump casing. A vacuum is generated at the impellers eye that continuously draws more fluid into the pump.

Pumps develop centrifugal force to increase the velocity of the fluid as it passes through the impeller and way out at the tip or periphery of impeller. This process changes mechanical energy into kinetic energy by accelerating the fluid to a higher velocity and pressure (potential energy). It is essential to be concerned about the vibrations because it has a major effect on the performance of pump. This vibration reduces the expected life of the pump components.

To confirm the safety of the pump and related plant components, the vibration must be kept within definite limits. Characteristic causes for pump failures can be established well in advance by applying the right kind of vibration testing, evaluation, analysis criteria during pump monitoring or troubleshooting problem [1].

In present days, the finite element methods (FEM) are widely used in the simulation of statics, dynamics system, or hydrokinetics, thermodynamics systems. And to do the numerical simulation; it has to make a decision simulation condition for the environment parameters of operating condition, temperatures, and external forces and so on in regard to the machine.

Finite Element Analysis (FEA) is used to find any root-cause failure studied, engaging unnecessary vibrations in case of vibration analysis. The finite element method (FEM) is a numerical procedure that can be used to approximate the modal parameters such as natural frequencies and mode shape of complex structural-mechanical systems/models [1].

Natural Frequency

Natural frequency is the chief rotating speed of the machine or shaft being observed and usually referred to as the running speed of the machine. The fundamental frequency is important because many machinery faults such as misalignment or unbalance occur at some multiples of the fundamental frequency, for example misalignment at 1×natural frequency [1].

The frequency of free vibration is called natural frequency of system. The natural frequency (f_n) is given by:

$$f_n=\sqrt{\frac{k}{m}}$$

Where, k=stiffness of system, and
m=mass of system.

Resonance

The condition in which a rotor's operating frequency of rotation coincides with the natural frequency of rotor system, it is known as resonance of rotor system. At resonance condition, large amplitudes are generated.

Critical Speed

The speed of rotor at the resonance condition is called the critical speed of rotor. The rotor can have one or more critical speed also.

Whirling

Because of unbalance generated in rotor system, rotating axis of rotor is displaced with the bearing axis of system; it generates perpendicular motion of rotor (Figure 2). This phenomenon is known as whirling motion of system. There are two types of whirling motion generated (Figure 3) [2].

Forward Whirling

In this type of whirling motion, the shaft rotation direction and whirl direction is same.

Backward Whirling

In this type of whirling, the shaft rotation direction and whirl direction are opposite.

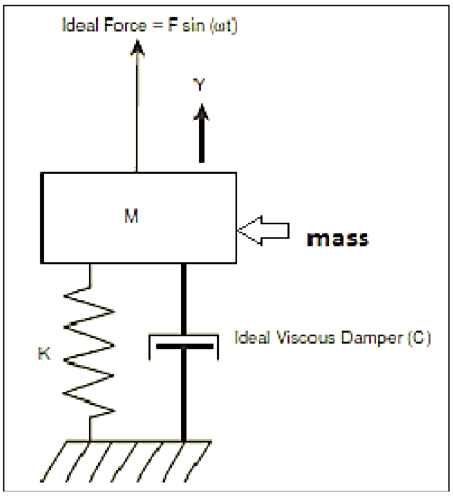

Fig. 1: *Simple Spring-Mass and Damper System with External Force.*

Campbell Diagram

This is a famous diagram in rotor dynamics called Campbell diagram. In this diagram, the horizontal axis is the rotating speed of the shaft; the vertical axis is the natural whirling frequency. At zero speed, we can able to see that these are the first natural frequency, then other frequency are accordingly second, third, fourth, natural frequencies (Figure 4) [2].

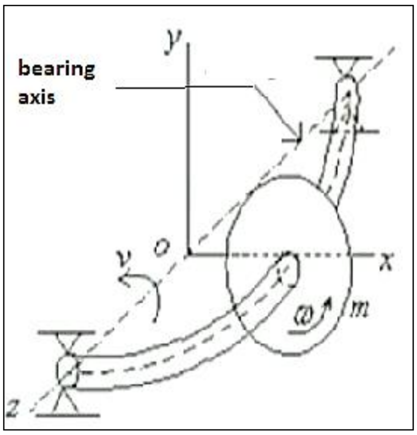

Fig. 2: *Jeffcott Model of Whirling of Rotor.*

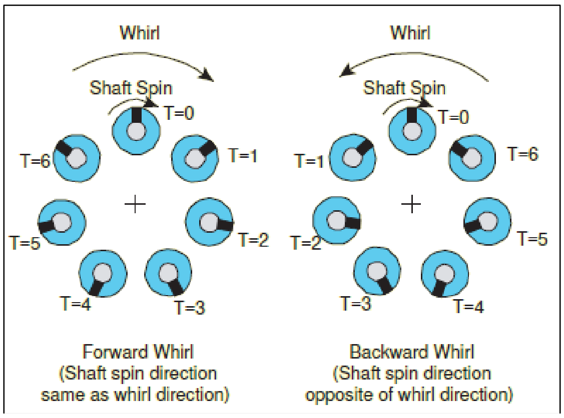

Fig. 3: *Whirling Motion Types.*

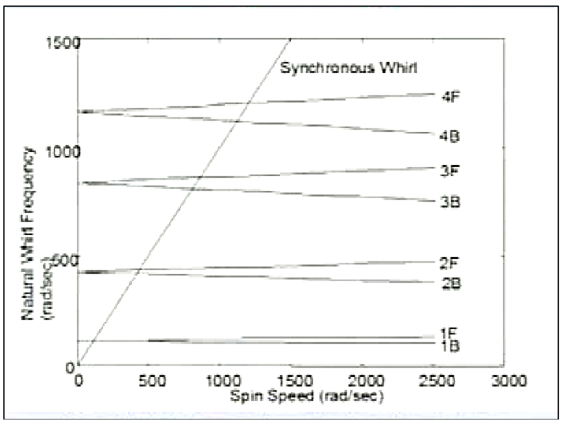

Fig. 4: *Campbell Diagram for Rotor Bearing System.*

Gyroscopic Effect

The gyroscopic effect is the important effect in the rotating element. The gyroscopic effect is demonstrated by gyroscope device. According to the equation of the gyroscopic effect, which describes that "The torque on the gyroscope applied perpendicular to its axis of rotation and also perpendicular to its angular momentum causes it to rotate about an axis perpendicular to both the torque and the angular momentum" (Figure 5). This rotational motion is referred to as precession. It causes the forward whirling and backward whirling phenomena [2, 3].

General Equation of Vibration

$$m\ddot{x}+C\dot{x}+Kx= \text{Force}$$

Where,
m= Mass of system,
$\ddot{x}$= Second derivative of displacement,
C= Damping coefficient of system,
$\dot{x}$= First derivative of displacement,
K= Stiffness of system, and
x= Displacement of system.

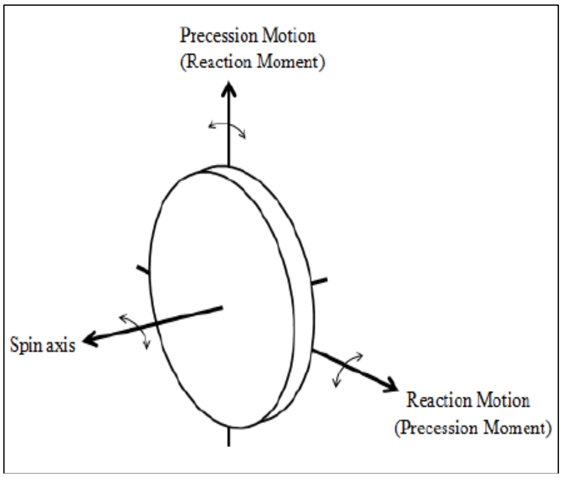

Fig. 5: *Gyroscopic Effect.*

Vertical Pump and Its Mathematical Model (Figure 6)

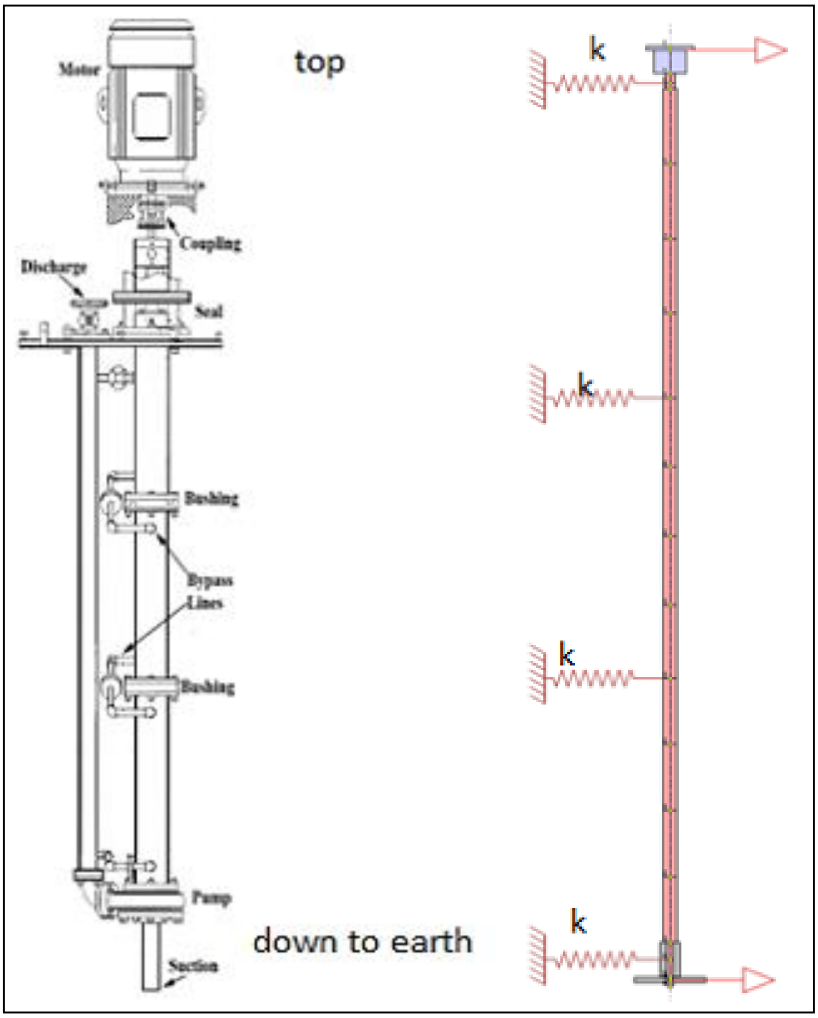

Fig. 6: *Vertical Pump and Its Mathematical Model.*

Literature Review:

Dalia M. El-Gazzar studied pumping station contained 6 units; FEA analysis was used to model the motor structure to estimate the dynamic characteristics using Ansys workbench 14.5. The FEA model was made for the original motor structure and simulation is made to find its natural frequencies and mode shapes. The model consists of a motor weighing, a steel base, and a concrete foundation. Concrete is assumed to be a uniform and isotropic material and to perform in linear elastic manner to evaluate and improve dynamic performance of a vertical pumping unit. Dynamic performance of the pumping system is affected very much by the changing in the motor weight. The low stiffness of the motor base gives to the relatively high oscillatory motion of the motor. Adding stiffeners decreased the amplitude of vibration. The increase in the stiffness of the motor base moves the natural frequencies away from forced vibration. Pump unit simulation results confirmed that the overall vibration level reduce approximate ≤ 89% after getting structural alteration of system. [1]

Pirogova *et al.* analyzed a micro gas turbine plant rotor with the working speed of 65,000 rpm. It contained two subtype systems: a turbocharger rotor and a rotor of the starter-generator linked with the elastic coupling. Evaluation of the critical speeds of the rotor was performed in two stages by calculation: an analytical method and numerical solution of the test problem firstly, in order to confirm the accuracy of FEA calculation in the Ansys software, followed by the critical speed assessment through the FEA computation on solid 3D model and based on calculation and experimental method, the suggestion for the construction of rotor are: rotor of turbocharger and the rotor of starter generator must be connected with flexible element with low bending stiffness; the design of elastic connection should allowance critical speed of the rotor dropout of the range ±30% of working speed [4].

Zhao *et al.* analysed large double suction centrifugal pump by FEA software Ansys to verify the natural frequencies of the rotor system and the critical speeds with the assistance of the Fluent software to simulate pump internal flow field and concluded that speed increase will not cause excessive vibration of the fluid in the pump using unsteady numerical simulation that impeller has suffering transient radial force which change periodically as well as the frequency size was calculated by multiplying the impeller speed and number of blades, resonance phenomena should create impeller to transient radial force frequency if defective, to avoid pump resonance when it is running away, the transient radial force frequency should keep away from frequency range which can cause resonance [5].

Dong *et al.* compared various modelling and analysis methods for rotating shaft system. They evaluated the simulation results from Msc Partan/Nastran software and Ansys software by a 3D model and the results by solving Matlab based on FEM using a 2D model of system; and concluded that it was the element size which is serious affected in the solving time and result. In accumulation, the result with the 2D model was in a permissible error of difference ≤10%, when it was evaluated with the results from others software; and the analysis time was very dissimilar among them [6].

Kumar *et al.* discussed the various features available in Ansys mechanical program to study the dynamic features of rotors and their supporting systems; they used various analyses done in software and concluded that the Ansys mechanical program suggests it being widespread and practical for rotor dynamics analysis ability and also used them for solution of big and complex models. The pre-processing, solution/analysis and post processing communications is the regular thread between the machinery of basics, materials, and equation solvers. An incorporated infrastructure, the new concept of Workbench Simulation and Design Explorer, APDL customization and work combine to provide great simulation capacity in rotor dynamics [3].

Eduard Egusquiza *et al*. dealt with the dynamics response of pump and turbine impellers. For this investigation, the impeller of an existing pump-turbine unit with an install power of

110 MW and a diameter of 2.87 m was calculated. They inspected the experimental results of a numerical model using FEM software. Frequencies and mode-shapes were recognized numerically and experimentally and the characteristics of the structural response of system were analyzed; and concluded that because of the structural characteristics, the crown and band have much lower stiffness in the axial direction evaluated with the blades, mainly close to the outer diameter of the impeller in the suction side. Thus the deformation is mainly in outer diameter in axial direction. The impeller eye also deforms but in radial direction [7].

Chen *et al*. studied the random vibrations of a revolving cantilever blade with external and internal damping by FEM. Euler thin beam elements were used to give explanation of the system, with the base excitation and noise being the main methods of excitation. There was no effort to explain the gyroscopic moment contained by the system [8].

Heindel *et al.* demonstrated that theoretically and experimentally show that active bearings have capacity to reduce both bearing forces and the resonance of a Jeffcott rotor system. Active bearings can move a rotor such that its centre of mass (CG) always keeps on in the rotational centre. The proposed collocated controller is able to keep this state at any spinning speed and leading to a removal of bearing forces and resonance conditions [9].

Rao *et al.* studied the stiffness and mass matrix of a rotating twisted and tapered beam element. They also studied the displacement model and element stiffness matrix, and element mass matrices for rotating Timoshenko beam. By putting boundary condition, they got four natural frequencies of elements, and found the relation between effect of offset and rotation on the natural frequency on beam element; and concluded that increasing breadth and depth taper ratio increases the first two modes of vibration [10].

Ku concluded that a finite element model be in the right place for the study of whirl speeds and stability of rotatory bearing systems. In adding together to the effects of translational and rotary inertia and the gyroscopic moments, the joint effects of transverse shear deformations and the internal viscous and hysteretic damping are also integrated into the formulation results of forward and backward whirling speeds and damped stability are obtainable and compared. The good convergence and high accuracy of the present finite element model are established with numerical examples [11].

Yanhongmaa *et al.* illustrated a smart rotor support damper with variable stiffness made with a new multi-functional material is shape memory alloy metal rubber. The mechanical performance of the smart support damper has been examined at room and high temperature on a rotor test rig in system. The vibration capacity of the damper has been considered through FEM simulations and experimental tests, and both the results were compared. The study shows the practicability of using the material for potential applications of active vibration control at various temperatures in rotor dynamics systems. It is used where amplitude of vibration is frequently changed [12].

Li *et al*. studied that the effect of shaft bending in coupling vibration of rotor system. They also analyzed the influence of the number of blades, the position of disk, and the support stiffness of shaft on critical speed of system. For that they made a dynamic model of the system; and using dynamic eigen value matrix found the natural frequency of the system. They also analysed the mode shape of the rotor system and concluded that the number of blades has no significant effect on the mode shape of blade and rotor but the position of disk and rotational speed have an obvious effect on the mode shape of rotor [13].

Nikumbe *et al*. worked on comparing finite element analysis for vertical pump vibration in modal analysis type in Ansys software and experimental data. Experimental analysis is completed by using Fast Fourier Transform (FFT) analyzer. During this analysis, exciter mechanism is done by use of an instrumental hammer. They used this analysis for finding natural frequency of vertical pump shaft and found resonance condition. After both simulation and experimental result comparison, they were quite near and concluded that at operating speed, vertical pump shaft is resonance free [14].

Prajapati initiated out the solution for reducing vibration in vertical turbine centrifugal pump using harmonic frequency response analysis in Ansys. He specifies some methods of identifying vibration in pump and some possible cause of vibration. He find that the possible cause of vibration in pump is due to its structure and due to either weight of the motor placed at higher causing maximum vibration or due to improper misalignment between upper and lower base part of pump [15].

Kumatkar *et al.* conceded out a modal analysis of a vertical turbine pump to determine its dynamic features such as its natural frequencies and equivalent mode shapes. They have analyzed the rotor assembly of vertical turbine pump theoretically, numerically and experimentally. The system was modelled as a lumped mass structure to theoretically determine its torsion natural frequencies and as a continuous system to determine its transverse natural frequencies. The numerical model validated with the results of the theoretical analysis [16].

Naveena *et al.* studied rotor dynamics analysis of multi-stage centrifugal pump rotor using Ansys software. The results achieved from Ansys, analytical calculations and RBTS (Rotor Bearing Testing Software) were nearer with each other and the maximum amplitude of deflection of rotor for the applied unbalance loading was determined using API 610 standard, and the critical speeds for the centrifugal rotor were found from Campbell diagram [17].

Agostini *et al.* presented work on the vibration analysis of vertical rotors in gravitational and gyroscopic effects. Forward and backward modes were found independently through carrying them out in Matlab software of complex modal analysis in combination with the FEM simulation. They also analysed that the natural axial, torsion and transverse frequencies may be get the Campbell diagrams, graphs with complex and traditional modal analysis. Comparisons were made between the complex and traditional modal analysis, centre of attention was on the easy-goingness of whirl modes examination, since the complex modal analysis allows clear difference in element curves for the forward and backward whirling mode [18].

Hisham *et al.* analysed a single rotor system and identified unbalance parameters that could be present in rotating machinery, and developed a finite-element model of rotating dynamics system to produce a mathematical model of the system from the test data and then found the unbalanced parameters. During study, the raw data obtained from the experimental results were curve built-in by theoretical data stimulated from simulating it using Ansys model for comparison of the experimental in which one disc in the middle first mode and FE simulation; and the result of natural frequency and mode shape nearby matched each other [19].

Tony obtained four different pumps of different horsepower (HP) for analysing modal deflection. He also analysed Operational Deflection Shape (ODS) for each pump; for this, he used ME scope Visual ODS-pro software; for modal analysis, he used FEA method. He concluded that resonance testing and operational deflection shape studies are helpful tools for analyzing vibration problems. When resonance is recognized as the problem, a modal survey is essential to identify all of the natural frequencies and calculate each mode shape. Without knowing the mode shape, it is impossible to know how to define the resonance [20].

Tenali *et al.* concluded that by integrating rotor and bearing support flexibility characteristic in rotor dynamics features into the standard FEA-modal, harmonic and transient analysis measures in Ansys software. He used stem rotor for analysis. He analyzed and determined the design integrity of rotating equipment. He made use of elements BEAM188 and COMBI214 to mould the shaft and bearings in that order. And same modelling and results were also calculated from TMS-050 software element to confirm Ansys result with testing result for unbalance response [21].

Leader analysed the sub-synchronous vibration in vertical pump at higher operating speed. Vibration analysis including impact testing revealed that there were structural resonances at nearly half running speed. The excitation was believed to be coming from the liquid sulphur-lubricated pump line shaft bushings being in whirl similar to the familiar oil whirl. They concluded that there was sulphur whirl occurring and that the first lateral critical speed of the pump line shaft was also at half frequency. New line shaft bushings were designed that would increase the effective stiffness and damping from the bushings. Once the new bushings were installed, the sub-synchronous vibration was eliminated [22].

Hussain has studied the torsional vibration characteristics of multi-rotor system using FEM to find torsional natural frequencies for different probable cases of multi-rotor systems. The various mode shapes for some cases are also exposed to exemplify the state of the system at natural frequencies. The results obtained have been evaluated with Holzer's method and Ansys software version to set up the effectiveness of finite element method for this type of such systems [23].

Malgol *et al.* determined natural frequency, critical speeds and amplitudes of rotor system of rotor shaft system for three different positions of the disk. They first made a model of the single rotor system and did the modal analysis in the ANSYS software. After that, frequency response analysis was done for various positions of the disc. They also did transient analysis of system in Ansys software and compared result with the numerical method of system, and concluded that the natural frequency and critical speeds of the simply supported rotor system increases as the disk position distance decreases form the support [24].

Rajan *et al*. studied the vibration characteristic of the single rotor system and gave explanation of gyroscopic effect, critical speed, Campbell diagram and rotor unbalance of system. They used mathematical model of single rotor system, and ANSYS software for analysis of system to find natural frequency and critical speed. They concluded that forward whirling increases the natural frequency and a backward whirling decreases the natural frequency. A forward whirling increases the stiffness of a system while backward whirling decreases the stiffness of a system [25].

Sheng *et al.* presented paper on large-size vertical pump that has the specification of 2000 mm in diameter, 25 m in length, and 3000 kW in driven power unit system; and the effect of the water on the pump natural frequency is measured. The radial fluid force is calculated by the experiment and frequency response analysis. The expected results are proved to have a good conformity with the measured results of the actual pump system. The vibration intensity of the large-size vertical pump is lower than the vibration design standards [26].

CONCLUSION

Rotor dynamics are combination of the FEM and solid modelling process to generate simulations that put up the coupled behaviour of flexible disks, flexible shafts and flexible support structures into a solo multidimensional model. The investigation software in mechanical program offers wide-ranging, practical rotor dynamics analysis ability and capacity of solution of big models, complex models for complex systems [27]. The pre-processing, solution-analysis and post-processing infrastructure are the common points between the components of basics, materials, and equation solvers. This facilitates a general FEA model used for both stress and rotor dynamic analysis, the element size has serious influence in the solving time and result [28]. In accumulation, the result using the 2D/3D model simulation and analytical method and experimental method is in a permissible error, difference ≤10%, when it is compared with the other methods.

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