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Seismic qualification of a submerged fire-water pump

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ABSTRACT

Before its recommendation for use in a Nuclear Power Plant, it is necessary to ascertain the structural integrity and operability of an equipment under seismic conditions. This paper deals with the seismic qualification by analysis of a sumerged Fire-Water Pump for use in a Nuclear Power Plant of India. A brief description of modelling, analysis and a summary of the results are presented.

1.0 INTRODUCTION

The occurrence of fire in the event of an earthquake can produce large devastations to both life and property - the recent earthquake in Japan underscores the point. Thus it necessary to ascertain the functionality of the fire fighting system under seismic conditions and the seismic qualification of the fire-water pumps deserves special importance in this respect. The fire-water pump in consideration is a motor driven submerged vertical centrifugal pump which is to be used in one of the Nuclear Power Plants of India. Due to the presence of the sump shake-table testing is difficult to perform and qualification by analysis is resorted to and a report [1] has been prepared for submission to Nuclear Power Corporation of India. In this paper we shall give a brief description of the analysis alongwith a summary of the results. The check for allowable stresses is done in accordance with subsections ND and NF of ASME section-III code.

2.0 MODEL DESCRIPTION AND ANALYSIS

A sketch of the pump motor assembly is shown in Fig 1. The distinguishing feature of system is the large length of the discharge pipe which makes the system extremely flexible. This necessitates and accurate determination of the eigen-frequencies and therefore accurate modelling.

Fig. 2 shows the FEM model of the system. The pump shaft and the column pipe have been modelled as two noded beam elements. As the centre lines of the shaft and the discharge column is the same they have been shown with a relative shift for the sake of clarity. The suction bellmouth and the diffuser casings have been modelled as beam elements. For an element having a variable cross-section. the equivalent cross-sectional properties have been computed as the mean values over the element length. This is obtained from the equivalence of the strain energies for the two systems There are four diffuser casings each of 0.213m length. The main rising pipe consists of eight pipe segments each of length 1.515m The motor body and the stool have been modelled as beam elements with the centre line coincident with that of the pump shaft. The discharge nozzle is connected to the motor housing through the rigid beam element between the nodes 57-63.

The driving shaft of the motor is connected with the top spindle by the flexible coupling. Between the top spindle and the pump shaft there are eight intermediate spindles connected by couplings. The spindles and the shafts are modelled as beam elements. There are 4 pump bearings and 8 intermediate Finostos bearings. The thrust bearing is of hydraulic type and carries the entire weight of the pump shaft, rotor and intermediate spindles. The bearings on the motor shaft are radial type roller bearings with the one at the driving end capable of taking axial thrust. The bearings have been modelled as G-STIFF elements with the stiffness values determined from the linearized force-deflection curves. The flexible coupling has been modelled as a beam element with the sectional properties determined from stiffnesses of the coupling bolts, with the beam forming an equivalent elastic system.

2.1 Base-Plate (Local Model)

The discharge pipe is connected to the foundation through the base-plate and sole-plate. The base-plate and sole-plate are connected by eight 25mm dia bolts. The base-plate assembly has been modelled as spring elements with equivalent stiffness values. Since the foundation stiffness has a major influenceon the eigen frequencies an accurate estimation of the stiffness has been made through a fine FEM model [Fig. 3]. The base-plate and the sole-plate have been modelled as 3/4 noded plate elements and the bolts are modelled as beam elements.

2.2 Mass Distribution

For the structural elements mass lumping proportionate to the influence area has been performed. The masses of the pump rotors have been lumped at nodes 4,8,12,16. For the motor the mass of the rotor has been distributed on the driving shaft with the mass of the motor winding added at node 64 which is the C.G. of the rotor. The fluid which is water has been considered to be incompressible and inviscid. Its inertial effect has been taken by means of an added mass matrix (ADM) which in contrast with the diagonal mass matrix [2] for the structure is fully populated. The formulation of ADM is based on the potential flow theory and Fluid-Structure Interaction (FSI) [2,3]. The ADM is formed considering the water in the sump as well as that inside the pump. The FEM mesh for the fluid is given in Fig. 4. The fluid is modelled as four-noded elements and the ADM is obtained using axi-symmetric formulation. A proprietory software has been developed for the construction of ADM A brief derivation of added mass matrix for a submerged cylinder is given in Appendix A-1

2.3 Discharge Nozzle (Local Model)

A local analysis has been done for the discharge nozzle and support pipe assembly in order to access the structural integrity. The FEM mesh is depicted in Fig. 5. The modelling becomes complex due to the cut out portion of the support pipe. It is also the reason for which manual calculations cannot be carried out using the standard WRC-107/297 procedure.

2.4 Analysis

The system was analysed for levels A, B and C service conditions. Level A refers to the Normal Operating conditions. Levels B and C refer to upset and shutdown conditions for OBE and SSE respectively. The effect ~~of piping~~ reactions on the discharge nozzle has also been considered by the local analysis of the nozzle. The dynamic analysis was performed using the Response Spectrum (RS) method. Absolute summation is done for the combination of static and dynamic stresses. The RS curves for OBE (2% damping ratio) and SSE (3% damping ratio) are shown in Fig. 6 As a measure of additional check analyses have been done using lumped mass (displaced fluid mass) for the fluid. In the sequel we shall mainly deal with the ADM model unless we mention specifically about the lumped fluid model (LFM).

3.0 RESULTS AND DISCUSSIONS

The first 10 frequencies are shown in Table 1. The fundamental frequency of Model 1 is 0.501 Hz while that of Model 2 is 0.645 Hz. The low frequencies are due to the long unsupported length of the discharge pipe and the shaft. The low flexibility induces high stresses and displacements during seismic conditions. The maximum displacement for the seismic loading (SSE) is about 15cm at the suction bell-mouth. The maximum bending moment of 3600kg-m for SSE conditions occur at element 19 at the junction of the base-plate and discharge pipe. Table 3 gives the maximum stresses for the pump, delivery nozzle and the base-plate for different service conditions. It is observed that for the discharge pipe, large membrane stresses are induced. This is due to a high design pressure of $52kg/cm^2$. The nozzle loading due to piping reactions also induces high stresses. The local analysis yields an accurate estimate of stress distribution. The maximum stresses expectedly occur near the junction of the discharge pipe and delivery nozzle. The stresses for all the components are within allowable limits. The check for clearance for the critical components [Table 2] shows that the relative displacements are within allowable limits. The foundation bolts also have been found to be safe in the check for failure.

4.0 CONCLUSIONS

A fairly comprehensive description of the seismic qualification of a submerged FW pump has been presented. The analysis has demonstrated the structural integrity and operability of the pump. The ADM model is preferred to the LFM, since the system is extremely flexible and an accurate determination of the dynamic characteristics is required. The information obtained from the analysis can serve as useful guidelines for the qualification of similar pumps.

5.0 REFERENCES

1. Seismic Qualification of Vertical Fire-Water Pumps, Report No.M&P/91R01/01/SR-VOL - I; DCL Report, December 1993.
2. Zienkiewicz, O. C., The Finite Element Method, New York, 1977.
3. Planchard, J., Eigen Frequencies of a Tube Bundle. Computer Methods in Applied Mechanics and Engineering, **30**, 75-93, 1982.

Table : 1 Eigen-Frequencies of the system

Frequency (Hz.) Serial No.	ADM Model	LFM Model
1	0.501	0.656
2	3.297	5.144
3	6.975	15.401
4	16.759	20.58
5	22.234	31.126
6	33.779	36.358
7	37.682	36.488
8	37.779	49.477
9	53.170	50.589
10	54.355	55.131

Table 2 : Clearences at Critical Locations

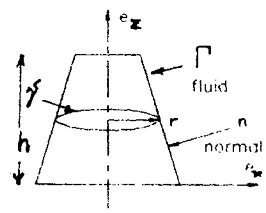
Serial No.	Location	Clearences in mm Actual	Allowable
1.	Suction impeller / Neck ring in suction bell mouth	0.60E-03	0.155
2.	Suction impeller / Neck ring in casing diffuser	0.11E-02	0.14
3.	Stage impeller / Neck ring in casing diffuser	0.11E-02	0.14
4.	Rotor winding & the stator	0.32E-06	0.90

Table 3 : Maximum Stress in Different Service Levels (Stresses in 10^5 Pa).

Member	Level A		Level B		Level C	
	$S_1^{(1)}$	$S_2^{(2)}$	S_1	S_2	S_1	S_2
El. No. 19 on Discharge Pipe	921	921	1014	1016	1106	1411
El. No. 14 at Nozzle-Discharge Junction [Local Analysis]	1080	1273	1474	2139	1299	1577
El. No. 354 of the Base-Plate [Local Analysis]	10	55	65	335	100	525

Note:- (1) S_1 - Membrane Stress
(2) S_2 - Membrane + Bending Stress

Appendix A-1: Formulation of Added Mass Matrix



BEAM IMMERSED IN FLUID
FIG. A1

Let us consider an axisymmetric beam element immersed in a fluid at rest [Fig. A1]
The equation of motion along $\mathbf{e}_x$ is as follows:-

$$m\,(\partial^2 u/\partial t^2) + \partial^2/\partial z^2(EI(\partial^2 u/\partial t^2)) = \int_{\gamma(z)} p.\mathbf{n}.\,\mathbf{e}_x\,.d\gamma \qquad \text{..........(1)}$$

where, m = mass per unit length; EI= bending rigidity; p = dynamic fluid pressure; t = time variable; u = displacement of the beam.
The fluid pressure can be expressed in terms of its density (ρ_f) and potential (ϕ) as follows:

$$p = -\rho_f\,(\partial^2\phi/\partial t^2) \qquad \text{..........(2)}$$

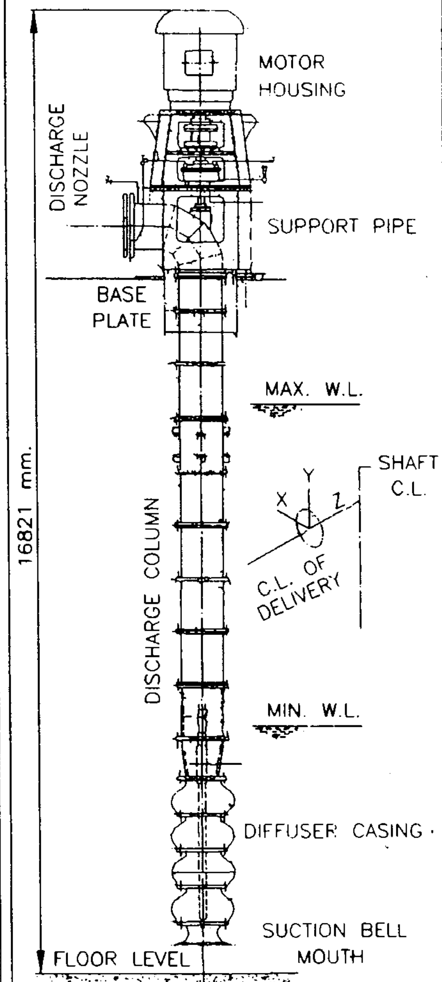
Assuming harmonic oscillations with circular frequency ω and invoking weak formulation in (1) alongwith (2) and Laplace's equation for ϕ we obtain the ADM ($\mathbf{M}_a$) as follows:

$$\text{Let } I^e = \int_{I^e}\int_{\gamma(z)} p.\mathbf{n}.\,\mathbf{e}_x\,.d\gamma.dl = \omega^2\pi\rho_f\,\mathbf{v}^{eT}\,\left(\int_{h^e} \mathbf{N}^e\,\mathbf{N}_\Gamma^{eT}\,\mathbf{n}\;r\,\sqrt{(1+(dr/dz)^2)}\;dz\right)\boldsymbol{\phi}_\Gamma^e$$

$$= \omega^2\pi\rho_f\,\mathbf{v}^T\,(\mathbf{T}^e.\mathbf{H}^e.\mathbf{P}^e)\,\boldsymbol{\phi}\,;$$

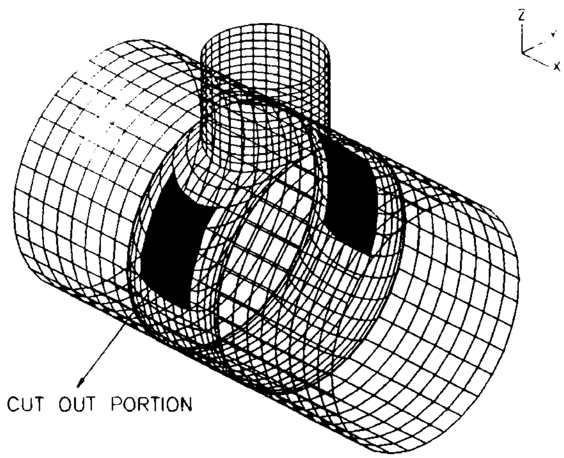
$$\sum_{e=1}^{Nel} I^e = \omega^2\pi\rho_f\,\mathbf{v}^T\,(\mathbf{H}^T.\mathbf{F}^{-1}.\mathbf{H})\,\mathbf{u} \quad \text{or} \quad \mathbf{M}_a = \pi\rho_f\,(\mathbf{H}^T.\mathbf{F}^{-1}.\mathbf{H})$$

where $\mathbf{v}$ is the nodal vector of the test function for u, $\boldsymbol{\phi}_\Gamma$ is the nodal vector for the trace of ϕ on Γ, with corresponding element shape function $\mathbf{N}^e$ and $\mathbf{N}_\Gamma^e$. $\mathbf{T}^e$ (resp. $\mathbf{P}^e$) is local to global transformation for the nodal displacement (resp. potential), $\mathbf{H}$ is the coupling matrix relating the fluid nodes on Γ to the global displacement vector and $\mathbf{F}$ is the fluid stiffness obtained from Laplace's equation.



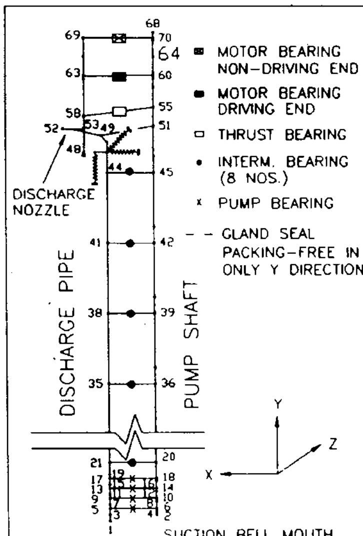
SKETCH OF PUMP ASSEMBLY

FIG. 1



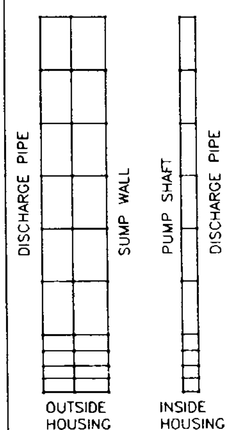
LOCAL F.E. MESH OF DISCHARGE NOZZLE

FIG. 5



F.E. MODEL OF PUMP ASSEMBLY

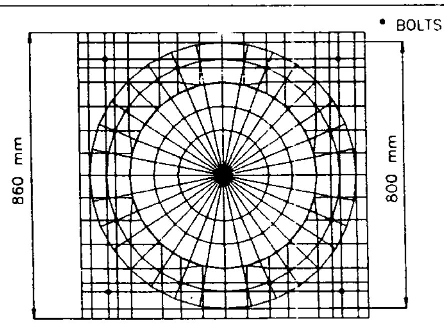
FIG. 2



F.E. MESH OF

THE FLUID

FIG. 4



F.E. MODEL OF BASE-PLATE ASSEMBLY

FIG. 3

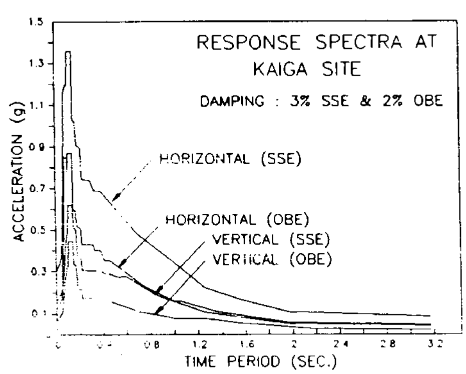


FIG. 6