Optimal foundation design of a vertical pump assembly

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Abstract

Generally, a vertical pump assembly consists of a pump, a driving motor on top and a foundation structure at the bottom to support the pump and motor assembly. They together constitute a system, which has its own dynamic characteristics. The prominent excitation to the assembly comes from the rotating speed and its related harmonics during pump operation. This calls for careful design of the pump support to keep the system natural frequencies well separated from the pump speed (as well as motor speed in case of a geared system) and its multiples for trouble-free operation. Since there is little scope for structural modification of the pump and motor unit, it is better to design the foundation structure adequately before installation of the pump to meet the desired objective. Such an attempt has been made for the design of a foundation structure using finite element (FE) analysis for a typical vertical pump to be installed in a research facility in BARC, Mumbai.

1. Introduction

Vibration-based condition monitoring for any rotating machinery is important from safety consideration and for trouble-free operation. Several codes give such guidelines for monitoring the operating condition of rotating machinery. ISO 10816 and ISO 7919 give vibration severity limit for horizontal rotating machinery. However, Hydraulic Institute Standards [1] give vibration severity limit specifically for both horizontal and vertical pumps. In many cases, it is often observed that the pumps installed at site have high vibration than the specified limits. Typically in

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vertical pump assembly it is often observed that the high vibration is due to resonance of the pump assembly at the pump RPM and/or its multiples. Few such typical cases are discussed by Rao et al. [2].

Generally, a vertical pump assembly consists of a pump, a driving motor at top and a foundation structure to support the pump and motor assembly. They together constitute a system, which has its own dynamic characteristics. Often, the support foundation is designed based on the static weight of the pump-motor unit without accounting for the dynamics of the complete assembly. In case of high vibration, the normal practice is to conduct a modal test [3] on the pump assembly at site to diagnose the root cause and take appropriate corrective measures. Such a practice is generally difficult due to many site constraints, especially when one has to modify the structural configuration of the foundation to shift the natural frequencies of the complete assembly away from the rotating speed. Since there is little scope for structural modification of the pump and motor unit, it is better to design the foundation structure adequately from dynamic consideration before installation. Such an exercise carried out to optimize the foundation structure using finite element (FE) analysis for a typical vertical pump to be installed in a research facility in BARC, Mumbai has been presented in the paper.

2. Pump-motor unit and its FE modeling

The pump-motor unit under discussion is around 2.2 m long and has a total mass of 918 kg. The motor mass alone is 68 kg and the pump with column weighs 850 kg. The motor is connected at the top of the pump and the pump column extends downward from it. It has a square seat plate at around 1.4 m from the top on which provisions are there for supporting the unit. Below the seat plate, the pump column extends downward for about 0.8 m on which discharge and suction provisions are there. Fluid enters vertically into the suction column and is discharged radially outwards into the discharge pipe. The pump operates at a speed of 4500 rpm (75 Hz). A simple schematic of the pump and motor assembly is shown in Fig. 1.

For designing a suitable foundation for such a specifically designed pump-motor unit, the FE modeling of the pump-motor unit itself is essential along with the foundation. Since the pump-motor unit is very rigid, it has been modeled as a rigid link with proper mass distribution all along its length to simulate the contribution of masses and moments by it.

3. Foundation structure

Depending on the site constraints for installation of the pumps, two types of support structures were suggested.

(1) Hangers from ceiling.
(2) Stool-type foundation.

Suitability study of both the foundation types have been carried out using FE analysis based on the dynamic characteristics of the pump assembly. The paper presents the details of the results of
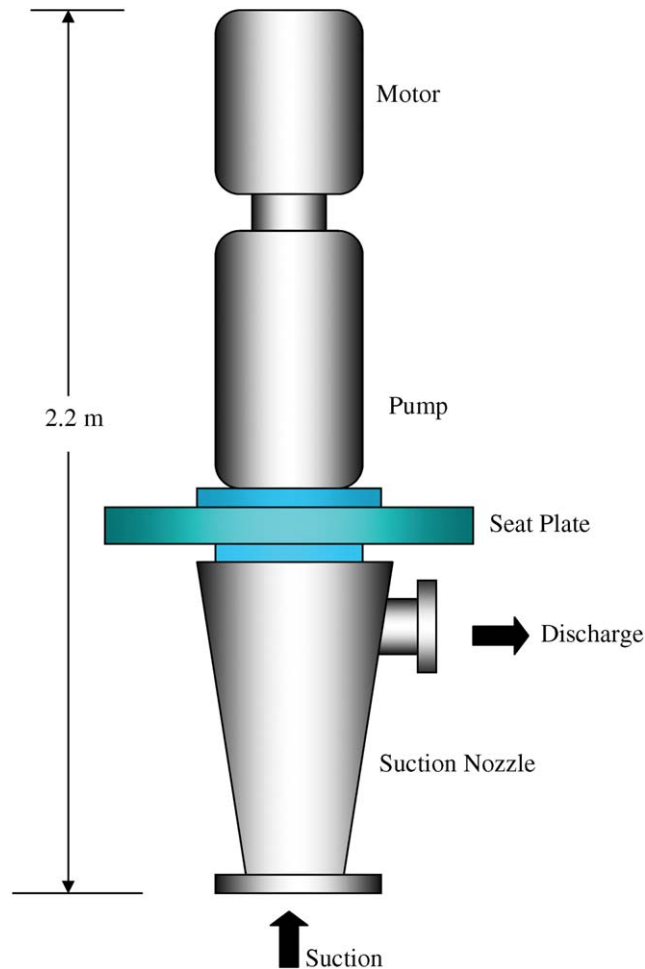
Fig. 1. Schematic of pump-motor unit.

the analysis carried out and their evolution to arrive at the final foundation structure. Considering the thrust on the conceptual aspect of the foundation design, the details of dimensions are not given here.

3.1. Hanger-type foundation

As discussed in Section 2, the pump and motor unit has been modeled as a rigid link with proper mass distribution all along its length. The seat plate provided with the pump for anchoring the assembly onto the foundation has been modeled using four noded plate elements. For the hanger type of foundation, the pumps seat plate has been attached to four springs and hung from the top. The bottom end of the suction pipe has also been supported to the bottom base plate, which is fixed to the floor. The complete modeling has been done using commercial FE code—Nastran Solver and Patran 2000 modeling tool. Fig. 2 shows the typical FE model of the
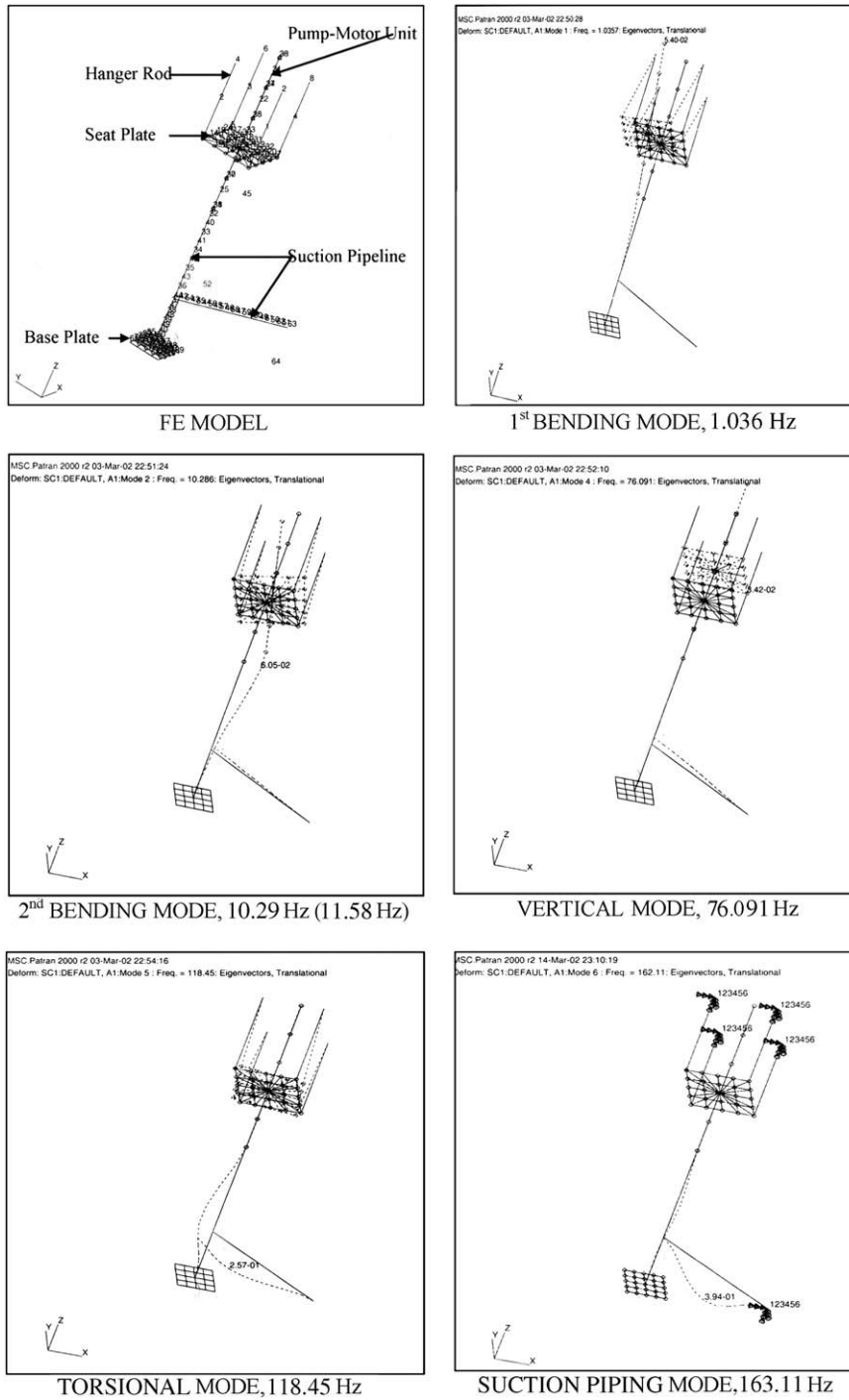
Fig. 2. FE model and its modes for pump assembly with Hanger-type foundation. (Frequency value in bracket indicates a similar mode in *y*-direction.)

hanger-type foundation assembly. Computation of eigenvalues and eigenvectors were carried out for the model. Few computed modes and their mode shapes are shown in Fig. 2. This model has three natural frequencies below the operating speed, i.e., 75 Hz and one at 76.091 Hz, which is close to the operational frequency. With such a support arrangement, the pump assembly has to pass through three critical speeds during start-up and run-down and the pump structure is likely to resonate at 76.091 Hz during normal operation. So, this foundation was not considered to be safe and suitable for the present requirement and hence not considered further. The effect of suction and discharge pipelines on the dynamics of the system was analyzed. It was found that their effects on the dynamics of the entire assembly are negligible and hence not considered in the present and subsequent models for clarity of understanding.

3.2. Stool-type foundation

The alternate option suggested to the hanger foundation was the stool-type support. As per the design suggested, the foundation consists of four I-section columns as legs of the stool and C-channel stiffener arranged as cross between legs. The top of the stool support is a C-channel square frame to accommodate the pump seat with bolted joints. The legs are welded to a base plate, which is fixed to the floor. Its feasibility as a foundation structure to the pump-motor unit was studied. The pump-motor unit has once again been modeled as a rigid link and its mass distributed evenly throughout its span to simulate the masses and moments of actual pump-motor unit. The foundation structure has been modeled using beam elements for legs and stiffeners, and plate elements for base and seat plates. A typical FE model and the computed natural frequencies and mode shapes are shown in Fig. 3. The model has six natural frequencies below 75 Hz and three close frequencies to the operating speed. The lowest modes in two lateral directions are computed to be at 21.642 and 22.313 Hz, which are the first bending mode of the structure as shown in Fig. 3. A sufficiently high value of the first mode as compared to the first mode of the hanger-type foundation indicates that the structure considered now is much more stable. However, this model also has three natural frequencies clustered around the pump rotating speed—75 Hz, which are prone to resonance. As compared to the hanger model, the present model has an advantage during the pump start-up and run-down as it will cross only one critical speed on either axes, but suffers the same drawback as hanger-type model at operating speed. Hence this foundation needed further modification.

3.3. Further modification in the stool-type foundation

As seen from Fig. 3, the deflection pattern of each leg of the foundation in the mode shapes shows no constraints in the bending rotation at the bottom which resulted in lower bending frequency. Hence all the four legs are required to be stiffened at the bottom base plate. It was decided to weld four gusset plates at the bottom of each leg in the previous foundation model. This was included in the above FE model. The modified FE model along with the computed natural frequencies and their mode shapes are shown in Fig. 4. The I-section leg used in the FE model was replaced by an equivalent-sized pipe to make the fabrication easy. The results were dramatically improved over the last model. The lowest bending modes in two lateral directions are now at 26.874 and 29.45 Hz, which are higher compared to the earlier model. However, a
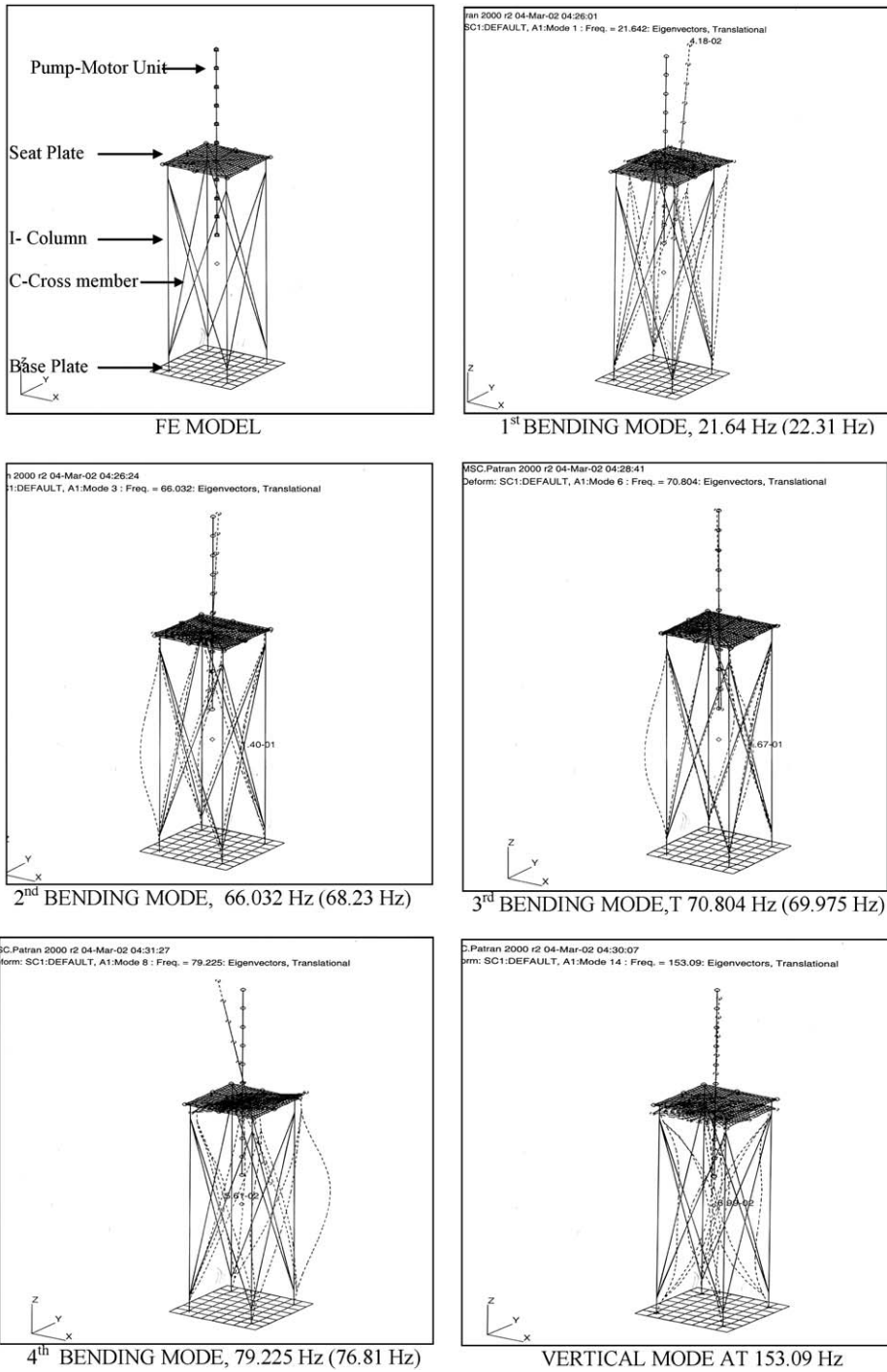
Fig. 3. FE model and its modes for pump assembly with Stool-type foundation. (Frequency value in bracket indicates a similar mode in *y*-direction.)
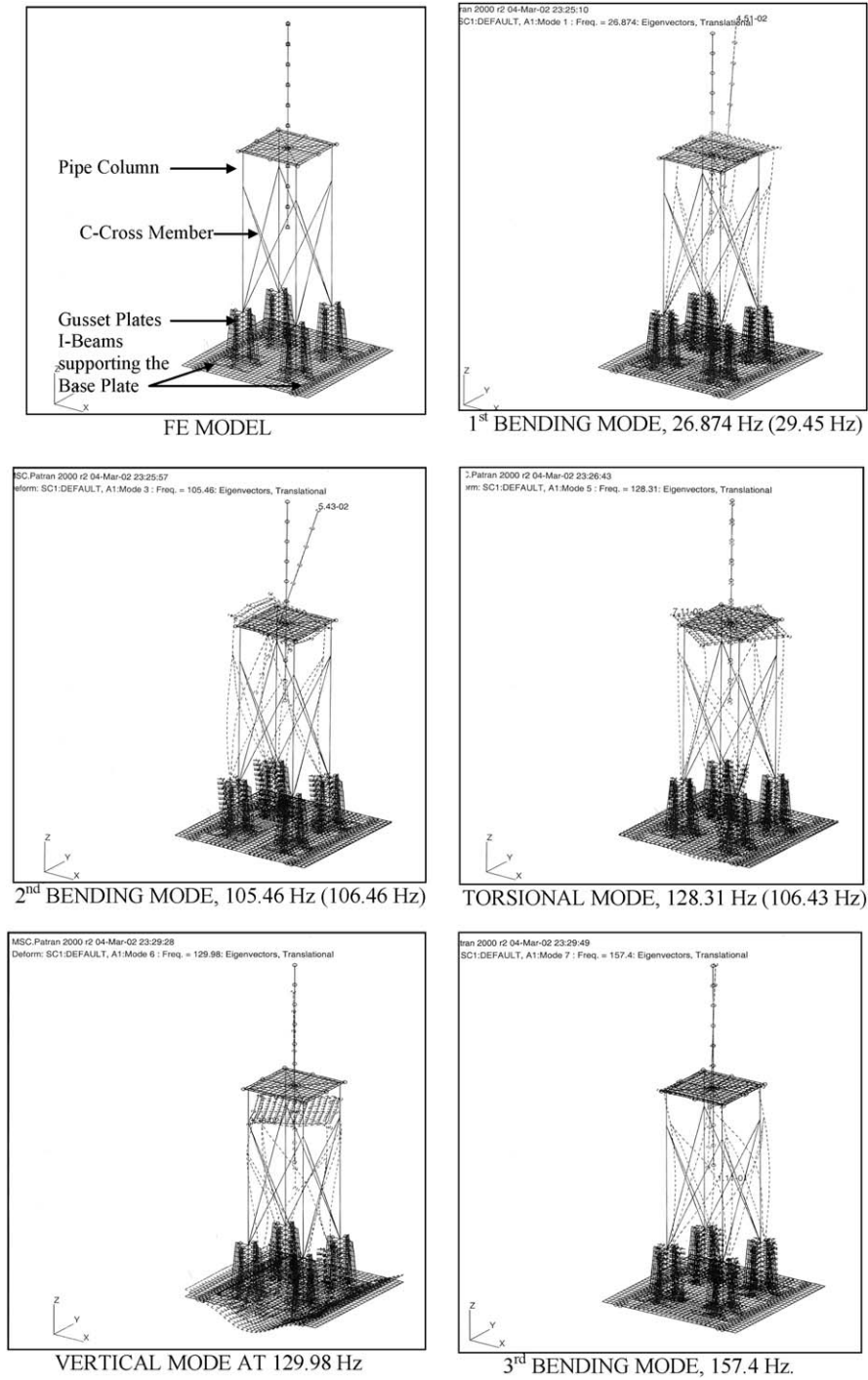
Fig. 4. FE model and its modes for pump assembly with modified Stool-type foundation. (Frequency value in bracket indicates a similar mode in *y*-direction.)
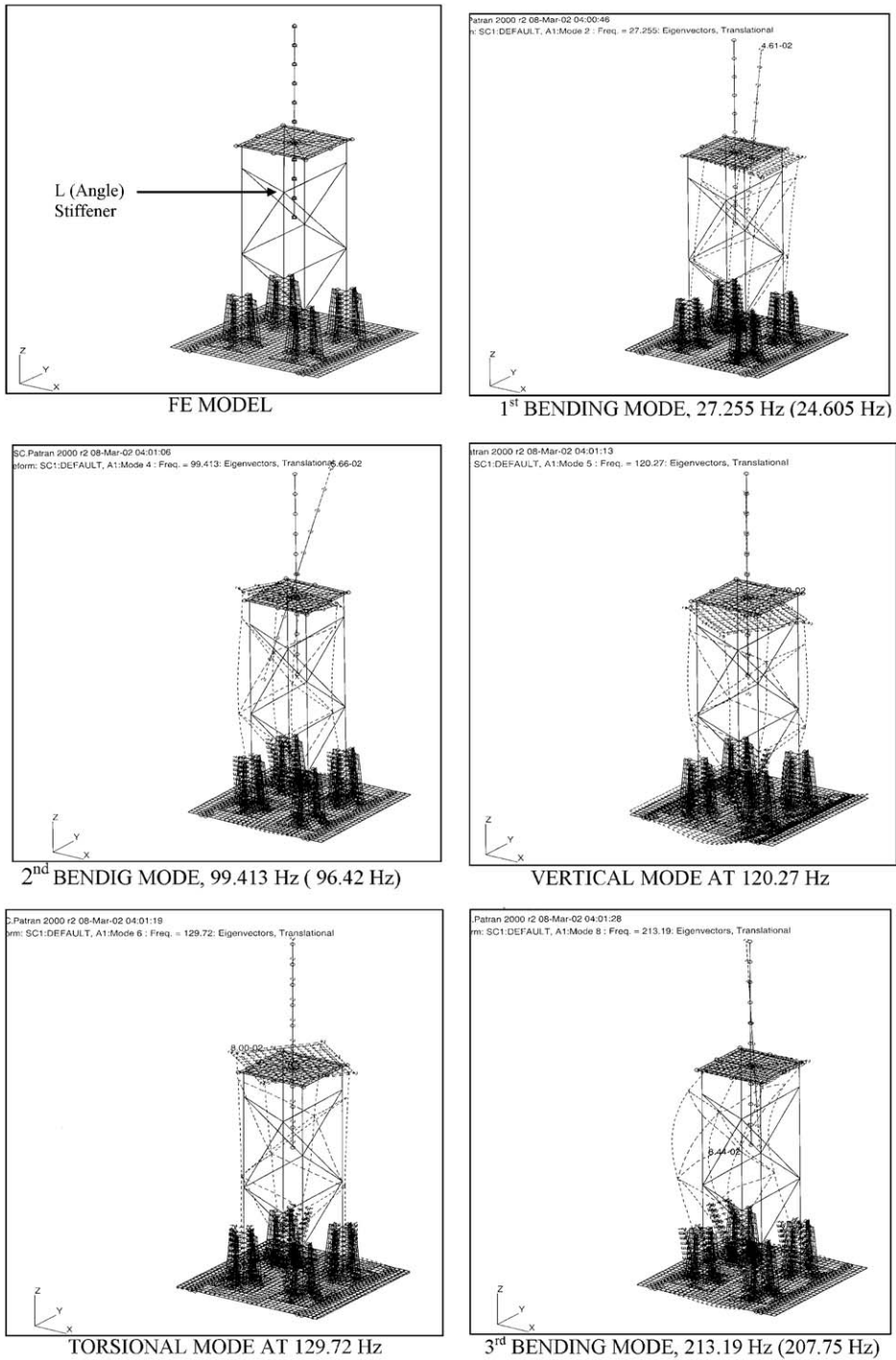
Fig. 5. FE model and its modes for pump assembly with final Stool-type foundation. (Frequency value in bracket indicates a similar mode in *y*-direction.)

significant rise in the higher frequencies was observed. The third mode was at 106.43 Hz, which is 31 Hz above the pump rotating speed—75 Hz that has a sufficiently safe margin. It was also observed that none of the higher modes are close to the multiples of the pump rpm.

3.4. Final stool-type foundation

The model discussed in Section 3.3 (Fig. 4) was fairly good in every respect. But the fabrication of C-cross stiffener in the prototype was difficult due to space constraint. Hence a zigzag stiffener pattern with L-section channel was attempted in the model. The zigzag arrangements were made such that it meets the space constraints and makes the fabrication easy. Fig. 5 shows the FE model, mode shapes and natural frequencies of this model. As can be seen from Fig. 5, there is little change in the dynamics compared to the model discussed in Section 3.3 and the design is favorable in every respect with a good margin from the operating speed and its multiple. Hence, this foundation structure model was recommended for fabrication.

4. Conclusion

An optimal design of the foundation structure for rotating machinery from dynamic consideration has been brought out through a typical example of a rotating vertical pump at design stage. The recommended foundation structure has structural frequencies, which are wide apart from the pump speed and its multiple. The model has sufficient margin in the dynamic parameters to accommodate the fabrication tolerance. An experimental modal test is also being planned on the system after installation to further strengthen the confidence in the design.

Acknowledgements

References

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[3] D.J. Ewins, *Modal Testing—Theory, Practice and Application*, second ed., Research Studies Press, UK, 2000.