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DESIGN METHODOLOGY FOR VERTICAL CENTRIFUGAL PUMPS

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ABSTRACT

The mechanical and structural design of vertical centrifugal pumps has strong dependency of the plants layout where it is intended to install them. Each situation becomes a specific design and a mutual agreement between the involved parts, i. e., equipment manufacturer, plant owner and erector, must be established. Furthermore, it has been reported in the literature a lot of problems with this type of equipment whose causes may be attributed to the lack of the integration in the design of the pumps themselves, their supportation and their building structures. Based on the assessment and discussion of typical problematic study cases, this paper presents a methodology to be followed during the design phase to avoid problems in the equipment tests and operation in the plant pre-operational activities. The development was done in general, but this methodology can and should be used in nuclear power plants.

1. INTRODUCTION

Vertical suspended centrifugal pumps have a particular configuration in each plant, that requires a specific design to attend all structural and functional requirements (see Fig. 1). Also, vertical pump and motor structures are particularly susceptible to a resonance condition created by the coincidence of the operating frequency with the natural frequencies of the pump structures. For instance, excessive resonant induced vibration occurs in a vertical pump when the natural frequency of the pump discharge head and vertical driver are the same as the speed of the pump and drive [1].

It is important to notice that vibration pre-operational shop tests are conducted in pump manufacturer test bed to vibration assessment. Unfortunately, the laboratory test rigs have interface and supporting structural conditions usually different from those found in the plant installation. So, many vibration problems that occur in the field are not identified in the design phases or in the pre-operational shop tests.

Thus, it is a common practice to the equipment manufacturers and to the plant owners to conduct vibration pre-operational tests in field to check the pump assembly under the plant installation conditions. Typically, some few readings from the bearing housings and sometimes from the shaft (displacement) both during steady and transient conditions of the pump allow to diagnose and identify the root cause of the excessive vibrations.

Identifying the source of the problem requires a troubleshooting investigation that plant and the manufacturer technical staffs can carry out to implement corrective actions.

Considering the time and costs associated to the troubleshooting investigation and to the corrective actions after pump installation, it will be very useful to avoid them by improving the mechanical and structural design procedures and assessment. Thus, this paper presents a methodology to be followed during the design phase to avoid problems in the equipment tests and operation in the plant pre-operational activities based on the so-called rational design or design by analysis to the mechanical and structural design. The development was done in general, but this methodology can and should be used in nuclear power plants.

Vertical suspended (VS) pumps mentioned in this paper are the ones classified in API 610 [2] as VS1, VS2 and VS3, even not API (American Petroleum Institute) pumps.

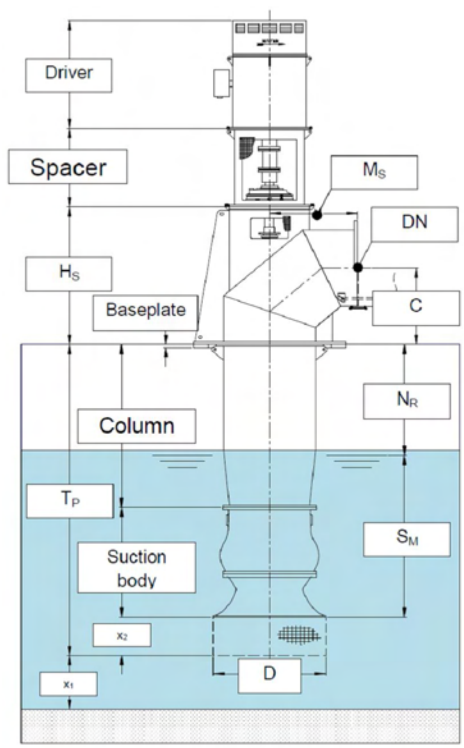

Figure 1. Vertical pump dimensions

2. DESCRIPTION OF A VERTICAL CENTRIFUGAL PUMP

A typical vertical suspended centrifugal pump, VS1 type, and its components are showed in Fig. 2. For design purpose the pump can be divided in three main parts, i. e., the suction bowl, the column and the discharge head (see Fig. 2).

The most important aspect of the development of the suction bowl design is that one related to the pump functional conditions. To define the pump characteristics, the manufacturers develop families of pumps depending on the expected process variables based on extensive analytical and hydraulic analyses. So, the mechanical and structural designs of the suction bowl and of its internals are usually manufacturers' proprietary information, not susceptible to design changes. In this way, having defined a suction bowl, a custom engineered vertical pump may have its design modified only in the column and in the discharge head to attend its vibration and structural requirements. For this reason, this paper concentrates all evaluations in these two pump parts.

Regarding to column design, important parameter is the intermediary radial bearing distance of each other. Besides pump speed and shaft diameter, it also depends on bearing bushing material and presence of solids in the fluid, such as sand. The Figure 37 of API 610 [2] shows some guidelines for this distance selection. This aspect of column design, rotor dynamic design, is related to structural design mentioned in items 3 and 4 of this paper.

In the discharge head design, it is defined the maximum allowable nozzle loads on discharge nozzle. It depends on each nozzle diameter.

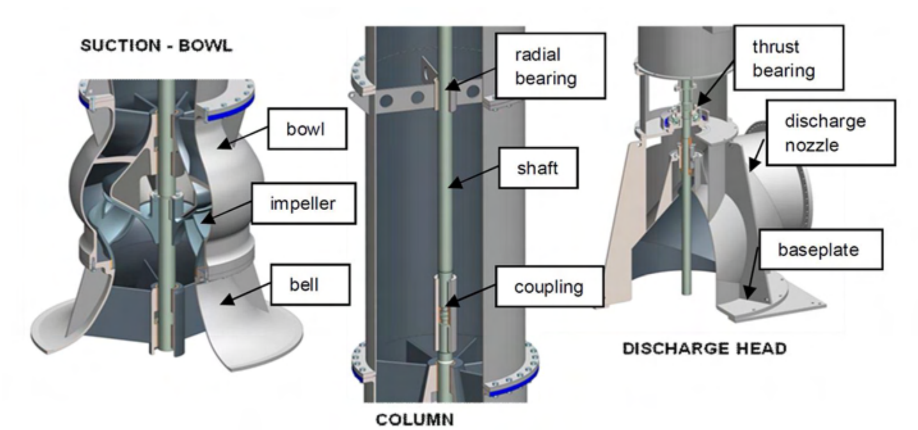

Figure 2. Vertical pumps divided in three parts

3. DESCRIPTION OF A VERTICAL CENTRIFUGAL PUMP

3.1. Performance: Shop Tests and Field Operation

Two aspects are evaluated related to the vertical pumps performance: hydraulic and mechanical. In the first one, the variables are the flow rates, the available head, the efficiency and the NPSH (Net Positive Suction Head), and in the second, the vibration levels, the noise levels, and the required power.

Any deviance on each one is a problem and requires corrective actions. The mechanical aspects are more sensitive to the final configuration of the pump in the plant [3].

As mentioned before, in this paper it is not discussed suction body. However, it is known that many hydraulic problems at field are due to poor suction layout design [4]. Regarding to this subject, there are already many guidelines for the correct suction layout design, such as HIS (Hydraulic Institute Standard) 9.8 [5].

3.2. Pump Start-up

In the start-up condition, the vertical suspended centrifugal pumps are not filled with fluid. During some seconds, there will be air in the discharge piping and intermediate bearings will operate in dry condition. The time they operate in this condition depends on each installation.

Other important factors are number of pump start-ups and the presence of abrasive solids, as sand, in fluid.

3.3. Discharge Head - Loads on the Nozzles and on the Supports

The loads from piping on the nozzles and the weight of the actuator loading the motor support cause stresses and strains in the discharge head which casing must have enough stiffness and strength to limit them to allowable limits.

This limitation is in order to avoid plastic deformations and shafts misalignments that may cause pump vibrations and upper bearing heating.

3.4. Column Vibration

The bearings arrangement and their stiffness define the rotor dynamic behavior of the shaft and the dynamic interaction with the column. Some standards, as API 610 [2], give some guidance to the design based on the pump rotation and on the shaft diameter.

The bearings types and materials also play an important role due to their relation with the damping and stiffness characteristics that have strong influence in the assembly dynamic behavior.

Besides this rotor dynamic vibration aspect, other variables such as the mass associated to the water level inside and outside the column, the pump fixture type to the building structures and their stiffness, and the mass of the internals of the column have also a strong influence in the assembly dynamic behavior.

The design must have proper consideration of all of these aspects to avoid unacceptable problems in the pump operation, in the field.

4. PROPOSED APPROACH

This paper concentrates the evaluations on the column and in the discharge head. So, the proposed approach is outlined below for both pumps parts (see Fig. 3).

4.1. Column

First, mechanical and structural analysis must be done according to general standards applicable to the pressure boundary such as ASME (American Society of Mechanical Engineers) Code Section VIII, Division 1 [6] to establish minimum thicknesses and reinforcement areas using the design by rules.

The next step is to perform static analyses using finite elements to model the column and its internals under all applicable loads and load combinations. The stress analyses is carried out using design by analysis as stated in standards like ASME Code Section VIII, Division 2 [7].

After these two steps, dynamic modal analyses with finite elements must be done to check if the column natural frequencies are not in resonance with the frequencies associated to the equipment rotation. Typically, a separation margin of 20% is desired.

The model for the dynamic analyses must be built with enough detail to capture the relevant mass, damping and stiffness characteristics of the column, its internals, the shaft, the bearings and the internal and external fluid.

The acceptance criteria for all assessments must be defined to assure the operational and structural integrity of the pump. It is important to mention that the vibration tests in laboratory and in the field have to be performed to qualify the equipment and the assembly to the operation.

4.2. Discharge Head

For the discharge head sizing, static analysis similar to those conducted for the column are performed. Again, mechanical and structural analyses must be done according to general standards applicable to the pressure boundary such as ASME Code Section VIII, Division 1 [6] to establish minimum thicknesses and reinforcement areas using the design by rules. After, the discharge head is modeled with finite elements and simulated with static analyses considering all applicable loads and load combinations described earlier. The stress analyses is carried out using design by analysis as stated in standards like ASME Code Section VIII, Division 2 [7].

4.3. General

Regarding to modal analysis, done for the entire pump, not only for each part, it is very important the consideration of pump installation interface, baseplate with ground and discharge nozzle with user pipeline. As a rule of thumb, in case stiffness of these interfaces is very high, it can be assumed that there is no moving between these parts. For boundary conditions they may be defined as bonded connections.

However, in case where the separation margin is not achieved, before any modeling modification or pump design change, this interface stiffness must be investigated to obtain the actual stiffness of the ground and the actual stiffness in the interface between pump discharge nozzle and pipeline installation.

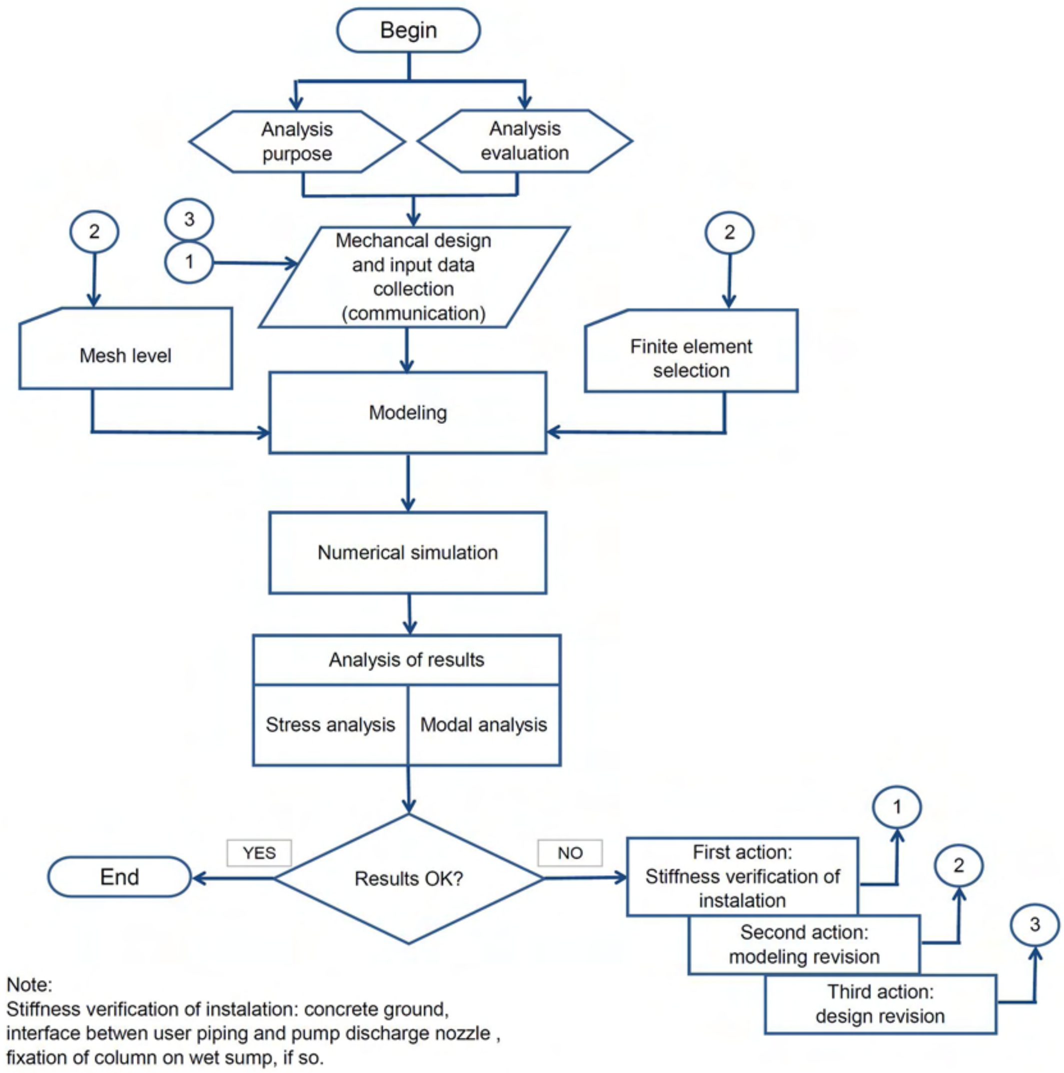

Figure 3. Methodology of vertical pump structural design

5. STUDY CASES

5.1. Três Lagoas Vertical Pump – River Water

Four vertical pumps with VFD (Variable Frequency Driver), VS1 type, were installed in Três Lagoas-MS (Brazil). The general dimensions are the nominal pipe diameter 508 mm, the height of vertical column 14500 mm, the height of motor stool 1985 mm, the height of vertical motor 2500 mm and the total pump height 18895 mm. The performance data are the rated flow 0.616 m^3/s, rated head 49 m and rated speed 1186 rpm. The pumped fluid is water.

To run a modal analysis a finite element model was built using shell elements for the external casing and beam and discrete elements for the shaft and internals. The simulations were carried out using a finite element with added mass and with shaft, sleeves and intermediate rubber bearings. The software ANSYS [8] was used in the numerical simulations.

From Loeser et. al [9], the comparison of the finite element modal analysis frequencies with those related to the operational conditions is showed in the Campbell diagram of Fig. 4.

Figure 4 indicates that the pump is not allowed to run with speed lower than 1022 rpm (86% of rated speed). This information should be informed to customer in order to avoid any misunderstanding. Usually, pumps are installed with VFD in order to run the pump with lower speed than rated, if necessary.

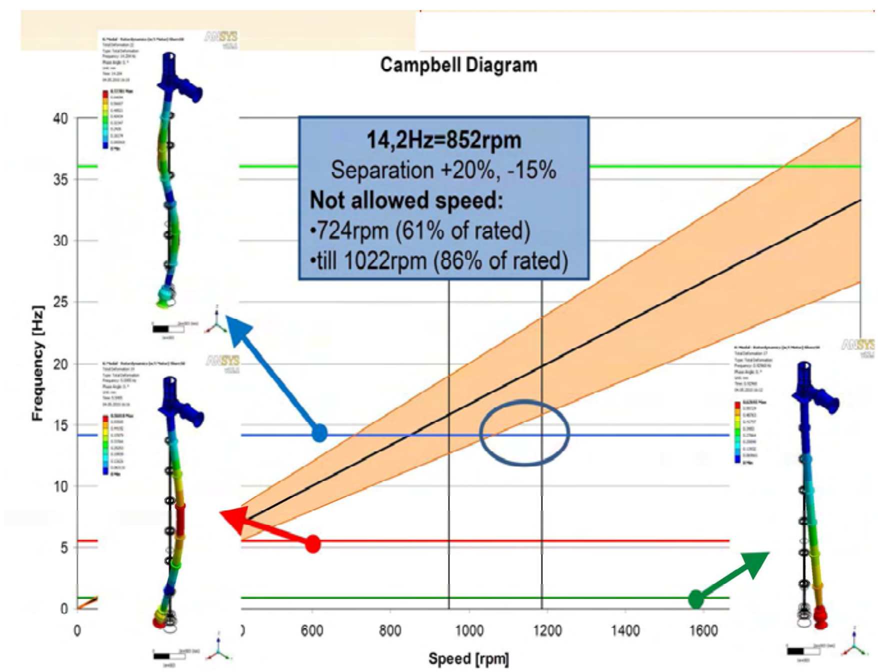

Figure 4. Três Lagoas vertical pump – Campbell Diagram

5.2. SABESP Pump – Sewage Installation

During SABESP (Companhia de Saneamento Básico do Estado de São Paulo) vertical pump design, to be installed in Rio Pinheiros, São Paulo city, it was detected that discharge head should be modified in order to have enough separation margin between excitation vibration of nominal speed and discharge head natural frequency. Pump speed is 8.5 Hz, capacity 3.2 m^3/s and rated head 23 m, power consuming of 831 kW. As result of modal analysis, see Fig. 5, no vibration problem to be expected in the column, but yes on the discharge head, because its natural frequency was 8.8 Hz.

By doing another modal analysis, with reinforcements welded in the discharge head, see Fig. 6, natural frequency was increased from 8.8Hz till 11.2Hz. Pumps are running well at plant.

5.3. São Francisco River Project Pump – Transposition Water System

For the São Francisco River Project big vertical pumps were manufactured. The general dimensions are the nominal diameter 2000 mm, the height of column 12670 mm, the height of motor stool 4950 mm, the height of motor 4200 mm, and the total height 21800 mm. The performance data are the rated flow 12.4 m^3/s, the rated head 36.1 m, the rated speed 300 rpm, and the pumped fluid is water.

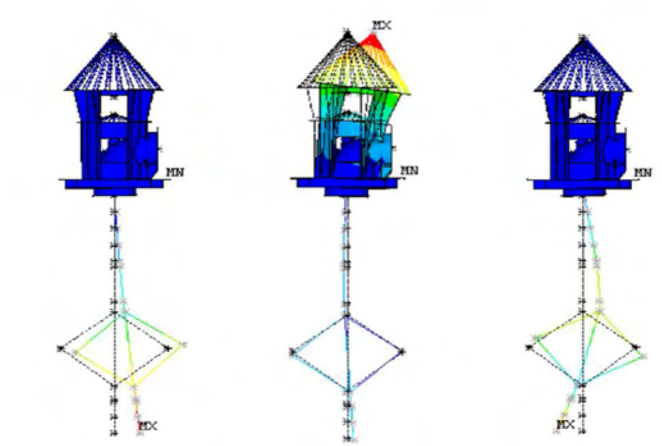

Figure 5. SABESP vertical pump – Modal analysis

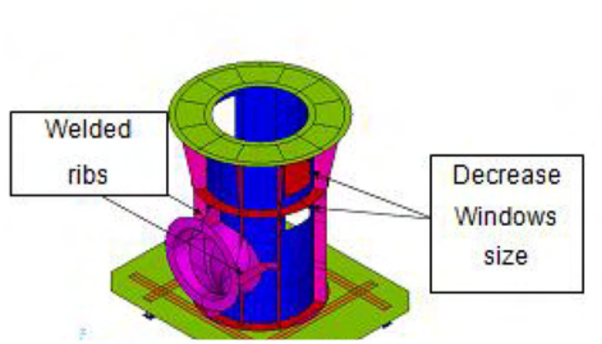

Figure 6. SABESP vertical pump – Discharge head modifications

A static finite element model of the pump casing was built using shell elements. The delivery bend was modeled also with shell elements and the motor was modeled was a discrete mass point (see Fig. 7). The software ANSYS [8] was used in the numerical simulations.

The applied loads were the internal pressure, applied on "wet surface", the pressure on "cover faces" applied as equivalent axial force, the motor torque, the nozzle loads, the rotor weight at axial bearing, and restraints at bolt locations and pipe.

The resultant von Mises equivalent stresses are showed in Fig. 7 and were below the allowable limits defined in ASME Code Section VIII, Division 2 [7]. It is important to notice the need for the detailed modeling to assess the stresses near the delivery bend.

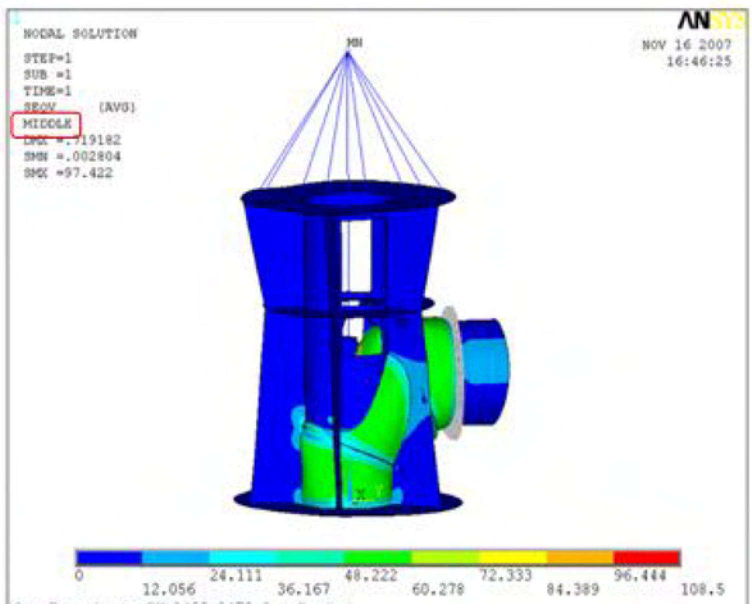

Figure 7. São Francisco vertical pump – Stress analysis (stresses in MPa)

6. CONCLUSIONS

The evaluations conducted in the three study cases indicate that it mandatory develop, in the design phase, detailed finite element models in order capture the main mass, damping and stiffness pump assembly characteristics to assess reliable results.

The design sequence must include the design by rules for pump sizing, the finite element static analyses for stress assessment and the finite element dynamic modal analyses for pre-operational vibration check.

The main difficult is to have all the information from the equipment manufacturer and plant owner with enough detail and in time to build the detailed finite element models. The communication and integration between the staffs from both sides must be established as soon as possible to provide the technical exchange and adequate design before the equipment manufacturing and shop tests and before the plant erection and field pre-operational tests.

The development was done in general, but this methodology can and should be used in nuclear power plants considering their particular issues like the seismic requirements for safety related equipment.

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