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EXAMPLE OF VIBRATION ANALYSIS AND MEASUREMENTS CONDUCTED ON CENTRIFUGAL PUMPS IN ACCORDANCE TO API 610 STANDARD

PRIMJER ANALIZE VIBRACIJA I MJERENJA VRŠENIH NA CENTRIFUGALNIM PUMPAMA PREMA STANDARDU API 610

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ABSTRACT
This paper will serve as a basic overview of lateral vibration analysis done in the program Ansys. Firstly, the Eigen frequencies of the pump for three separate cases of component stiffness obtained were obtained. Since there were several modes that fall within the operating speed and the structures Eigen frequency, a dynamic response analysis was carried out. The results obtained from the dynamic response analysis were used as a check to see if the pump vibration levels are within the limits defined by the API 610 standard to ensure the required quality of the entire pump design. The paper will also demonstrate the implementation of the API 610 requirements for the positioning of the centrifugal pump vibration measurement sensors. The readings from the vibration measurement sensors placed at the defined locations were obtained during the pump testing and compared to the API 610 requirements.

Key words: API 610, centrifugal pumps, vibration measurement, lateral vibration analysis, Eigen frequencies, comparison of results...

REZIME
Ovaj rad će poslužiti kao osnovni pregled analize lateralnih vibracija u programu Ansys. Prvo, dobijene su sopstvene frekvencije pumpe za tri odvojena slučaja krutosti komponenti. Budući da je bilo nekoliko modova koji su se nalazili u okviru radne brzine i sopstvene frekvencije konstrukcije, izvršena je analiza dinamičkog odziva. Rezultati dobijeni analizom dinamičkog odziva korišteni su kao provjera da li je nivo vibracija pumpe unutar granica definisanih standardom API 610 kako bi se osigurao potreban kvalitet cjelokupnog dizajna pumpe. U radu će se također prikazati primjena zahtjeva API 610 za pozicioniranje senzora za mjerenje vibracija centrifugalne pumpe. Očitanja senzora za mjerenje vibracija postavljenih na definisanim mjestima dobijena su tokom testiranja pumpe te su poređena sa zahtjevima standarda API 610

Key words: *API 610, centrifugalna pumpa, mjerenje vibracija, analiza lateralnih vibracija, sopstvene frekvencije, poređenje rezultata*

1. INTRODUCTION
Centrifugal pump vibration varies with flow, usually being a minimum in the vicinity of best efficiency point flowrate and increasing as flow is increased or decreased. The change in vibration as flow is varied from best efficiency point flowrate depends upon the pump's energy density, its specific speed and its suction-specific speed. Often, small insignificant vibrations

can excite the resonant frequencies of some other structural parts and be amplified into major vibration and noise sources. A fundamental requirement in all vibration work, whether it is in the design of machines which utilize its energies or in the creation and maintenance of smoothly running mechanical products, is the ability to obtain an accurate description of the vibration by measurement and analysis.

2. ANALYSIS

2.1. Analysis method

The results in this report have been calculated by using the Finite Element Method. The FEM software is Ansys workbench 17.0. For a free vibration analysis, the natural circular frequencies ω_i and mode shapes ϕ_i are calculated from:

$$([K] - \omega_i^2[M])\{\phi_i\} = 0$$

The following assumptions are made:

1. [K] and [M] are constant
    - Linear elastic material behavior is assumed
    - Small deflection theory is used, and no nonlinearities included
    - If damping is present [C] will be included
    - If excitation is present {F} will be included
    - The structure can be constrained or unconstrained
2. Mode shapes {ϕ} are relative values, not absolute

2.2. Eigen frequencies

There will be three scenarios depending on deck and spider bearing stiffness and type of connection:

- Case1: Use the assumed stiffness for both spider bearing and deck.
- Case2: Use the assumed stiffness for the spider bearing and rigid deck with infinity stiffness.
- Case3: Use rigid connection for spider bearing and rigid deck.

Eigen frequencies obtained by FEM for these three cases are listed for 50 modes but the modes of interest for these three cases will bre presented in Table 1.

API Section 9.3.5 ref. [1] states that a separation margin of 20% should be maintained between the operating speed and the structures Eigen frequencies. With an operating speed of 1790 rpm or 29.833 Hz, there shouldn't preferably be any Eigen frequencies between 23.866 to 35.8 Hz. In case 1, mode 36-43 (mode 44 is torsional mode) fall within this range, in case 2 mode 33-45 and in case 3 mode 21-27 fall within this range, a dynamic study is required to see how this will influence the vibration levels of the structure. The following picture shows some of the modes that are of interest for case 1.

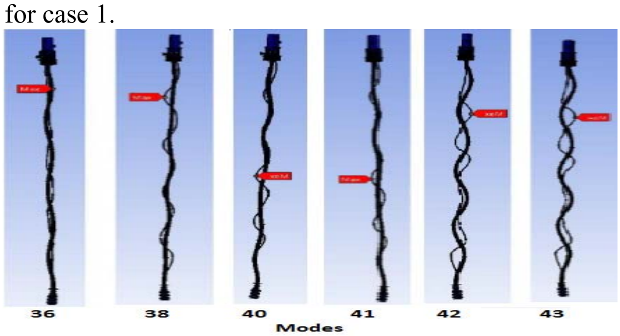

Figure 1. Visual representation of modes of interest for Case 1

Table 1. Eigen frequencies of interest for all three cases

Mode	Frequency			Mode	Frequency		
	Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
20	9.069	12.305	23.076	36	25.079	26.564	65.443
21	10.881	12.345	27.626	37	25.262	27.691	65.870
22	10.975	14.850	28.650	38	26.279	29.389	66.659
23	12.330	15.034	28.722	39	26.579	29.894	70.268
24	12.371	15.975	29.467	40	29.887	30.313	71.526
25	14.852	16.012	34.851	41	30.306	31.172	71.946
26	15.035	18.742	34.887	42	31.166	31.219	74.615
27	15.990	19.036	34.959	43	31.204	33.128	75.071
33	20.511	25.078	54.823	44	33.271	33.774	75.239
34	22.500	25.257	59.087	45	33.771	34.091	76.921
35	22.904	26.252	59.227				

2.3. Vibrations close to operating speed

For the dynamic response analysis close to operating speed the following forces where applied to the model:

1. The spider bearings are excited by the maximum shaft unbalance according to ISO grade 2,5 [2].
2. The pump bearings are excited by the maximum impeller unbalance according to ISO grade 6,3 [2]. This force was applied on all impellers.
3. Electric motor rotor i excited by the maximum rotor unbalance according to ISO grade 2,5 [2].

The unbalance loads were applied in phase and out of phase with the closest Eigen frequency, in order to calculate the maximum vibration (worst case). Therefore, four cases will be studied:

A. Unbalance load in electric motor rotor out of phase with both the pump impeller and riser shaft.
B. All unbalance loads are in phase.
C. Unbalance load in pump impeller out of phase with both the El-motor rotor and riser shaft.
D. Neglect the unbalance load in the El-motor and assume only unbalance loads in phase in the both pump impeller and the riser shaft.

2.4. Unbalance response analysis

A harmonic analysis requires a value for damping. In this case, global damping was applied with a relative damping of 2%. For a bolted structure, a value of 5% is common. The pump unit and part of the riser shaft shall be submerged in the crude oil, where the crude oil will acts as damping, but for the worst-case scenario, the damping effect of crude oil and bolted structure will be neglected, and the assumed damping ratio is 2%.

Section 2.2. of this paper shows that some frequencies are present in this range. Therefore, an unbalance response analysis was needed to determine the resulting vibration levels. Figure 2 shows the location of the measured vibration levels (sensors are simulated virtually).

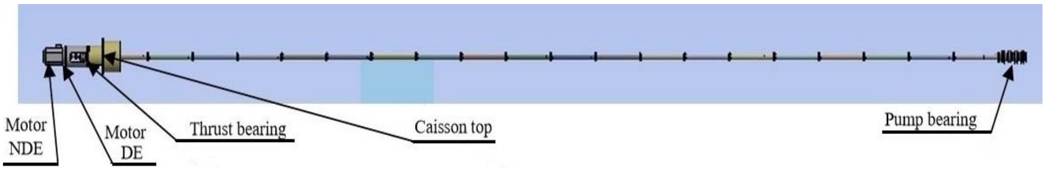

Figure 2. Measured vibration levels location

3. RESULTS

3.1. Harmonic analysis results

The vibration levels close to operating speed fall well within the requirements defined by the API 610 standard. The maximum speed of 4.4 mm/s (0-peak) in motor NDE is below the maximum of 5 mm/s (RMS). The result from all cases are shown in Table 2.

Table 2. Analysis results obtained from measured locations

Location	Vibration, velocity Vx RMS (mm/s): Case	Vibration, velocity Vx RMS (mm/s): Case	Vibration, velocity Vx RMS (mm/s): Case 3
	Results for case A		
Motor NDE	0.420	4.400	4.100
MOTOR DE	0.230	2.200	2.210
Thrust Bearing	0.140	0.350	0.380
Caisson top	0.080	0.140	0.160
Pump bearing	1.030	1.060	0.670
	Results for case B		
Motor NDE	0.480	4.000	3.700
MOTOR DE	0.280	2.120	1.980
Thrust Bearing	0.140	0.380	0.330
Caisson top	0.090	0.161	0.159
Pump bearing	1.020	1.150	0.370
	Results for case C		
Motor NDE	0.480	3.900	4.100
MOTOR DE	0.250	2.160	2.100
Thrust Bearing	0.150	0.380	0.330
Caisson top	0.094	0.155	0.165
Pump bearing	1.130	1.200	0.127
	Results for case D		
Motor NDE	0.042	0.300	0.077
MOTOR DE	0.028	0.127	0.037
Thrust Bearing	0.031	0.042	0.010
Caisson top	0.019	0.013	0.007
Pump bearing	1.100	1.093	0.544

3.2. Overall/Discrete measured frequencies at different motor operating speeds

The measured pump vibration levels (for overall/discrete frequencies) at different motor run speeds are within the requirements defined by the API 610 standard. The maximum vibration of 2,4/0,5 mm/s for motor run at 75% speed (45Hz) is well below the maximum of 5 mm/s (RMS). The result from all three tests are shown in Table 3.

Table 3. Measured overall/discrete frequencies

	Rated flow	Preferred Operating Region	Allowable Operating Region
Pump Vibration: Overall / Discrete Frequency	Test 1: Motor run at 105% speed (63Hz)		
	2 / 0,8 [mm/s]	2,3 / 0,9 [mm/s]	2,3 / 0,9 [mm/s]
	Test 1: Motor run at 90% speed (54Hz)		
	1,5 / 0,5 [mm/s]	2,3 / 0,5 [mm/s]	2,4 / 0,5 [mm/s]
	Test 1: Motor run at 75% speed (45Hz)		
	2,4 / 0,4 [mm/s]	2,4 / 0,5 [mm/s]	2,4 / 0,5 [mm/s]
	Test 1: Motor run at 50% speed (30Hz)		
	2,3 / 0,5 [mm/s]	2,3 / 0,6 [mm/s]	2,3 / 0,6 [mm/s]

3.3. Readings from vibration sensors mounted at locations defined by API 610

Defining X, Y and Z directions:

- X: direction of discharge
- Y: transverse to discharge direction
- Z: axial direction

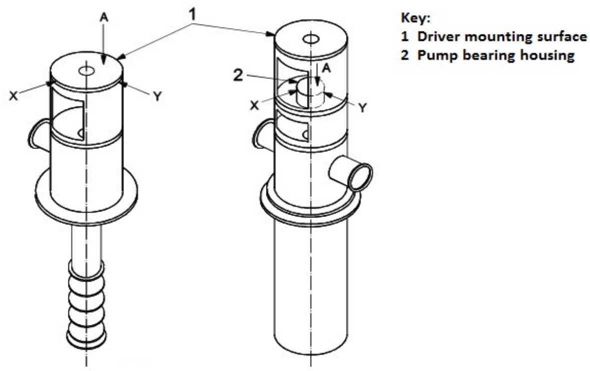

Figure 3. Vibration sensor location recomendations by API 610

Figure 4. Vibration sensors mounted on locations according to API 610:
a) Bearing housing , b) Driven mounting surface

Table 4. RMS value of overall measured vibration levels

Location	Flow $\left[\frac{m^3}{h}\right]$ / Motor RPM				
	1002 / 1793	840/1793	762/1793	735/1794	255/1796
Bearing housing					
X	1,12 mm/s	1,14 mm/s	1,09 mm/s	1,10 mm/s	1,15 mm/s
Y	1,39 mm/s	1,65 mm/s	1,42 mm/s	1,57 mm/s	1,62 mm/s
Z	1,44 mm/s	1,94 mm/s	1,42 mm/s	1,63 mm/s	2,26 mm/s
Driven mounting surface					
X	1,83 mm/s	1,81 mm/s	1,77 mm/s	1,82 mm/s	1,87 mm/s
Y	2,73 mm/s	2,50 mm/s	1,90 mm/s	1,91 mm/s	1,99 mm/s
Z	1,54 mm/s	1,46 mm/s	1,45 mm/s	1,42 mm/s	1,87 mm/s

4. CONCLUSION

This report describes the lateral frequency analysis of a centrifugal pump to in order to prove that the pumps meets the API 610 vibration and frequency specifications.

- Damping ratio for bolted structure is common 5% but 2% were used(worst case) while the damping effect of crude oil was excluded.
- An unbalance response analysis shows no vibration levels exceeding the limits specified by API 610.
- The readings from the vibration sensors placed on the defined locations do not exceed the limits specified by API 610

From the above mentioned facts, it can be concluded that the design of the pump meets the vibration level requirements defined by API 610 and that the analysis that was carried can serve as a reliable tool for checking of the pump design in regards to vibrations.

5. REFERENCE

[1] API 610 - Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries
[2] ISO 1940/1, Balance quality requirements of rigid rotors.
[3] J. D. Smith : Vibration Measurement and Analysis, 1989
[4] S. Graham Kelly : Advanced Vibration Analysis, 2006.
[5] S.S. Rao : Mechanical Vibrations 5th edition, 2011.