Analysis of oil pump vibration in long distance oil transportation system

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Abstract. The dynamic forces of mechanical and hydraulics may cause vibrations and noises of centrifugal pumps. To prevent the pumps from the vibrations and noises, we investigate the relationship between the oil properties/flowrate and vibration levels. The time-domain analysis and spectral characteristic analysis are used to analyze pump vibration data, it is found that the vibration level is more sensitive for the lightweight oil, the vibration becomes more severe when a specific adjacent pumps run together. Several modification suggestions are provided to the pumping station for preventing pump failure.

1. Introduction

There are many oil pumping stations in China with different types and installation. The reliabilities of these stations are important to assure energy supply for industries and public transportation for people daily usages. Vibration is a common problem caused by mechanical and hydraulic forces which are generated by the dynamic loads and stresses. High-speed pumping unit and transporting lightweight oil i.e. gasoline may result in increasing of the vibration excitation and leading to severe vibration problems [1]. It is necessary to conduct vibration analysis of pumps to prevent pump failure early [2-3]. The sources of vibration in centrifugal pumps can be categorized into three types: mechanical sources, hydraulic sources and peripheral causes [4-5]. In this study, we will only investigate the effect of hydraulics on the pump vibration level since another two sources can be eliminated because maintenance service has been done recently.

The long-distance oil transportation station in this paper has four 250GKN210 centrifugal pumps (labelled as P4, P5, P6 and P7), three of which are single-suction, two-stage, horizontal split-open type and one is single-suction, one-stage, horizontal split-open type. They are designed to transport petroleum oil products such as refined oil and crude oil at a temperature of less than 80 °C. The pump information is listed in Table 1.

| Pump | Power (Kw) | Stage | Flowrate (m³/h) | Speed (rmp) | Inlet/Outlet diameter (mm) | Head (m) | Maximum pump pressure (MPa) |
|------|------------|-------|-----------------|-------------|---------------------------|---------|-----------------------------|
| P4   | 355        | 1     | 450             | 2980        | 250/200                   | 210     | 10                          |
| P5   | 710        | 2     | 450             | 2980        | 250/200                   | 420     | 10                          |
| P6   | 710        | 2     | 450             | 2980        | 250/200                   | 420     | 10                          |
| P7   | 710        | 2     | 450             | 2980        | 250/200                   | 420     | 10                          |
The pipe connections of the four pumps are shown in Fig. 1. The direction of the arrow in the figure is the medium transporting direction.

![Figure 1. Parallel pump connections.](image)

According to the on-site monitoring reports, when P7 is used alone to transport gasoline, the vibration becomes greater than the transportation of diesel. For long-distance oil transportation, two-pumps (e.g. P5 and P6 or P6 and P7) should be used to provide enough power. Regardless of transporting diesel or gasoline, the vibrations of two pumps exceed the safe vibration level. In addition, the vibration at the non-driving end is greater than the driving end. Since the pump set has undergone preventive maintenance and foundation adjustment, the mechanical problem of the pump's rotor and foundation deviation can be eliminated from the vibration cause roots. In the following section, several trials have been conducted to quantify the effect of oil properties/flowrates on the vibration levels.

2. Vibration experimental tests
All measurements were conducted based on Chinese national standards: GB / T6075.3-2001 "Measurement and evaluation of mechanical vibration of machines on non-rotating parts". Two measurement locations were set near the bearing seat at the pump outlet end (shown in Fig. 2). Three dimension deviations were measured at each measurement location. 8 pump running conditions were used to investigate the vibration levels, they were: (1) normal diesel delivered by P7 (~410m³/h); (2) normal gasoline delivered P7 (~410m³/h); (3) reduced diesel flow rate by pump P7 (the diesel mass delivered is approximately equal to the gasoline mass when the gasoline is transported at the normal gasoline flow rate (~410m³/h)); (4) increased gasoline flow rate by pump P7 (the gasoline mass delivered is approximately equal to the diesel mass when the diesel is transported at the normal diesel flow rate (~410m³/h)); (5) Normal diesel delivered by P4 and P7; (6) Normal diesel delivered by P5 and P6; (7) normal diesel delivered P5 and P7; (8) normal diesel delivered by P6 and P7.
3. Data collection and basic analysis

According to operating records, the output of this pumping station was 400-450 m³/h. To ensure the accuracy of the test data, each test was performed after the pump reached a stable situation.

(1) For the first test, the gasoline flow rate was set up as 410 m³/h by a single pump P7 on March 27, 2019. The maximum vibration value of the non-driving end (Z direction) of P7 was 5.91 mm/s (the maximum vibration level limit is 4.5 mm/s from the pump manual). Its vibration value belongs to range C according to GB/T6075.3-2001 standard. It was in warning range, vibration analysis should be conducted to find a solution to reduce the vibration level back to range B or A. After calculation, if the same mass of diesel was transported, the flow rate of diesel should be 365 m³/h. On March 31, 2019, the pump P7 was used to deliver diesel. The target flow rate was about 400 m³/h. The diesel flow rate was reduced for our test. When the pump outlet flows were 400 and 365 m³/h, corresponding vibration values were measured. The vibration maximum values were listed in Table 2.

| Oils                | Vibration (mm/s) | Gasoline (410 m³/h) | Diesel (400m³/h) | Diesel (365m³/h) |
|---------------------|------------------|----------------------|------------------|------------------|
|                     | Z direction      | 5.91                 | 3.09             | 3.29             |
|                     | Y direction      | 1.37                 | 1.85             | 1.87             |

The maximum vibration value in the vertical direction for gasoline transportation was much higher than diesel transportation cases. For diesel transportation cases, the vibration values were almost unchanged for different flow rates.

(2) For the second test, the diesel was transported by the single pump P7, its flow rate was set up as 400 m³/h first on March 31, 2019. The maximum vibration value of the non-driving end (Z direction) of the pump P7 on that day is 3.09 mm / s, which belongs to range B. If the same mass of gasoline corresponding to diesel flow rate 400 m³/h was delivered, the flow rate of gasoline should be 460 m³/h. On May 8, 2019, the pump P7 was used to transport gasoline, the planned flowrate was 410 m³/h. The gasoline flow rate was then increased to 460 m³/h. All maximum vibration values for different flowrate and oils were listed in Table 3.
Table 3. Vibration maximum values from the second test.

| Oils                        | Diesel (400 m³/h) | Gasoline (410 m³/h) | Gasoline (460 m³/h) |
|-----------------------------|-------------------|---------------------|---------------------|
| Z direction                 | 3.09              | 5.87                | 5.90                |
| Y direction                 | 1.85              | 1.43                | 2.09                |

It could be seen that the vibration values of gasoline transportation were much higher than the diesel transportation case. And when the gasoline flow rate was increased from 410 m³/h to 460 m³/h, the corresponding vibration values were slightly increased. We may conclude that the transportation medium had more impact on the vibration levels comparing to flow rates.

(3) Several tests for two-pump pairs were conducted on May 22, 209. The vibration values were measured after the flowrate reached stable situations. The maximum vibration values were listed in Table 4.

Table 4. Vibration maximum values from the third test.

| Pumps          | P4 and P7 | P5 and P7 | P6 and P7 | P5 and P6 |
|----------------|-----------|-----------|-----------|-----------|
| Vibration (mm/s) | 3.18      | 3.40      | 3.56      | 5.50      |
| Z direction     | 1.51      | 1.44      | 1.66      | 1.60      |
| Y direction     |           |           |           |           |

From Table 4, we could observe that the vibration values belong to range B (accepted) for most two pump combinations except P5 and P6 combination whose vibration level belongs to range C (warning). Further vibration analysis using spectra information would be discussed in the following section.

4. Vibration analysis
A spectrum is a useful tool for equipment failure analysis relating to vibrations [3]. Figures 3 and 4 showed vibration data and spectra information for gasoline and diesel transportation respectively.

Figure 3. Vibration analysis for delivering gasoline.
In Figs. 3 and 4, when transporting both media: gasoline and diesel, the largest and second-largest vibration levels occurred at frequencies 296.87 and 300.03 Hz, the vibration levels were small for rest frequencies. This phenomenon could eliminate potential problems such as imbalance, misalignment, friction, and looseness of the shafting.

The speed of the pump was 2980r / min, so the rotation frequency was 49.7Hz; while the number of pump blades was 6, its passing frequency was equal to 49.7×6=298.2Hz. From Figs. 3 and 4, it can be seen that no matter whether gasoline or diesel is transported, there is the highest amplitude at frequency 296.87 Hz, which is very close to the blade passing frequency. According to the common vibration cause theory of rotating machinery, when the maximum vibration level appeared at the passing frequency, it could be confirmed that the vibration was mainly caused by the blade rotation [4-5]. The most common reason for the vibration failure of the vane passing frequency of the pump was dynamic stiffness of the connection between the equipment and the pipeline, and it was amplified under the action of pressure pulsation, and even resonance occurred. In addition, the deterioration of the operating environment of the pump would also stimulate the vibration of larger blade passing frequencies [6-7]. This kind of vibration was also called fluid-induced vibration. Basically, all pumps would have such problem, but the vibration levels would be different for each case.

The reason why the vibration value of gasoline was greater than that of diesel was that the gasoline fluid became more excited (greater fluid excitation consumes velocity energy). It may because the density of gasoline was lower, and as a consequence, larger flow velocity would be generated at the pump’s outlet. It may cause dynamic pressure fluctuations or pulsations. When the flow passed a restriction pipe, turbulence or flow-induced vibrations would be produced. After checking the previous operation records, the pressure difference between the inlet and outlet of the pump was about 3.19 MPa (5.85-2.66) when gasoline was transported, the difference for diesel transportation was 3.65 MPa (8.25-4.60). It can be explained that when transporting gasoline, more velocity energy was converted into fluid-induced vibration energy. To illustrate the explanation CFD simulations were conducted and shown in Fig. 5.

**Figure 4.** Vibration analysis for delivering diesel.
Figure 5. CFD simulations for showing fluid-induced vibration energy: (a) diesel transportation, (b) gasoline transportation.

By comparing Fig. 5 (a) with Fig. 5 (b), we could observe that the turbulence kinetic energy for gasoline transportation (highest value is $1.593 \times 10^4$ J/kg) was higher than diesel transportation case (it highest value is $1.533 \times 10^4$ J/kg), it mean that there was more energy causing vibration for gasoline transportation. 

The vibration of the pair pumps: P5 and P6 were larger than other pairs. The inlet and outlet pressure differences were listed in Table 3. The pressure difference between P5 and P6 pair was around 0.1 MPa lower than other pairs. It indicated that more pressure energy was converted into fluid-induced energy, as a consequence, the vibration level would increase.

In summary, the vibration of the oil pump was mainly caused by fluid excitation induced by the fluid pressure fluctuation. The vibration level for gasoline transportation was much higher than diesel transportation. The vibration level was not significantly increased by increasing the flow rates for either gasoline or diesel.

5. Conclusions and recommendations

In this paper, pump vibration caused by fluid dynamics was investigated. The vibration of gasoline transportation was much higher than diesel transportation since more velocity energy was converted to fluid-induced vibration energy. The vibration level for the pair P5 and P6 pumps was higher than other pairs. For the current situation, the pump station should avoid using pair P5 and P6 pumps. For reducing the vibration, pipeline and pump modification should be considered as:

- adding the frequency converter to adjust the speed of the pump so that the impact on the impeller and volute can be reduced;
- modifying the number of blades of the pump to avoid passing frequency vibration;
- changing the fluid flow direction e.g. adding diversion or the return pipe.
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