Degree and nature of shaft misalignments in pumping units assessed against vibration criteria

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Abstract. The paper shows that the degree and type of shaft misalignments, along with imbalances, have a decisive impact on vibration levels in centrifugal pumps. An accurate assessment is impossible without a unit shutdown to measure shaft alignments with special devices. A method for determining misalignments is proposed to assess the degree of misalignment against vibration spectra, the so-called rotational harmonics.

1. Introduction
The most recognized techniques to backup centrifugal pumps involve detecting misalignment, shutting down a machine and measuring shaft alignment with special devices.

When actuating pumping units, the vibration level in many respects depends on whether the rotors constituting a unit are properly coupled, i.e. on their proper alignment. According to Fixtur-Lazer AB (Sweden), in 49% of cases, misaligned machinery causes premature breakdowns, and for pumping machinery this accounts to 60%! [3]. According to the laboratory of vibration diagnostics of USPTU branch, Öktyabrsky city, pumping units exploited at RPM OGPD, which have alignment capacity worse than the demanded specifications, make up about 90% of all examined units [1-3].

Shaft alignment is generally inspected once a unit is shut down exclusive of the stress applied to the elements of the unit during its operation. For RPM and OHP OGPD units, that is stress from the suction and discharge pipelines, insufficient rigidity of the foundation frame of the unit, etc. (dynamic misalignment), from various thermal expansion of the motor and pump (thermal misalignment). These phenomena are considered in detail in [4].

2. Materials and methods
There are four types of shaft alignments: axial, radial (or parallel), angular (or end), and combined. Misalignment can be estimated indirectly based on vibration spectra [2], however, the well-known criteria (based on vibration levels and rotational harmonics) are general [1].

To assess the effect of misalignment on the level of vibration and the possibility to diagnose it against vibration signatures (spectra), the authors conducted an experiment on a TsNS180 centrifugal pump, widely used in the industry, according to the research plan shown in Table 1.
Table 1. Types and degrees of misalignment

| Type | Horizontal | Vertical |
|------|------------|----------|
|      | parallel   | angular  | parallel | angular |
|      | $R^{11m}$ | $R^{21m}$ | $R^{21m}$ | $R^{22m}$ |
|      | μm | ° | μm | μm | ° | μm |
| up   | 2  | 860 | - | - | 1190 | - | - |
| up   | 2  | 670 | 0°8′57″ | 495 | 530 | - | - |
| up   | 2  | 285 | 0°3′37″ | 200 | 360 | 0°2′ | 110 |
| -    | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| down | 1  | -380| -0°4′42″ | -260 | -230 | -0°3′31″ | -195 |
| down | 1  | -750| -0°9′40″ | -535 | -570 | -0°6′09″ | -340 |
| down | 1  | -900| -    | -    | -925 | -0°10′08″ | -560 |

Note: 1. Approximation for angular misalignment was subject to a rear bearing offset about the axis of the pump (in μm).

3. Results and discussion

Unit No. 1 selected as a research object (CPS No. 14, RPM OGDU Arlanneft JSOC Bashneft) was mounted onto the capital foundation and comprised an asynchronous electric motor – 4AZMA 800/6000 and a centrifugal pump – TsNS 180-1200 coupled by an MZP toothed clutch with a shortened intermediate shaft in accordance with GOST 5006-83E. The misalignments were measured with a PTs-2 aligner equipped with dial gauges; the gaskets were calculated using a specialized Center calculator (Laboratory of vibration diagnostics of USPTU branch, Oktyabrsky city [5]). Vibration was measured with an AU014 vibration analyzer (DIAMECH, Moscow), while data processing was ensured by the TrendTest and Diamant software packages (DIAMECH).

Figure 1. Schematic for measuring vibration level: RMB, FMB, FPB, RPB – rear motor bearing, front motor bearing, front pump bearing, rear pump bearing, respectively; 1, 2, 3, 4, 5, 6, 7, 8 – unit supports – measuring points of vibration on the lugs, frame and foundation.
Figure 2. Levels of reduced vibration $V/V_{\text{total}}$ in the frequency band 0 ... 200 Hz and 200 ... 1000 Hz

Figure 3. Malfunction spectrum “misalignment” of the shafts: about the X axis – frequency, about Y – vibration velocity (mm/s).

The vibration level was measured against the rms-vibration velocity in the frequency range 10 ... 1000 Hz on the bearings, in three orthogonal directions (Fig. 1), according to GOST ISO 10816-1-97.

Due to some bulkiness, vibration velocity measurements, as well as vibration-offset graphs, are not completely presented in the paper. Figure 4 shows a typical graph of the relationship between a dimensionless vibration level and the degree of offsets.

The target spectra were proved to contain the frequency band most sensitive to changing alignment values, namely the frequency range of 0..200 Hz (Fig. 2), i.e. the range to the fourth shaft rotational harmonic $f_0$ (basically these are the first three shaft rotational harmonics $f_0$, $2f_0$, $3f_0$ (Fig. 3), comprising ~ 90% of the energy of the entire frequency band.

Therefore, we decided to monitor the changes in the vibration level of the first three harmonics $f_0$, $2f_0$, $3f_0$, as well as in the frequency band up to 150 Hz, inclusive, which are most affected by the misalignment.
Figure 4. Vibration (reduced vibration velocity) vs misalignment: l, l50, l100 and l150 – respectively, total level, harmonic 50 Hz, 100 Hz and 150 Hz.

4. Diagnosis of misalignment by measuring the total level
For measurements, it is necessary to have the total vibration values in the band of 10 ... 1000 Hz. In the case under study, the total vector [4-5] in the band of 10 ... 150 Hz (p=4) $V_{ijklm}^{klm}$ is close to this value.

The misalignment for the total level is difficult to diagnose, only the following rules can be indicated (unlike [4], when processing measurement outputs, a polynomial approximation of the relationship between the rms-vibration velocity and the misalignment degree is accepted, namely, the quadratic dependence subject to parity parameter $m$):
- horizontal angular misalignment: there is a regular increase on all bearings and the whole unit, with a rate of 4 ... 9 1/mm² with an accuracy of over 0.85;
- vertical angular misalignment: there is a regular increase in radial vibrations at RMB and FMB, with a rate of 5 ... 19 1/mm² and 5 ... 9 1/mm² (FMB and RMB as a whole) with an accuracy of over 0.95;
- vertical radial misalignment $R_{2lm}^{klm}$: there is an increase with an accuracy of 0.9 with a rate of 2 1/mm² (RMB, axial and vertical).

In general, the above rules do not contradict generally accepted ideas. However, for a more accurate assessment (type, degree) of misalignments, it is necessary to analyze the variation spectra and establish the relationship between vibration growth at individual harmonics and misalignment signatures.

5. Diagnosis of alignment by vibration spectra
The scope of the studies, the cumbersome enumeration of the types of misalignment, the points of X, Y and Z vibration measurements at the corresponding rotational harmonics all suggest the formalization carried out in a pseudo-tensor format [6-9] $R_{ijklm}^{klm}$ (Table 2) and the corresponding vibration velocity values $V_{ijklm}^{klm}$, where $k$ is the direction of misalignment, respectively, horizontal and vertical, or 1 and 2; $l$ is the type of misalignment, respectively, radial and angular or 1 and 2; $m$ is the nature of misalignment, respectively, “up” and “down” (for vertical misalignment, for horizontal alignment the “up” position is taken to be the forward rotation of the coupling by 90 °, and “down” is
the rotation of the coupling by 270 °) or 1 and 2; i is vibration measurement point (Fig. 1), respectively, RMB, FMB, FPB and RPB or 1, 2, 3 and 4; j is the direction of measurement, respectively, X, Y and Z, or 1, 2 and 3; p is the rotational harmonic or frequency band, respectively, 50, 100, 150 and 0 ... 150 Hz or 1, 2, 3 and 4 (rationale for these harmonics is provided below). Thus, the “vertical” “radial” “up” misalignment of 300 μm will be presented in the form \( R_{211} = 300 \mu m \), and the corresponding vibration velocity of 12 mm/s at the RMB about the X axis at a frequency of 100 Hz – in the form \( V_{212} = 12 \text{mm/s} \).

The j convolution gives the value of the vibration vector on the whole bearing over the shaft rotational harmonics. The X, Y and Z summation is performed:

\[
V_{iklm}^{jop} = \sqrt{\sum_{j=1}^{3} V_{ijp}^{klm} \cdot V_{ijp}^{klm}}
\]  

(1)

The i convolution gives the value of the vibration vector on the whole unit. The summation is performed for the bearings:

\[
V_{iklm}^{jop} = \sqrt{\sum_{i=1}^{4} V_{ijp}^{klm} \cdot V_{ijp}^{klm}}
\]

(2)

For example, \( ijp \) indices equal to 10p or 00p mean, respectively, the vibration vector for 1 bearing (RPB) as a whole – convolution solely for \( j \) index, or for the unit as a whole – convolution for \( i \) and \( j \) indices.

\[
V_{iklm}^{jop} = \sqrt{\sum_{j=1}^{3} V_{ijp}^{klm} \cdot V_{ijp}^{klm}}
\]

(3)

In addition, non-dimensionalization through normalization is preliminarily performed for the vibration level when misalignment is “zero” (\( m=0 \), which herein corresponds to the minimum radial misalignment achieved of no more than 30 μm and angular – no more than 0'23°):

\[
\tilde{V}_{iklm}^{jop} = \frac{V_{iklm}^{jop}}{V_{klm}^{jop}}
\]

(4)

Hereinafter, the reduced vibration velocity is being discussed and, hence, the “~” sign is omitted.

The diagnosis [10-12] requires a rotational spectrum and its first two harmonics (\( p=1, 2, 3 \)). Then, the procedure for diagnosing the type and degree of misalignment will consist in applying the tensor \( V_{iklm}^{jop} \) to the mask (Table 3) constructed based on experimental data. Subject to the corresponding values of vibration velocity, the type and degree of misalignment is determined.

Moreover, the formalization of the comparison procedure allows such an assessment to be made in any algorithmic language or in Microsoft Excel. The degree of \( P \) forecast reliability is estimated in a usual statistics-related way [2-4] provided that the estimates for individual harmonics are independent. For example, in the case of “coincidence” \( F \) of the values \( V_{iklm}^{jop} \) for independent features, according to Bayes’ theorem, the probability of misalignment is

\[
P = P(r) \cdot \prod_{i}^{F} P_{ijp}^{ui}(r) \cdot \left[ P(r) \cdot \prod_{i}^{F} P_{ijp}^{ui}(r) + (1 - P(r)) \cdot \prod_{i}^{F} P_{ijp}^{ui}(o) \right]
\]

(5)

where \( P \) \((r)\) is the frequency of “misalignment” occurring. Given that it is equal to 0.6 [5], then \( (1 - P \) \((r)\) is equal to the frequency of misalignment (according to the probability theory, these events make up a complete group); \( P_{ijp}^{klm} (r) \) and \( P_{ijp}^{klm} (o) \) are the probability of increasing the vibration level at a point with “coordinates” \( k, i, j, p \) for a misaligned \((r)\) and aligned \((o)\) unit.
Table 2. Mask of different misalignments affecting the level of vibration

|        | $R^{21m}$ | $R^{22m}$ | $R^{11m}$ | $R^{12m}$ |
|--------|-----------|-----------|-----------|-----------|
| klp    | 1 2 3 4   | 1 2 3 4   | 1 2 3 4   | 1 2 3 4   |
| 11p    | - - - -   | +3 ± - -   | -5 +2 +7 +5 |
| 12p    | ± - - -   | +21 - - -  | -23 +10 +3 |
| 13p    | - - ± ±   | - - - -    | 7 ± +8 +5  |
| 21p    | - - - -   | +7 - - -   | +9 - 4 +9  |
| 22p    | ± +3 - -  | +14 - - ±  | -13 +27 +5 |
| 23p    | - - - +28 | ± +3 - -   | +20 - 2 +2 |
| 31p    | - - +8 +7 | - +5 +2 - -| 16 +5 ± +7 |
| 00p    | - - +8 - -| - +5 +7 - -| +6         |

Note:

1. The “+” sign indicates a positive correlation with high accuracy (over 0.75), “-” indicates its absence, “±” indicates a positive correlation with low accuracy (less than 0.75).

2. The digits next to the “+” sign indicate the tempo (constant at degree 2 in the polynomial approximation function (Fig. 4), and generally characterize the effect of this type of misalignment on the value of vibration velocity.

6. Conclusion

1. Informative frequencies (frequency bands) have been established to make it possible to detect a “misalignment” malfunction.

2. A “mask” of relative vibration levels for rotational harmonics and a relevant comparison procedure have been developed to diagnose the type and degree of misalignment of the shafts.

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