Effect of spiral outlet hydraulic passage geometrics on the radial thrust

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Abstract. The article presents the results of investigation of the effect of geometrics of a double-volute outlet hydraulic passage on the magnitude and direction of acting of the radial reaction forces in a between-bearings single-stage centrifugal pump with a double entry impeller. The investigation has been performed with the use of a computing experiment. Characteristic curves as well as values and directions of the radial thrust have been compared for three variants of outlet hydraulic passages differing in the width at their entrance.

1. Introduction

Between-bearings double flow volute casing centrifugal pumps are widely used in the various branches of industry. A dependable service of those pumps is conditional primarily on the reliable operation of their bearings.

A non-uniform pressure distribution around the impeller results in arising radial forces that act on the pump rotor. If a resultant radial reaction is calculated correctly, one can select adequate bearings to meet the reliability criterion: mean time between failures (MTBF) of at least 100,000 working hours.

In case of a single-volute pump casing design the radial thrust is the largest, especially at flows other than the best efficiency point. The application of the double-volute casing design enables to reduce the magnitude of the radial thrust, though it makes the pump casing manufacturing technology more sophisticated and such pumps less economical.

At present, there is a great number of calculation and experimental techniques for determination of radial forces in the centrifugal pumps. However, the calculation techniques are empirical and do not take account of actual flow conditions in the pump hydraulic passages, and the experimental ones call for considerable material and time costs as well as availability of expensive measuring instruments. Nowadays, as computing machine capacity increases, computing investigations have emerged into a really new trend in the research.

Geometrics of an outlet hydraulic passage affect directly the pressure distribution around the impeller, and hence, the resultant radial reaction force arising in the pump casing. The current radial thrust calculation techniques [1, 2] do not permit to take into account all the factors, including also outlet hydraulic passage geometrics affecting the magnitude of the radial thrust. Thereupon, it is appropriate to do computing investigations with the application of numerical flow analysis technics, which, in minimizing the material and time costs, allow to evaluate the magnitude of radial thrust as
well as to carry out a factorial experiment that prevents from being influenced by production deviations that may occur while making variants of hydraulic passages.

2. Theoretical analysis

Radial forces arise in the pumps as a result of a non-uniform distribution of static pressure around the impeller. The very existence itself of a spiral outlet hydraulic passage in the casing design causes a radial thrust because of the axial symmetry breakdown. It goes without saying that in the diffuser-type pumps a set of (5 to 12) spiral channels between the diffuser vanes, axially symmetrized around the impeller, give rise to little if any radial forces, cancelling each other. Therefore, the case in question is a volute-casing type design.

Generally, the radial thrust ($F_R$) can be estimated from the following formula:

$$F_R = k_R \cdot \rho \cdot g \cdot H \cdot D_2 \cdot b_2$$

where:
- $k_R$ – radial thrust factor;
- $\rho$ – density of handled medium;
- $H$ – head per stage;
- $D_2$ – outside diameter of the impeller;
- $b_2$ – impeller outlet width including shrouds.

Stepanoff has proposed the following formula for calculating the magnitude of the radial thrust applicable with single-volute casings [2]:

$$F_R = 0.1 \cdot 0.36 \cdot [1 - (Q / Q_n)^2] \cdot H \cdot D_2 \cdot b_2$$

where:
- $Q$ – current value of capacity;
- $Q_n$ – rated (nominal) capacity.

It should be noted that just the "nominal capacity" (rate of flow) is indicated in the book by Stepanoff. However, in the judgement of the writers, it should be understood that the nominal capacity in this case shall be the same as the capacity at best efficiency point.

A number of other authors [1, 3] have suggested with reference to the investigations [4] to use relations (characteristic curves), experimentally obtained during the investigation of various types of outlet designs of a pump pressure stage with the specific speed $n_q = 19$, for calculating the magnitude of the radial thrust.

In any case, neither referenced technique represents the effect of outlet hydraulic passage geometrics on the magnitude of the radial thrust. That’s why in this paper we bring to your attention a study into the effect of the width of a double-volute outlet hydraulic passage on the magnitude of the radial thrust.

3. Computing experiment

The computing experiment has been undertaken for three variants (designs) of outlet hydraulic passages, designed for the same impeller, which have different volute entrance widths but the same volute throat area. Some impeller and spiral hydraulic passages geometrics and ratios are presented respectively in Tables 1 and 2.

| Table 1. Impeller Geometrics. |
|-------------------------------|
| Description                   | Symbol | Unit | Value  |
| Outside diameter of the impeller | $D_2$  | m    | 0.515  |
| Impeller outlet width including shrouds | $b_2$  | m    | 0.091  |
| Number of impeller blades     | $Z_{imp}$ | pieces | 7      |
Table 2. Spiral Hydraulic Passage Geometrics.

| Description                                      | Symbol | Unit | Outlet No. 1 | Outlet No. 2 | Outlet No. 3 |
|--------------------------------------------------|--------|------|--------------|--------------|--------------|
| Diameter of volute pitch circle (cutwater diameter) | $D_3$  | m    | 0.525        |              |              |
| Volute entrance width                            | $b_3$  | m    | 0.105        | 0.110        | 0.120        |
| Width ratio of volute entrance to impeller outlet | $b_3/b_2$ | -    | 1.15         | 1.21         | 1.32         |
| Throat height                                    | $h$    | m    | 0.0725       | 0.0690       | 0.0625       |
| Volute throat area                               | $A_{3q}$ | m$^2$ | 0.0248       | 0.0249       | 0.0248       |

The computing experiment has been conducted for hydraulic passages of a volute pump that has a casing with double-volute outlet and semi-spiral inlet hydraulic passages, and a double entry impeller. Assuming that the flow in the pump is symmetric relative to the vertical axis of the outlet hydraulic passage, the calculations have been performed only for the half of the pump hydraulic passages. Besides, as a simplification of the computational grid, the flow in the impeller sidewall gaps and leakage joints has not been simulated. In order to obtain an actual flow pattern at the pump inlet and outlet, adjacent runs of the suction and delivery pipelines have been additionally simulated. A model of the pump hydraulic passages is shown in Figure 1.

Figure 1. Model of Computation Domain.

To enable computations, unstructured tetrahedral meshes for elements of the computation domain, namely: inlet hydraulic passage, impeller and volute outlet passage have been generated. Block-structured computational grids have been plotted for the adjacent runs of the suction and delivery pipelines. The total number of computational grid elements amounts to 3.6 million cells. The common computational grid comprises 1.4 million nodes in total.

Numerical computations have been conducted for the steady flow conditions. Mass rate of flow and static pressure have been taken as a boundary conditions respectively at the pump inlet and outlet. Leakproofness has been assumed as a boundary condition for all solid walls. To close the RANS (Reynolds-averaged Navier–Stokes) equations we have used a standard k-ε turbulence model with scalable near-wall functions. The computations have been done for four pump duty points: rated flow (1.0 $Q_{BEP}$), overload (runout) flow (1.25 $Q_{BEP}$) and two part load flow conditions (0.5 $Q_{BEP}$ and 0.75 $Q_{BEP}$).

4. Analysis of the computing experiment results

As a result of the completion of the computing experiment we have obtained patterns of pressure distribution around the impeller. Then the region around the impeller has been divided into cross-sections and the magnitude and the vector direction of radial forces have been determined for each
cross-section. By adding up the vectors, the magnitude and direction of the resultant radial reaction force (thrust) has been determined. Figure 2 shows the results of determination of the magnitude and direction of acting of the radial thrust for each of three variants of outlet hydraulic passage designs at the four operating points of the pump.

![Figure 2](image)

**Figure 2.** Results of Determination of the Magnitude and Direction of Acting of the Radial Thrusts: (a) – for the variant No. 1 of outlet hydraulic passage design, (b) – for the variant No. 2 of outlet hydraulic passage design, (c) – for the variant No. 3 of outlet hydraulic passage design).

It is of interest to note that the direction of the maximum radial thrust practically has not changed for various volute entrance widths, though in case of the widest outlet hydraulic passage the thrust vector direction has somewhat shifted towards the smaller cross-sections. The direction of acting of the minimum radial thrust depends substantially on the volute entrance width. In case of outlet hydraulic passage variants No. 1 and No. 2 with smaller width the thrust vector is directed towards smaller cross-sections at an angle of 90° with the cutwater. The radial thrust vector is directed towards the cross-sections of larger area for the outlet hydraulic passage design with the maximum volute entrance width.

The computation results are also represented in Figure 3 as a plot of radial thrust magnitude versus pump operating conditions. Here characteristic curves constructed according to the techniques [1, 2] are also presented for comparison.

It should be noted that the minimum value of the radial thrust does not fall at the best efficiency point but it is shifted to the left towards the 0.75 Q_{BEP} duty point. In case of the variant No. 1 with the narrowest outlet hydraulic passage we have obtained the value of the radial thrust for the 0.75 Q_{BEP} duty point, which is greater than that in case of the variant No. 2. However, notice should be taken of the fact that among all the design variants, if their characteristic curves are considered over the entire range of flows, the outlet hydraulic passage variant No. 1 is the most preferable, as its characteristic curve has the minimum values of the radial thrust at the 0.5 Q_{BEP}, 1.0 Q_{BEP} and 1.25 Q_{BEP} duty points, i.e. its graph of radial thrust against pump duty point is more flat. The maximum values of the radial thrust have been obtained for the widest outlet hydraulic passage of the variant No. 3.
5. Conclusions
Based on the results of the computing experiment, the effect of spiral outlet hydraulic passage width on the magnitude and direction of radial static (reaction) forces acting on the impeller has been analyzed by applying, to this effect, a numerical investigation in the flow through hydraulic passages of a between-bearings single-stage volute-casing centrifugal pump with a double entry impeller.

The behavior of the $F_r(Q/Q_{BEP})$ characteristic curves, on the whole, is similar for all the three investigated outlet hydraulic passage designs and correspond to their presentation described in [1, 2], where the radial thrust has its maximum values at the part load and overload operating conditions, and its minimum value near the best efficiency point. It has been revealed that the radial thrust magnitude is the minimum for all the three investigated variants at the $0.75 Q_{BEP}$ duty point.

On the grounds of the results obtained during the investigation conducted, we have come to the conclusion that the variant No. 1 featuring a narrow outlet hydraulic passage is the most preferred in terms of minimizing the radial thrust.

In view of the fact that making physical experiments is costly, the application of the computing experiment has enabled us to take account of and to analyze the effect of volute entrance width on the magnitude of radial thrust, which cannot be taken into account when using empirical calculation techniques.

References
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