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Some Aspects of Influence of Turbopump Unit Fabrication and Assembly Method on Seal Clearances

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Abstract. Each element of turbo-pump unit has its own dimensions, tolerances of form and surface arrangements that differ from the rated ones. When assembling a turbo-pump unit they are located with some skew due to the mounting offsets of the rotor and stator sealing surfaces. Such skew arise due to a combination of hard-to-predict factors, such as the inaccuracy of the machine, the clearance of the centering surfaces, the rigidity in machining, the reliability of the fixing of the component, the state of the component, the balance of the system, and so on. The main factors affecting the installation bias of the rotor and stator sealing elements include the structural diagram of the unit, the workflow for manufacturing component parts, the workflow of assembling and controlling quality. The present article considers the dependencies for calculating the values of the mounting bias. It is necessary to reduce the effect of the installation bias on the size of the sealing gap to reduce leakage in the seals of pumps and turbines.

1. Introduction
Turbo-pump units of liquid rocket engines represent a complex structure having numerous parts and interfaces included. Both the turbo-pump unit stator and rotor are a complex spatial structure representing a package of parts tied together with fixing elements. For instance, the oxidizer pump rotor of RD-170 engine turbo-pump unit is a complex structure where nine parts and four ball bearing inner rings are mounted and tightened with the help of three fastening nuts and four screws. Each of these elements has its own dimensions, tolerances of form and surface arrangements that differ from the rated ones. As a result, when assembling a turbo-pump unit they are located out-of-alignment, with some skew [1, 2, 3], due to the mounting offsets of the rotor and stator sealing surfaces.

2. Factors affecting the value of the mounting offsets
Usually, non-contact seals [4] are utilized in the liquid rocket engine turbo-pump units, the working clearance (δRW), in which is equal to the difference of the mounting clearance (ΔRM) and the total strain and temperature deformations of the rotor and stator sealing elements during its operation, and the local minimum clearance is equal to the difference of the radial working clearance and the sum of all mounting offsets during fabrication and assembly:

\[ δR_u = ΔR_m - \int (δR_r + δR_s) dl \]  

(1)
\[ \delta R_{\text{min}} = \Delta R_{m} - \int_{l} \left( \delta R_{x} + \delta R_{y} \right) dl = \Delta R_{m} - \int_{l} \left( \delta R_{x} + \delta R_{y} \right) dl \] (2)

Generally, three basic groups of factors affect the value of the mounting offsets (offsets of the sealing surfaces axes relative to the centerline):

- Unit structural arrangement determining the quantity and relative position of the rotor and stator elements;
- Component parts' fabrication processes determining the accuracy and actual errors of the parts fabrication;
- Assembly and its quality control processes determining the relative positioning accuracy, as well as the relative offset of the rotor and stator sealing parts.

In order to accurately determine the mounting offset values, it is required to carry out highly laborious calculations considering the influence of each error, stiffness of each part and value of the axial drawing-up force for each fastening nut or other fixing elements.

The following maximum allowable errors of the rotor and stator elements fabrication shall be known and set in the course of fabrication:

- Misalignment of seat and seal diameters;
- Non-parallelism of thrust faces;
- Non-perpendicularity of thrust faces relative to seat diameters;
- Seat surfaces form deviation;
- Gaps in bearings and seatings.

The influence of some distinctive features of the high-speed turbo-machines' parts and assembly units' fabrication on the surfaces location tolerances affecting the seal clearances is given below.

Figure 1a shows the result of the shaft machining upon the misalignment of centers due to the misalignment of holes for the centers. As shown on the figure, the misalignment of the centers results in the surfaces form deviations (tapering). The machined surfaces are coaxial, but such machining produces deviations from the specified seating clearances, the component parts joint stiffness and setting strength change leading to the seal clearance change.

When the machine is in a continuous operation, the regular adjustment of the centers' similar height and parallelism of their joint axis shall be carried out. If such activities are not carried out, the misalignment of the machined surfaces will appear (Figure 1b).

Figures 2, 3 show, in a quite extreme form, the location deviations that may occur due to machining process imperfection. If the force of the shaft contraction with the tailstock center FA is much less than the radial force FR, the alignment hole may not be fully adjacent to the center surface (Figure 2). The same misalignment of the alignment hole with respect to the center may be present if the alignment surface is damaged. In this case, the axis of the shaft centers will be out-of-alignment relative to the part rotation axis that will result in the machined surfaces misalignment unequal with respect to the centers axis. These surfaces will remain coaxial with respect to each other.
Figure 2. The surfaces misalignment due to the insufficient contraction force $F_A$

1 - axis of rotation; 2 - grinding wheel (knife); 3 - misalignment

Figure 3. Misalignment at high values of $F_R$ and $F_A$ contraction forces

1 - axis of rotation; 2 - misalignment relative to the centers axis; 3 - misalignment between A and B surfaces

At high values of FA and FR forces, a shaft elastic bending is observed (Figure 3). In this case, the shaft bent axis turns around the part rotation axis during machining. After removing the shaft from the machine, its axis draws straight, the machined cylindrical surfaces become out-of-alignment and the end surfaces become non-parallel.

The misalignment of the seat surfaces for bearings and seals in the rotor is usually significantly less than in the stator, since these surfaces are often made in one part; the quantity of the rotor parts is usually less than that of the stator. However, due to the greater amount of skew addends in the unit, the shaft misalignment shall be set quite accurately. The non-parallelism of the parts' faces attached to the shaft results in considerable skew (offset) values of the sealing surfaces. The rotor part face non-perpendicularity with respect to the seat surface upon the considerable length and absence of clearance for the seating on the shaft also results in the skew increase.

The location deviations of the sealing surfaces of the stator sealing elements, especially housings, result from a combination of various, often hard-to-predict, factors such as the actual inaccuracy of the machine and machining device, clearance for the alignment surfaces, runout variation error, stiffness of the machine - device - part - cutting tool system, possible contamination of mounting seats, part fixing reliability, device condition, system balance, etc. It is extremely difficult to determine by calculation the possible fabrication errors due to the reasons specified [1].

The vast majority of housings and other large stator elements are machined in two settings. When machining in the second setting, the minimum diameter surface machined together with the surfaces available in the first setting (D in Figure 4) is used as the reference one. The reference surface runout
is controlled in the second setting and if it does not exceed the value specified in the design documentation then the machining is allowed. The surfaces machined in the second setting may have rough location deviations with respect to the surfaces machined in the first setting.

![Diagram](image)

**Figure 4.** Diagram for possible surfaces location deviations during the housing machining

1 - axis of rotation; 2 - reference axis; 3 - device plane; 4 - plane perpendicular to the spindle axis

Figure 4 shows a possible option of the housing machining errors at the device face runout δ1, housing face runout δ2 and housing axis offset by δ3 relative to the axis of rotation (this offset can reach the values comparable to the value of the radial sealing clearance). In this case, the surface offset D up to the value δ4 allowable in accordance with the design documentation results in the misalignment of the machined surface relative to the seat surface for the bearing reaching the value of

\[
\delta_4 = \frac{\delta_1 \cdot \delta_2 + \delta_3 \cdot (\delta_5 + \delta_6)}{l_1}
\]

that will exceed the value specified in the documentation, usually equal to δ4.

The incorrect application of the device may entail even more rough fabrication.

The assembly is the final, labor-intensive and costly process that defines the performance characteristics, cost of production and competitiveness of any product. The relative labor intensity of the assembly works over the past 40-50 years has been continuously increasing due to the fact that the workpiece preforming and machining methods are advancing faster than the assembly method [5].

When assembling the unit, the offset value is affected by the offsets of the rotor and stator parts within the mounting clearances, rotation of the rotor parts with respect to each other, tightening forces of the rotor fastening nuts and coupling screws, as well as the method for the housings mutual alignments and connection. The correctly selected method to control the assembly process and quality of the complete assemblies allows to identify the parts and assembly units with unacceptable combinations of fabrication errors affecting the offset values.

The process of the turbo-pump unit assembly and control may be carried out according to one of the three options.

Option I. The parts having errors within the design documentation requirements are submitted for assembly with no restrictions. The errors are summarized in the assembly units in a random manner. In this case, the probability of assembly with both minimum and maximum sum of errors exist. With this method, the maximum possible sum of errors shall not exceed the level allowable for the normal operation. This option with the large number of parts may require an improved accuracy of fabrication [6].
The second process option is based on the fact that the probability of assembly with the worst combination of errors is low. As in the first case, the assembly is carried out using any set of parts, but the complete assemblies undergo special inspection and if the assemblies with the unacceptable level of overall errors are found they are sent for rearrangement and reassembly. The rotor surfaces' runout inspection may be an example of the above. The rotor sealing surfaces are, as a rule, used as the reference surfaces. The inspected runout values include:

- Runout due to the rotor mounting deformations;
- Runout due to the misalignment of the rotor elements’ interfacing surfaces;
- Runout due to the offset of the rotor elements within the seating clearances between the rotor elements;
- Runout due to the non-parallelism of the interfacing faces and non-perpendicularity of the thrust faces and the seat diameters;
- Runout due to the accuracy of the reference surfaces fabrication.

The third process option provides for the use of special fabrication, assembly and inspection operations ensuring the errors minimization to the required level, for example, the sealing surfaces machining in the assembled rotor or stator. Such operations are widely used in the aircraft industry when manufacturing gas turbine engines.

As a rule, the second process option is used. In this case, an accurate and careful calculation of the mounting offsets of the rotor and stator sealing elements is required. In turbo-pump units the inaccuracies (dimensional tolerances, surfaces location tolerances) of the large amount of the rotor and stator parts and assembly units have an influence on the offsets. The degree of influence depends on both the actual deviation values and the relative position of the parts with respect to each other as per the angle of turn in the particular unit example. The deviations summation may be performed using two methods: Probabilistic method and minimum-maximum method. The probabilistic method considers the phenomenon of scattering and probability of various combinations of the constituent elements' deviations. The minimum-maximum calculation method considers only the extreme deviations of the constituent elements.

The practice of testing the turbo-pump units fabricated in small series has demonstrated that it is possible to securely protect the unit against the adverse influence of fabrication errors if the overall deviations calculated as per the minimum-maximum method do not exceed the allowable values. Since the turbo-pump units are produced in small series or in single quantities and the issue of reliability of the unit and its elements is of paramount importance, the calculation as per the probabilistic method is irrational. It should be also taken into account that the minimum-maximum method calculations in the course of the unit design allow to identify the error combinations that are dangerous for the operation and take the required measures in advance, during the design stage. When the investigated parameter maximum values are unacceptable, the measures excluding the possibility of such values occurrence in the actual units shall be provided. Definitely, the fact that the actual values of skews in the unit, at least the mounting ones, are usually less than the maximum values determined as per the maximum-minimum method is considered in this case.

The turbo-machines' rotors represent a structure designed as a package of individually fabricated parts centered relative to each other or to the shaft, tightened with a common nut or other fastening elements. The misalignment of any sealing surface is the resulting error of all the parts included in the rotor, that significantly complicates the calculation of the mounting offset values. The tightening, as a rule, is carried out using significant axial force in order to eliminate the joint clearances. The shaft shoulders' non-perpendicularity with respect to the threads may result in the rotor bend. When being installed on the shaft, the nut, within the thread clearance, may radially offset and rotate to eliminate the skew ensuring the firm adherence of the nut face against the rotor mating part, as well as circumferentially equalize the tightening force. In this case, the nut face runout relative to the pitch diameter not exceeding the half minimum thread clearance may be allowed. If the threaded connection is coated, the thread clearance decreases and the same shall be considered when specifying the tolerances. In order to achieve the steady-state and axially-symmetrical rotor stiffness, it is required to
provide for the tight zero-clearance adherence of all faces of its parts due to the tightening force. The sufficient tightening of the both rotor and stator parts shall be provided at deformations resulting from the internal and external loads, for instance, the hydro-gas-dynamic and unbalanced loads. The required tightening force value depends on the parts dimensions, their fabrication error values, their stiffness, the value and nature of external and internal loadings. It should be noted that when attaching the parts included in the rotor or stator packages with the help of a group threaded connection, an additional error occurs due to the unequal tightening force associated with the material elastic deformations and contact deformations on the joint surfaces. These additional errors shall be considered when calculating the angular deviation of the rotor or stator sealing surfaces.

Another special feature of the rotors is that their constituent parts: Bushings, turbine wheels, screws, impellers may be installed in various relative positions equivalent from the structural point of view. However, the presence of macro deviations and deviations of the contacting surfaces location results in the fact that by changing the relative angular position of the parts it is possible to obtain the versions of the same rotor with different characteristics including those not satisfying the specified accuracy requirements. The rotor assembly is the process of forming its assembly axis by selecting the optimal relative position of the parts. The rotor axis formed in such a manner may be only rectified by disassembling the rotor with subsequent turn or replacement of the parts. This process is highly labor-intensive and requires the rotor parts modifications in some cases [7].

3. Calculation the value of the mounting offsets
In the result of generalizations based on the application of the dimension chain theory with inherent assumptions, we receive a dependence to determine the mounting offset of the seal diameter in the housing with respect to the diameter for ball bearings due to the misalignments:

$$\delta R_{E,\delta}^E = \frac{l}{L} \left[ \left( E_u + \frac{\delta_u}{2} \right) + \sum_m \left( E_m \right) + \sum_n \left( \frac{\delta_n}{2} \right) \right]$$

(3)

$$l$$ – distance between the sealing and the thrust ball bearing;

$$L$$ – distance between the ball bearings.

$$E$$ – misalignment between the elements forming the stator part of the sealing from the bearing to the sealing surface, in terms of radiality;

$$\delta$$ – diametrical fit clearance between the elements forming the stator part of the sealing from the bearing to the sealing surface, in case of the interference fit the value in the calculation shall be assumed equal to 0.

The mounting offset of the rotor sealing element with respect to the rotor centerline shall be determined as per the following dependence:

$$\delta R_{E,\delta}^{rot} = \frac{l}{L} \left[ \left( E_{rot} + \frac{\delta_{rot}}{2} \right) + \sum_m \left( E_{rot} \right) + \sum_n \left( \frac{\delta_{rot}}{2} \right) \right]$$

(4)

$$E$$ – misalignment between the elements forming the rotor part of the sealing from the bearing to the sealing surface, in terms of radiality;

$$\delta$$ – diametrical fit clearance between the elements forming the rotor part of the sealing from the bearing to the sealing surface.

The clearance in the seals with fixed wall (groove and labyrinth seals) and the clearance setting are influenced by the mounting offset due to the both stator and rotor elements misalignments and fit clearances. The clearance in the floating and semi-flexible ring seals is influenced only by the mounting offset of the rotor elements, i.e. $$\delta R_{E,\delta}^E = 0$$.

The mounting offsets reach significant values even for small-sized units. To provide for the non-contacting operation of the seals, the radial clearance value may be considered as sufficient if it exceeds the sum of the half of the rotor sealing surface mounting offset value and the mounting offset.
value of the shaft axis passing through the axes of the mounting surfaces of the ball bearings' inner rings.

In order to reduce the minimum clearances in the pumps and turbines, it is required to reduce the mounting offset effect. Measures to reduce these values may be divided into four directions, all related to improving the fabrication accuracy:

- Reduction of the bore diameters misalignments;
- Reduction of the fit clearances influence due to the strengthening of tolerances and change-over to tight fits (interference fits);
- Limiting the sealing diameter misalignment during the assembly of housings, pumps and turbines;
- Co-machining - grooving of the housings seal diameter or the rotor assembly.

These measures are quite sophisticated and costly. They shall be implemented only after a careful analysis of the requirement and feasibility. If possible, the desired result shall be achieved in a different way, since the improving of accuracy, as a rule, results in the improved quality, but also increases the fabrication cost.

4. Conclusions

The following may be concluded based on the above considered influence of the turbo-pump unit fabrication and assembly method on the seal clearances:

- Mounting offsets have a significant effect on ensuring the noncontacting operation of the seals;
- Mounting offset calculation requires the consideration of the large number of factors;
- it is reasonable to calculate the mounting offsets of the rotor and stator sealing as per the minimum-maximum method.

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