Conclusion

Abstract of development results and maintenance of reducers on the basis of WGIRB in structure of drives of various assignment gives the opportunity to state the following main conclusions and set problems for realizing broader application of the given type gear:

- Wave gear with intermediate rolling bodies are the perspective type of transmission possessing merits of wave gear and having a set of advantages supporting high resource, lost motion, stiffness values and oters;
- Primary tasks of WGIRB integrated study group are carrying out additional theoretical studies and their development to engineering design procedures including CAD as well as the development and production of processing equipment and instrument for manufacturing details with working surface high quality and supporting high capacity with low cost.

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PRECISE REDUCER OF INCREASED DURABILITY

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The results of works on creation of precise reducer being a part of spacecrafts have been presented. Modular composition of reducer construction on the basis of wave gear with intermediate rolling bodies was described. Reducer construction with modular composition of kinematic circuit was offered. In this circuit the gears with adaptive generators supporting elastic tightness in interlock were applied.

High demands of space technology determine the parameters of all blocks and components being a part of spacecraft. The main parameter for the spacecraft is a high resource. One of the blocks defining spacecraft working capacity is navigation system which includes also electromechanical actuators. In some of them the rotation drives of cardan suspension frame (RDF) are applied. The progressive trend in RDF drives creation is electromechanical reduction drive.

Presence of reducer in drive composition allows obtaining certain advantages but imposes high requirements to its parameters.

Works on RDF reducer creation were started since 1975 at «SPC «Polyus» in Tomsk [1]. The first attempts to solve the problem using known gear constructions did not achieve positive result. The most difficult task was to eliminate gaps in reducer kinematic circuit that as one of the main requirements. Lost motion of output shaft should not exceed 2 ang. sec. per the whole resource which is more than 10 years. As a result of carried out researches including theoretical ones from creation of new constructions, development of parameters design procedures to the development of production and control techniques of reducers elements and experimental

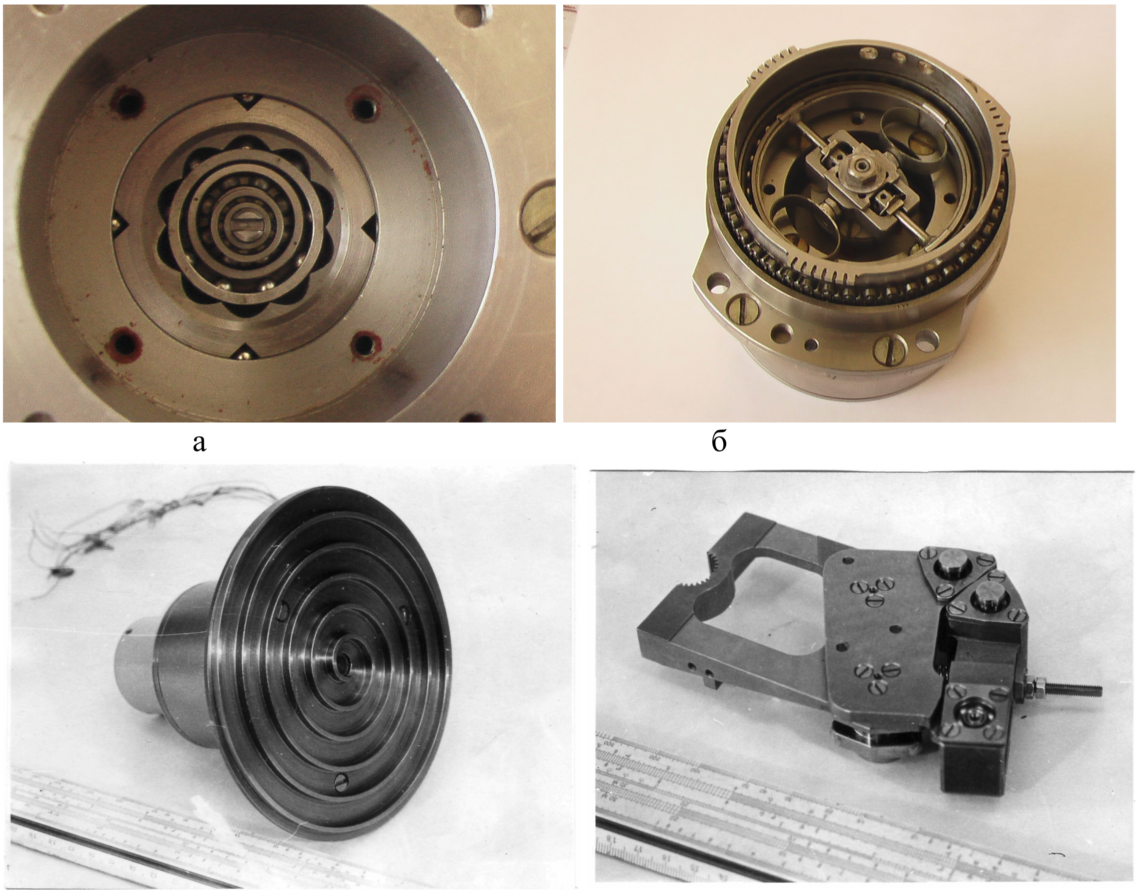

Fig. 1. *RDF-1: a) the first stage, b) the second stage, c) the cam of the third stage, d) the lever*

ones up to use in spacecraft structure, the constructions of precise reducer of increased durability were created. These constructions are also applied in new designs of electromechanical actuators.

The first constructions of RDF-1 reducer contained three different gears: the first (entry) stage was the wave gear with intermediate rolling bodies (WGIRB); the second one was the wave gear with serpentine spring [2] and the third one was the cam gear [3–5]. The cam gear consists of the butt cam with Archimedean spiral and the lever with rolls entering into the slots of cam spiral. The cam is fixed on the output link of the second stage, the race with serpentine spring and the cam on the shaft of cardan suspension. Such construction of kinematic circuit of RDF-1 reducer complicated process design and increased the cost of its manufacturing.

Complex experimental testing included also determining changes of reducer characteristics in the process of resource operating time. First of all, it is a lost motion and accuracy of kinematic circuit which depend on wear of gear detail working surface.

For comparison together with the reducer RDF-1 the reducer RDF the kinematic circuit of which consisted of five pairs of fine-module wave gears and the same cam gear as in the reducer RDF-1 was similarly tested. The output stage of fine-module tooth part of the reducer contained a split spring loaded wheel for gaps eliminating.

New reducers were tested on output link control motion in the structure of electromechanical actuator. It should be equal 4,32 ang. sec. per each step of step motor. Lost motion and kinematic circuit errors of the reducer RDF resulted in output link motion had an error more than 13 ang. sec. per each step of the motor. The output shaft could remain static or even move in the opposite direction at rotor motion by 3 steps and move by 13 ang. sec. at further rotor motion by one step. The results of testing with the reducer RDF-1 showed that each step of step motor is accurately tracked by the output link and the error, even at reverses, does not exceed a half of the design value.

After resource operating time the test showed that the error of output link motion of the reducer RDF has increased by 50 % but no error changes of output link motion of the reducer RDF-1 was not recorded. Visual test of lubrication VNIINP-271 state which was applied in both reducers for all gears showed that it has changed its initial color least of all due to the presence of wear debris in it on WGIRB elements.

Control of working surface sizes of gear elements showed that WGIRB details were worn out least of all. Tooth profile of static spline is less than 1 mkm; balls diameter is 6 mkm; race slot is 10 mkm; generator outside diameter is less than 1 mkm. There are also low values of wearing the details of wave gear with serpentine spring

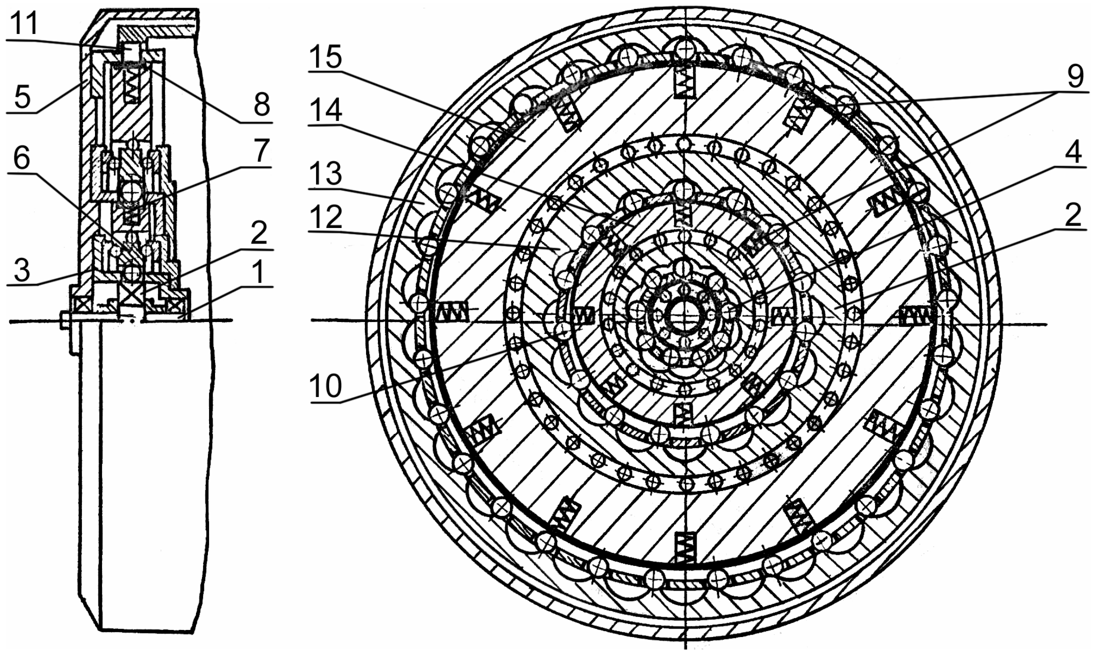

Fig. 2. Reducer RDF-2

which were balanced by elastic tightness. The results of the experiments are confirmed by the results of spacecraft operating which resource is 20 and more years which include also reducers RDF-1 in their structure.

The experience of the reducer RDF creation at Tomsk «SPC «Polyus» [1] allows drawing a conclusion about the availability of WGIRB application in space engineering. Use of balls or rolls in the given gears at proper performance of static spline and generator supports high resource with its surviving. These balls and rolls are quantity produced in ball bearing industry with high quality of geometries, working surface roughness, thermal treatment, applied steel types etc.

The experiment of reducer RDF-1 creation and the results of its researches showed that creation of reducer construction on the basis of one type of gears is more efficient and preferable that was made in paper [1]. The suggested construction of the reducer RDF (Fig. 2) consists of three stages, made by modular composition of kinematic circuit. Unified WGIRB is meant by module; in this case each previous gear is placed in the next one. The input gear is placed inside the second one both of them are inside the third stage. The output links of the first and the second stages of the reducer are the input links of the second and the third ones correspondingly without intermediate links (shafts, clutches etc.).

Such construction of the reducer RDF supports maximum efficient volume filling and minimal reducer dimensions which are practically defined by the output stage dimensions. This construction allows optimizing the reducer kinematic circuit; the design model was suggested for this purpose. The dimensions of rolling bodies (balls and rolls) produced by ball bearing industry are accepted as variables defining further gear calculations and reducer construction. Limitation of minimal and maximal dimension values is accepted by manufacturing capability condition of gear element production and low loading of output shaft. The ranges of gear reduction ratios and their proportions by stages are determined; reducer dimensions and mass and the equivalent moment of inertia were the main criteria in this case. Size of gear details at slight simplification of their configuration are determined by rolling bodies dimensions and reduction ratio that allowed automating the calculation process on optimization of kinematic circuit, tooth profiles of static splines, forces in contact zones of rolling bodies, equivalent moment of inertia, mass and dimensions.

The construction of the reducer RDF-2 with modular composition of its kinematic circuit is presented in Fig. 2. The first stage is carried out in traditional circuit, input shaft – 1 is made with eccentric neck where the radial ball bearing performing functions of generator – 2 is installed. Race – 3 with radial slots, with balls – 4 placed inside them, is fixed to the housing – 5. The output link of the first stage – static tooth wheel – 6 is installed in angular-contact bearings the races of which are performed on lateral surfaces of wheel – 6 and on stationary parts fixed on the housing – 5. External cylindrical surface of the wheel – 6 is made with eccentricity relative to rotation axis and acts as inner race of generator ball bearing of the second gear.

Lost motion of reducer kinematic circuit should be minimal during the whole operation life. To secure this requirement the wave gear with elastic tightness in contact zones of balls with generators, race slot walls and static spline tooth was proposed [6]. It was used in the second and third stages of the reducer RDF-2. Ball bearing outer race of wave gear generator with elastic tightness in contact zones of balls is performed by a compound. It consists of split rings – 7, 8 and resilient members – 9 which springs in radial direction of the ring – 7, 8 into contact zones of balls – 10 and rolls – 11 with generator, race slots walls and static splines tooth – 12, 13. The resilient members are installed in radial slots of outer rings – 14, 15 of generator ball bearing. At the second and third stages the static tooth wheels – 12, 13 serve as the output link. For the static spline – 12 of the second stage the supports are made as angular-contact bearings similarly to the installation of static spline of the first stage. Bearings of actuator Cardan suspension serve as the supports of static spline – 13 of the third stage.

Continuation of works in creation of WGIRB with elastic tightness in contact zones of rolling bodies resulted in creation of new constructions [7–9] of gears. Application of these gears supported defect removal inherent to the previous construction of the reducer RDF-2, first of all it is:

- presence of split ring contacting with rolling bodies, the gap between junctions results in contact knocks in this place;
- large values of radial sizes of outer ring of generator ball bearing where the resilient members are placed increase reducer radial dimensions;
- absence of elastic tightness in contact zones of rolling bodies of reducer first stage increases lost motion magnitude.

Reducer RDF-3 in which the abovementioned wave gears are applied is presented in Fig. 3. Wave gear is used as the first stage [7, 8]. The elastic tightness in contact zones is achieved by the following: the outer surface of ball bearing of generator – 2 is performed as conical one and is constantly closed to the rolling bodies – 1 by resilient members – 3 which bear on the gear box – 5 of the reducer through the thrust bearing – 4. Rolling

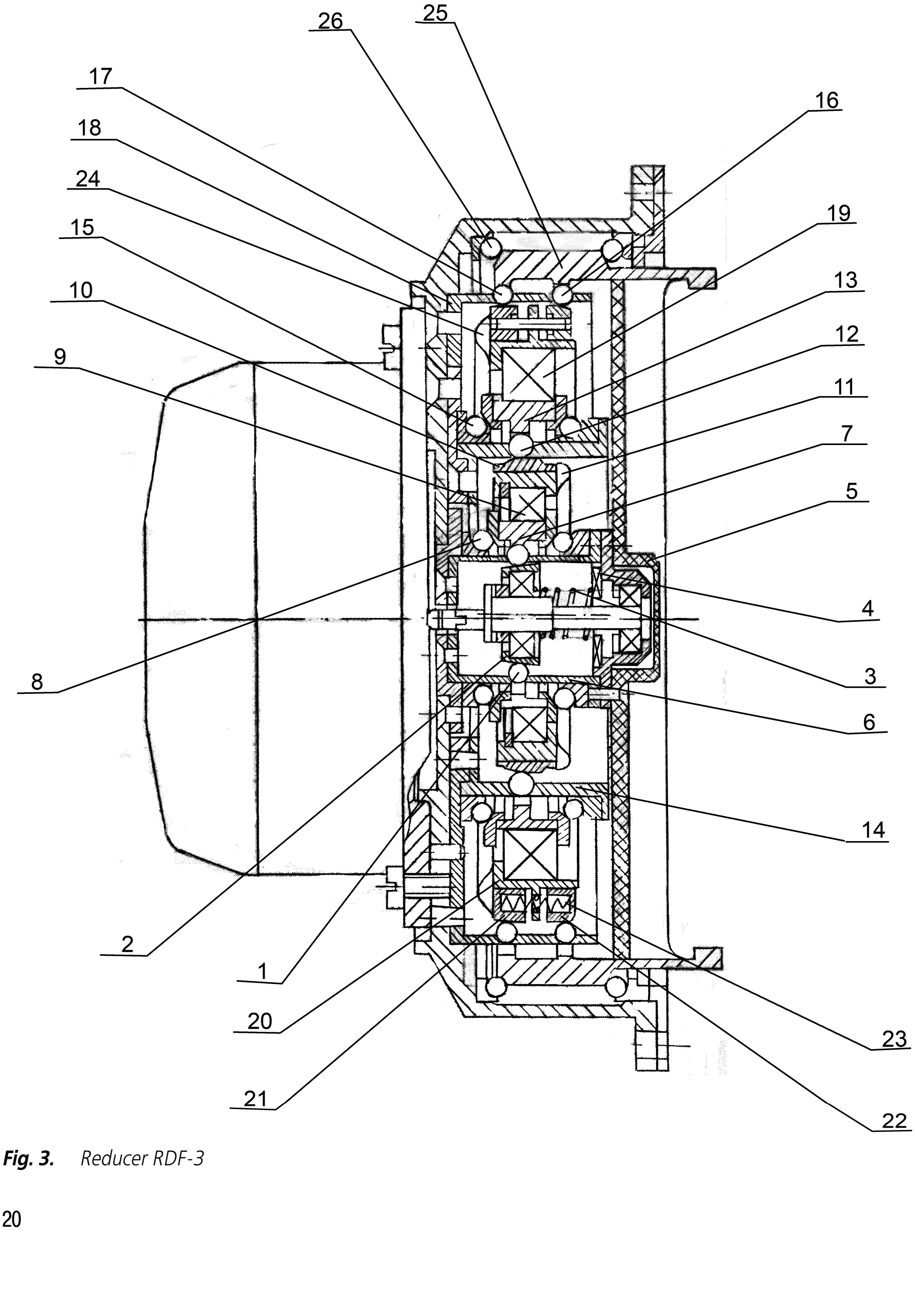

Fig. 3. *Reducer RDF-3*

bodies – 1 are placed in radial slots of race – 6 fixed in housing – 5. The output link of the first stage is the static spline – 7 with eccentric outer cylindrical surface being included in generator of the second stage.

The wave gear is used in the construction of the second stage [8]. Angular-contact bearings – 8 is the ring supports – 7. Ball bearing – 9 on the outer ring of which the ring – 10 with conical outer surface is fixed with minimum positive allowance is installed on the ring – 7. The outer ring of the bearing – 9 and the ring – 10 are connected by the resilient membrane – 11 which has axial fragility and radial stiffness and high values of torsional stiffness. The membrane – 11 shifts the ring – 10 relative to the bearing – 9 and ring conical surface is pressed to the rolling bodies – 12 forming elastic tightness in zones of their contact with ring tooth – 13, race slots walls – 14. The ring – 13 is set up on angular-contact bearings – 15 in the housing – 5 to which the race – 14 with radial slots is anchored. In these slots the rolling bodies – 12 are placed. For the third (output) stage of the reducer RDF the wave gear is used [9].

To increase the output capability of the outlet stage of reducer RDF-3 the gear is carried out with two rows of rolling bodies – 16, 17 placed in the race – 18 fixed on reducer housing – 5. The generator of the third stage consists of: external eccentric ring surface – 13, on which the ball bearing – 19 is installed; barrel – 20 built-up on the outer ring of bearing – 19; two barrels – 21, 22 with conical outer surfaces. Barrels – 21, 22 can move along the axis under the influence of resilient members – 23 set up between them pressing rolling bodies – 16, 17 into zones of their contact. The transfer of rotation from the barrel – 20 to the barrels – 21 and 22 is carried out by the elastic membrane – 24 having low axial and radial stiffness but high value of torsional stiffness anchored with one end on the barrel – 20 and with another one on one of the barrels – 21 or 22. The static spline – 25 set up on angular-contact bearings – 26 acts as the output shaft that supports reducer autonomy at its assembly, adjustment and test.

The results of works on reducer RDF creation of electromechanical actuators for spacecraft controlling and orientation and field experience allows drawing the following main conclusions:

- WGIRB support operating capacity for long operation period (20 years and more);
- WGIRB constructions with elastic tightness in contact zones of rolling bodies in gear practically eliminate lost motion of reducer kinematic circuit;
- Use of modular composition of reducer kinematic circuit allows decreasing significantly the dimensions and mass, simplifying construction due to reducing the number of intermediate elements between the stages;
- Modular composition simplifies CAD that decreases costs for development of new constructions.

The conclusions confirm the availability of WGIRB use in precise reducers of low power drives with high values of such its parameters as low inertia, lost motion, durability, stiffness, mass and dimensions.

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