New generation of the satellite hydraulic pumps

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NEW GENERATION OF THE SATELLITE HYDRAULIC PUMPS

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Abstract: Hydraulic satellite machines are known and produced in many versions, recognizable by the number of humps on their inner rotor and external gear, and therefore by the number of cooperating gears (satellites). All known shapes were however designed on the base of preliminary assumption that rotor's and external gear's pitch lines are formed by merging arcs, tangent to each other in the. This assumption makes calculations easier, but the curvature radius of the pitch lines changes instantly in their merging points. Tests made in the Department of Hydraulics and Pneumatics of the Gdańsk University of Technology proved that satellite motors may work also as a pump. All known shapes were however designed for motor work - mainly for low-speed, high-torque motors. Sudden changes of the pitch line's curvature strongly affect velocity and acceleration of pump's moving parts and forces between them. Because of that, in the pump mode fast wear of teeth in the points of small curvature radius is visible. The obvious effect is reduced durability and high noise emission. To eliminate all those problems the new mechanism, designed for the pump is necessary. The author worked out the new method of calculating satellite mechanism's shape. Instead of merged arcs this method allows to form pitch line as a smooth shape with constantly variable curvature (no rapid changes in any point). Such a mechanism with two-humped rotor, four-humped external gear and six satellites was designed with the use of the new method. Curvature radii of all cooperating elements are relatively high. The proposed shape reduces rapid changes of velocity and forces between pump's elements. It should result in more durable hydraulic satellite pump.

Keywords: satellite pump, gear mechanism, pitch line

1. INTRODUCTION

Hydraulic satellite motors were first time introduced almost half a century ago, and different versions of those motors are now produced by many companies. The satellite mechanism shown in Fig. 1 consists of a non-circular gear with external teeth (rotor), non-circular external gear with internal teeth, and circular gears (satellites) between them. Gear modulus of the produced motors ranges from 0,4 mm (high speed motors, displacement 5-10 cm^3/rev) to 4 mm (high torque motors, displacement up to 6.3 dm^3/rev). High speed motors, called SM motors emerged on the market thanks to research conducted by the team of Hydraulics and Pneumatics of Gdańsk University of Technology in cooperation with Stosowanie Maszyn company. Laboratory tests of the SM motors proved their ability to reach 1800 rpm with working pressure up to 25 MPa. It means that power density of those motors is very high and may exceed 4 kW/kg.
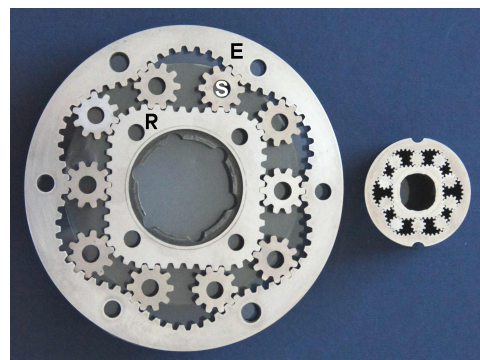

Fig. 1.   Examples of 4/6 satellite mechanisms: R – rotor, E – external gear, S – satellite

One of the main advantages of SM satellite motors is also their ability to work with different fluids like: mineral and vegetable oil, non-flammable fluids and even the pure water [1, 2].Thanks to this ability and low weight satellite motors have found wide use: especially in mining and marine industries.

2. DESIGN AND PERFORMANCE OF SATELLITE PUMPS

Parameters of the SM motors encouraged to test their ability to work as a pump. The new PSM pump (Fig. 2) was designed on the basis of the SM motor and subjected to tests in laboratory. Tests results confirmed it's ability to pump different fluids (i.e. mineral oil, water, HFAE emulsion) within the wide range of working parameters.
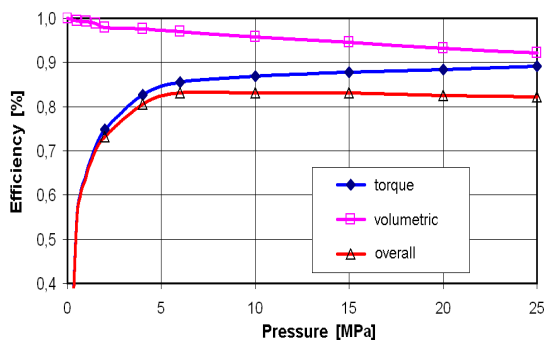

Fig. 2.   PSM satellite pump [3]

Fig. 3.   PSM pump performance, speed - 1000 rpm, fluid - mineral oil HG 46 [5]

Efficiency of the PSM prototypes reaches the same level as efficiency of modern hydraulic vane or gerotor pumps produced by leading manufacturers (Fig. 3 and 4) [5], after improvement of it's compensation unit the new pump may exceed 90% and reach the efficiency level of the gear pumps.
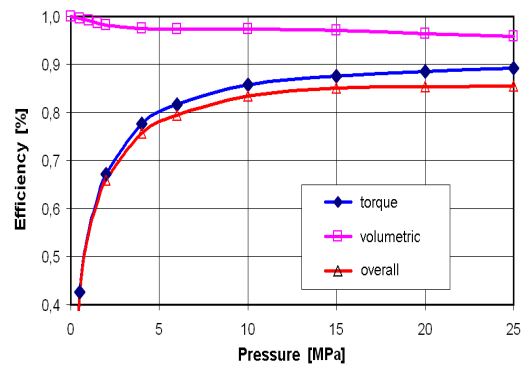

Fig. 4.   PSM pump performance, speed – 1500 rpm, fluid – HFAE emulsion [5]

3. TECHNICAL PROBLEMS

Laboratory tests of the PSM pump prototypes confirmed ability of the satellite mechanism to work as a pump and to reach parameters like rotational speed and pressure required in modern hydraulic drive systems, but revealed also some disadvantages of the new concept.

First problem is a little radius of rotor's curvature near it's humps. It causes harmful conditions of cooperation between teeth and their fast wear. This phenomenon mainly affects the strongly curved, convex areas of the rotor marked in Fig. 5a. After a relatively short period of time rotor's teeth in those regions show significant wear (see Fig. 5b [6]).
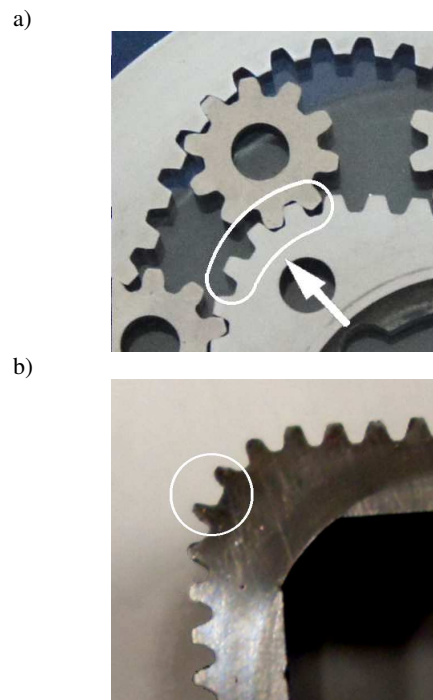
a)

b)

Fig. 5.   New mechanism (a) and worn out rotor (b) [6]

Such a phenomenon significantly reduces the durability of the pump and may lead to it's damage. The shapes of the presently produced satellite mechanisms were primarily designed for high torque hydraulic motors. The gear modulus in those machines ranged from 1,5 mm up to 4 mm, and motor's speed was usually less than 250 rpm. Under those conditions teeth wear was negligible. On the contrary, pump's rotational speed is usually high - 1500 rpm or more, while teeth modulus ranges from 0.4 to 1 mm. This makes the teeth wear problem much more important.
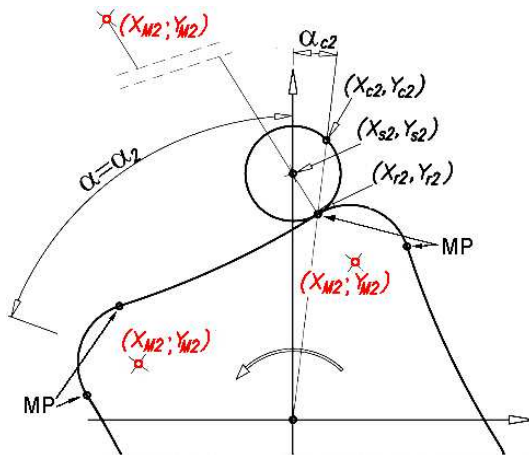

Fig. 6. Pitch lines of the rotor and satellite in present 4/6 mechanism. MP - merging points [4]

The second problem stems from the design methods used for determining the shapes of both the rotor and external gear. In all present versions the pitch lines are formed from arcs merging in certain points (marked as MP in Fig. 6) and tangent to each other in the MP. Points shown in red mark positions of the centers of curvature of successive arcs. Such a shape of the pitch line makes the mechanism design process much easier, but badly affects the performance of high speed pumps or motors.
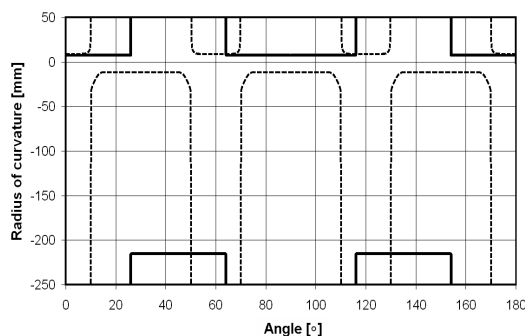

Fig. 7. Changes of curvature radii in present 4/6 mechanism: solid line - rotor, dashed line - external gear

The pitch line in every MP changes rapidly it's radius of curvature (both value and sign - see Fig. 7). Positive values of the radius mean convex shape of the pitch line, negative – concave shape. For the commonly used present 4/6 mechanism with 0.75 mm teeth modulus the most important minimal positive value of the curvature radius of the rotor's pitch line equals 7.5 mm. Corresponding value for the external gear is 7.65 mm. Cooperating satellites have constant curvature radii: +3.75 mm. Such a shape causes also rapid changes of speed and acceleration of the cooperating satellite in the moment when it crosses the merging point (see Fig. 8 and 9) and thus big forces exerted on all parts of the mechanism.
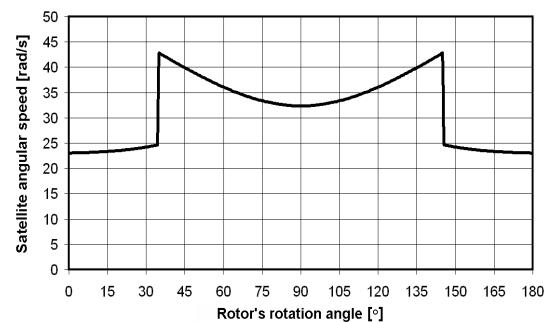

Fig. 8. Changes of the satellite's rotational speed in present 4/6 mechanism. Rotor's speed $\omega = 10$ rad/s [4]
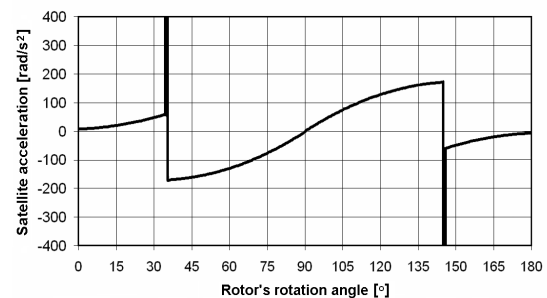

Fig. 9. Changes of the satellite's acceleration in present 4/6 mechanism. Rotor's speed $\omega = 10$ rad/s [4]

4. THE NEW MECHANISM

Each satellite gear mechanism to work properly must fulfill three basic conditions [7]:
- contacting pitch lines must roll over each other with no slip between them,
- pitch lines must have cyclic shape with no sharp edges (if pitch lines are formed as a set of merged arcs, those arcs must be tangent to respective one in their merging points),
- lengths of all pitch lines must be in rational proportion to each other (teeth numbers must be integral).

Calculation methods for existing satellite mechanisms are described in [4, 7], but those methods are

applicable only in case of pitch lines formed as a set of arcs. To solve mentioned above problems with rapid changes of curvature and fast teeth wear the new shape calculation method is necessary. The pitch lines for rotor and external gear have to be based on the single mathematic formula describing the pitch line's shape instead of set of tangent arcs. Such a line must also meet two additional criteria:

− constantly variable radius of curvature,
− possibly high value of the minimal curvature radius.

All three previously mentioned conditions are, of course, still obligatory.

4.1. The new layout of the mechanism

On the contrary to all present shapes the new mechanism was designed to work as a pump, not as a motor. Theoretically, many variations of the satellite mechanism are possible [9]. They vary in number of humps on both rotor and external gear (Fig. 10). The number of satellites in all cases equals to the sum of the rotor and external gear hump numbers. As an example, the most popular version of the satellite mechanism, marked as 4/6 mechanism, consists of four-humped rotor, six-humped external gear and ten satellites (see Fig. 1).
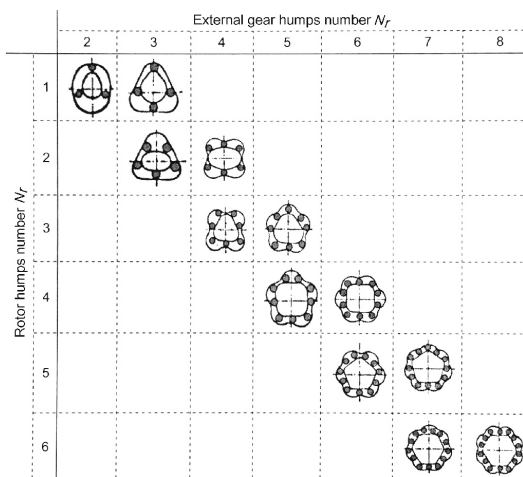

Fig. 10. Some possible layouts of the satellite gear mechanism [9]

From the set of theoretically possible layouts the 2/4 mechanism was chosen for the new pump. The rotor in such a mechanism has only two humps, while external gear has four of them. Both gears cooperate with six satellites (Fig. 10 and 11). The proposed shape reaches high displacement-to-dimensions ratio and thanks to smaller number of satellites reduces the total number of working cycles for every revolution of the rotor.

4.2. Calculation of the new shape

To meet the criteria mentioned in chapter 4 the completely new method of shape calculation was

required. What's more, the analytic method of shape calculation cannot be used. Rotor's shape in the 2/4 mechanism is based on the ellipse equation. Precise calculation of the ellipse length is known in mathematics as one of the insolvable problems. On the other hand, precise length value is necessary to establish the number of teeth, otherwise the satellite mechanism cannot work properly. The only solution for that case was to apply numerical calculations with dense partition. Such a software was designed and tested. The results obtained thanks to the new method confirmed the possibility of creating many new versions of the satellite mechanism, all capable of meeting the mentioned above requirements. Some examples of the new mechanism with the respective teeth numbers are shown in Fig. 11.
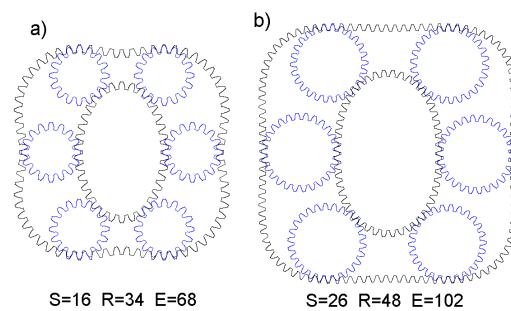

Fig. 11. Examples of the new 2/4 pump mechanism: S - number of satellite teeth, R - rotor teeth, E - external gear teeth

4.3. Properties of the new mechanism

The new 2/4 mechanism (version a) in Fig. 11) was subjected to the same analysis as the 4/6 present one. In both cases the same values of the teeth modulus and rotor's angular speed were assumed – 0.75 mm and 10 rad/s respectively.
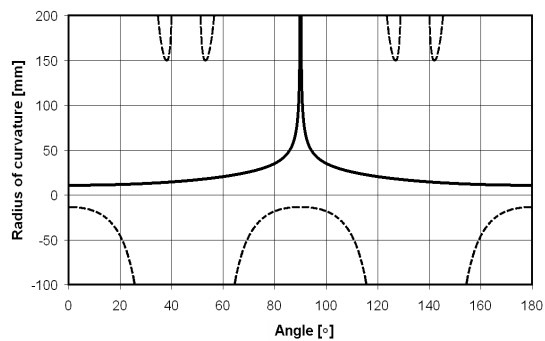

Fig. 12. Changes of curvature radii in new 2/4 mechanism: solid line - rotor, dashed line - external gear

Figure 12 shows changes of the curvature radii of both rotor and external gear. The most important minimal positive values for the convex parts of the pitch lines equal: 10.63 mm for the rotor and 150 mm

for the external gear. The satellite's pitch line radius is 6.0 mm. What's more, curvature radii of the new mechanism don't change so rapidly as in the present one (compare Fig. 7).
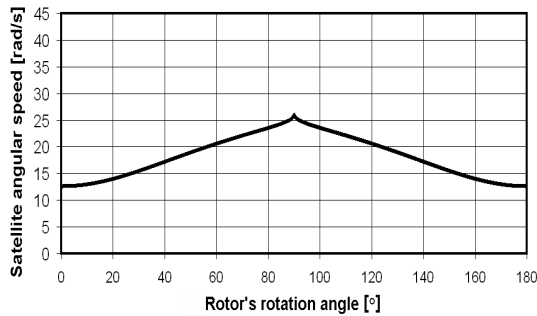

Fig. 13. Changes of the satellite's rotational speed in new 2/4 mechanism. Rotor's speed ω = 10 rad/s [10]

The satellite angular speed values dropped from 23-43 rad/s range to 13-26 rad/s. What's important, there are no sudden speed changes, similar to those shown in Fig. 8.
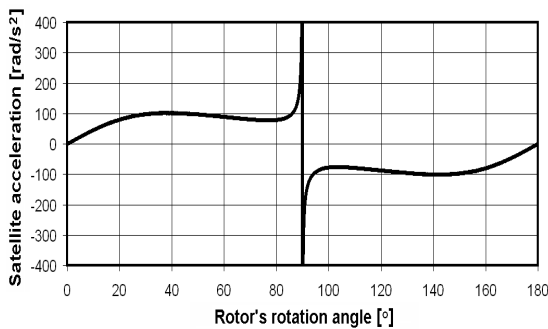

Fig. 14. Changes of the satellite's acceleration in new 2/4 mechanism. Rotor's speed ω = 10 rad/s [10]

Thanks to reduction of speed changes values of angular acceleration of the satellite are also significantly smaller. For more than 90% of the working cycle acceleration changes slowly, and doesn't exceed the range of ±105 rad/s². For every full revolution of the rotor two peak values of the acceleration occur, both reaching ±1600 rad/s². In the present 4/6 mechanism the typical acceleration range is ±175 rad/s², while number of peaks rises to four per each revolution and their value exceeds ±20 000 rad/s² (Fig. 9). Similar results were obtained for the second version of the new pump shown as b) in Fig. 11.

5. REVERSE KINEMATICS OF THE SATELLITE MACHINE

It is possible to build satellite pumps and motors in two versions. In the first one, machine's kinematics is typical: internal gear rotates while external gear remains fixed. The second version - reverse kinematics – applies rotating external gear and fixed internal gear [11, 12]. The complex satellite's motion in both machines remains similar.

The reverse kinematics has many advantages: commutation windows are much larger, reducing pump's internal pressure drop and improving it's efficiency. Thanks to high power density such a pump can be installed inside the typical electric motor, allowing to create compact and effective pumping unit (Fig. 15) [13]. The new 2/4 mechanism in the reverse kinematics version perfectly matches such a design.
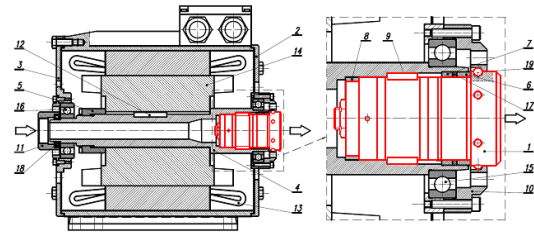

Fig. 15. Pumping unit with the reverse kinematics satellite pump (marked in red) [13]

The weight and length of the whole pumping unit is smaller than weight and length of the electric motor itself . For safety reasons it is also important that there are no external rotating parts.

6. SUMMARY

The preliminary analysis confirmed possibility of reduction of harmful phenomena occurring in the mechanism of satellite pump. Thanks to higher curvature radii of all cooperating elements, smooth pitch lines and smaller number of working cycles per each revolution reduction of the teeth wear is likely. The new calculation method is capable of creating different shapes founded on different mathematic formulas, all of them meet the required criteria.

To create fully operational pump the next step of research is necessary. Both rotor and external gear shapes need optimization. The target is reduction of the pump's flow ripple and noise emission with simultaneous maximizing of its displacement [8]. Similar modifications may be also applied in high-speed satellite motors, where the fast teeth wear may also occur.

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Biographical note

Leszek Osiecki received his M.Sc. degree in Mechanics and Machine Design from Gdańsk University of Technology, Faculty of Machine Design, in 1981. After 10 years of industrial practice (mainly in Ship Machinery Works "Hydroster" as a designer of hydraulic pumps and cylinders) he started his research work in Gdańsk University of Technology, Faculty of Mechanical Engineering, where he still works as an associate professor. In 1999 he received his PhD from Poznań University of Technology and in 2007 DSc from Gdańsk UT. His scientific interests focus on design and testing of hydraulic pumps, high pressure systems and satellite mechanisms.