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MODIFICATION OF THE SICKLE INSERT OF AN INTERNAL GEAR PUMP

Krzysztof TOWARNICKI [1✉], Algimantas DANILEVIČIUS [2], Šarūnas ŠUKEVIČIUS [2]

[1]*Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Łukasiewicza 5, 50-371 Wrocław, Poland*
[2]*Faculty of Transport Engineering, Vilnius Gediminas Technical University, Vilnius, Lithuania*

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Abstract. The reduction of the weight of high-pressure components and systems (including hydraulic) is especially important in aircraft or mobile machinery. An interesting trend that began in the first half of the 20th century in the aviation industry is the weight reduction of structures by using components made of composite materials in place of those made of conventional materials. This trend is not only not diminishing, but is actually increasing year by year. This paper investigates the effect of modifying the design of the sickle insert on the volumetric efficiency of the pump. Moreover, this work presents the replacement of the sickle insert of an internal gear pump made of bronze with plastic materials, reducing its weight by 80%. To ensure similar performance, its design was modified, increasing the pump's efficiency while additionally reducing its weight. This material substitution allows the reduction of weight, but it can adversely affect the performance of the hydraulic component, this also applies to the displacement pumps. For this reason, the design had to be changed to obtain similar operational parameters after changing the material.

Keywords: gear pump, capacity, internal gearing, sickle insert, hydraulics.

✉Corresponding author. E-mail: ***krzysztof.towarnicki@pwr.edu.pl***

1. Introduction

There are many factors to consider when designing an aircraft. One of the important factors is its mass (Galiński, 2016). One way to achieve weight reduction is by incorporating new materials, such as composites, into the hull plating of a ship. Another solution is to reduce the weight of the drive system components, this includes hydraulic systems (Lubecki et al., 2022). An important direction in the construction of hydraulic elements is the use of new materials, for example, for the bodies of pumps, valves or hydraulic cylinders. There are known research works on the use of Polyoxymethylene (POM) in the construction of the above-mentioned elements (Stryczek et al., 2014, 2017). The main goal is to minimize the mass of the element while achieving comparable operational parameters (e.g., nominal operating pressures for actuators of 30 MPa and more). The significant advantages of the hydrostatic drive include obtaining an exceptionally high power flow density in the drive system. Working pressures at the level of 35÷40 MPa are now completely normal. Power of 1 kW, at these pressures, can be obtained from a stream of working liquid with a volume flow rate of only 30÷25 cm^3/s (1.8÷1.5 dm^3/min). Due to the achievement of higher discharge pressures by internal gear pumps (Patent PL241281), their scope of application increases (Lewis & Cyndi, 2005). There are numerous structural variations of internal gear pumps, which can feature distinctive body designs (Marciniak & Stryczek, 2014) or the exclusion of a drive shaft coupling, depending on specific requirements. They have many advantages as energy sources for a number of ship components. This application offers notable benefits, including lightweight construction, high power density, adaptability to specific installation sites, energy conversion ranging from several to several dozen kW, efficient control signal flow, smooth operation, compatibility with other aircraft installations and systems, as well as resilience to atmospheric electricity discharges. The primary drawbacks include significant variability in the main parameters of the working fluid and limited durability of sealing elements. When it comes to aircraft, questions of reliability and dependability of all components and subassemblies are very important. Therefore, the impact of introducing a new material on the number of failures is being frequently studied (Karpenko, 2022). The first hydraulic systems were installed in the 1930s to drive the retractable landing gear. In the following years, the number of functions performed by hydraulic systems increased. Jet power sources for aircraft forced the use of hydraulic drives to tilt the control surfaces and mechanize the wing. The introduction of hydraulic actuators makes it easy to operate medium and large helicopters. The hydraulic drive system consists of a power source in the form of a displacement pump driven by an electric or combustion engine. The displacement pump converts mechanical energy into pressure energy in the stream of flowing liquid transported to the receivers, which in aviation technology are usually actuators. Pipeline elements are used to supply liquid between the pump and the receivers, the arrangement of which is shown below (Figure 1).

For the proper operation of the hydraulic system, various types of valves are also needed to control the direction of the flowing liquid, the flow rate directed to the receivers and the pressure in a given hydraulic line. In order to reduce their weight, valve blocks are made of aluminum alloy, while the control elements are made of steel due to their high durability. Composite materials (mainly polymers based on epoxy resins, reinforced with continuous carbon fibers) are slowly being introduced into the production of hydraulic elements, such as accumulators. The gain resulting from weight reduction is significant in this case, and the design methodology and manufacturing technology bear many analogies to the well-known pressure vessels. Another element of hydraulics where the appearance of composite materials can be observed is the production of actuators (Lubecki et al., 2023). Designs from companies such as Parker, Hanchen and Polygon are available on the market. They are characterized by varying degrees of use of these materials and, consequently, varying weight reductions – from 60 to 80% compared to conventional structures. A classic double-acting hydraulic actuator consists of a cylinder, piston, piston rod, covers and handles. The main place where composite can be used is the cylinder. However, making a cylinder of appropriate dimensions and strength is only seemingly simple. One initial challenge that may arise involves the precise design (geometry, material selection, fiber arrangement) (Mantovani et al., 2020) and accurate execution of the cylinder. Another requirement is to ensure appropriate tribological conditions when the piston and cylinder cooperate (Scholz & Kroll, 2014). This is done in two ways: making an internal steel liner – a thin-walled tube whose task is to ensure a low coefficient of friction and minimize wear in the friction pair. This eliminates the problem of dimensional tolerances by making them with the required accuracy. The second method is to apply an internal coating to the wound cylinder to ensure tightness and proper cooperation with the piston, while maintaining the required internal dimensions of the cylinder. This method allows for a greater reduction in the weight of the element. The piston rod of the actuator is a rod that carries mostly axial loads (tensile and compressive) and, to a small extent, radial loads can be made by pultrusion, while maintaining the required dimensional tolerances and surface roughness. Execution of other elements, i.e., the cover and piston made of composite materials, is economically unjustified due to the small reduction in the weight of the entire element. From the above, it can see that although the construction of the actuator itself is not too complicated, there are new challenges associated with the use of new materials. This can also be expected in other hydraulic components using new materials, in particular in the displacement pump.

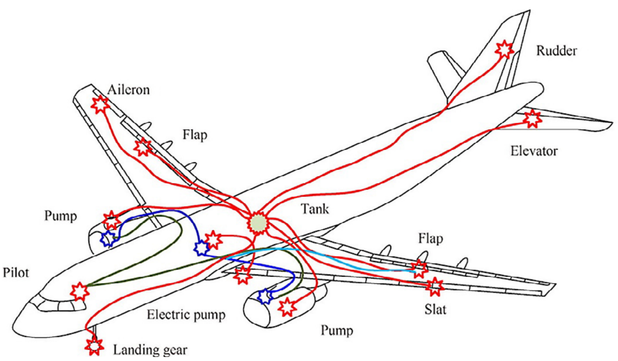

Figure 1. Distribution of aircraft hydraulic pipeline system (Gao et al., 2021)

2. Internal gear pump with a modified sickle insert

Significant development of devices with gear drives, along with hydraulic drives, has been observed for over 400 years. An intriguing aspect to explore is the examination of the key types of these machines, considering the incorporation of gearing within them and the influence of design solutions on the machine's functions and the technical parameters it meets. Gear pump developed by Johannes Kepler (1571–1630) was one of the most important hydraulic gear devices (Osiński et al., 2016). The need to build this machine was the lack of a self-priming pump, which the miners lacked. Its task was to remove water from shaft wells. It was the first valveless pump, much less troublesome than the piston pumps of the time. The inventor focused on its advantages, which allowed for diverse applications such as draining shafts and wells, removing water from ships, and pumping water in park fountains. Currently, manufactured pumps around the world operate according to this principle, which remains unchanged from that time. The gear pump today is one of the most widely used positive displacement pumps in hydraulic drive systems, it has high efficiencies, and the lost power is converted into heat (Osiński et al., 2018). There are many design variations depending on the application (Świtalski, 2009). Internal gear pumps, commonly used in hydraulic drives, appeared only in the second half of the 19th century. As with an external gear pump, one wheel acts as the driving wheel. An external drive is connected to the axle of this wheel. Within the rotor of the driving wheel, there is a rotating internally geared drive wheel, also referred to as a gear ring in some instances. The liquid is transferred between the teeth, and the tight separation of the suction space from the pressure space is achieved using an additional element called a sickle insert. It owes its name to its characteristic appearance. The surface of this insert works closely together with the surface of the tops of the gears. Pumps of this type are designed to transport all types of liquids. Internal gear pumps have many advantages over external gear pumps. These include lower noise emissions, a lower coefficient of irregular performance, and a more compact design (Antoniak et al., 2019; Osiński et al., 2021). This is due to the smooth interaction of the inner-toothed wheel and the outer-toothed wheel. Moreover, they are characterized by much lower losses when filling the suction space while sucking liquid. The above advantages result in the desire to increase the discharge pressures of this type of pump (Novak et al., 2023; Rundo, 2017). Pumping liquids at higher pressure requires achieving high internal tightness, which is measured by volumetric efficiency. To obtain greater tightness when the pressure increases, it is possible to introduce a partial incision in the classic sickle insert. As a result of such modification, two flexible tongues are obtained, which, when subjected to pressure from the side of the discharge space, reduce the clearance between the insert race and the tops of the gear wheel. Below is a view of the introduced solution (Figure 2).

The radial compensation presented above increases the volumetric efficiency of the hydraulic machine by reducing internal leakage as the discharge pressure increases. Photos of sickle inserts without the modification presented below, made of B101 bronze (Figure 3) and POM plastic (Figure 4). Inserts made according to patent no. P.431145 made of POM and PA, with a cut of ¼ of the length of the insert (Figure 5, Figure 6), called the first modification (modification of the first type) and with a cut of ½ of the length of the insert (Figure 7, Figure 8), called the second modification (modification of the second type).

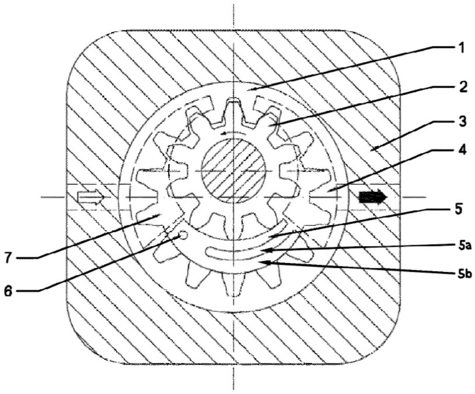

Figure 2. Cross-section of the pump with a modified sickle insert: 1 – toothed rim, 2 – gear wheel, 3 – pump body, 4 – discharge space, 5 – sickle insert, 5a – bay inside the sickle insert, 5b – elastic tongue of the sickle insert, 6 – locating pin, 7 – suction space (Towarnicki et al., 2021)

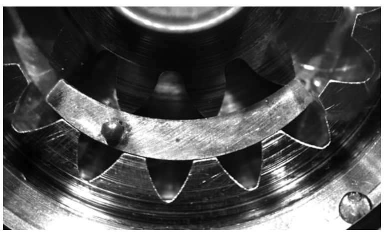

Figure 3. View of the insert made of bronze B101 – without modification, n = 1000 rpm (source: own work)

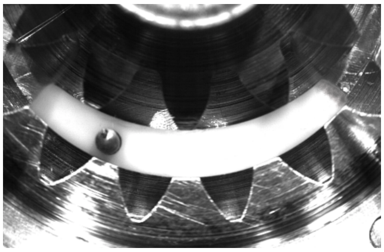

Figure 4. View of the insert made of POM – without modification, n = 1000 rpm (source: own work)

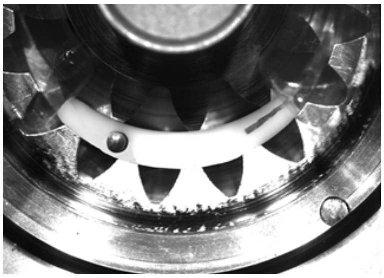

Figure 5. View of the modified insert made of POM – first modification, n = 1000 rpm (source: Towarnicki et al., 2023)

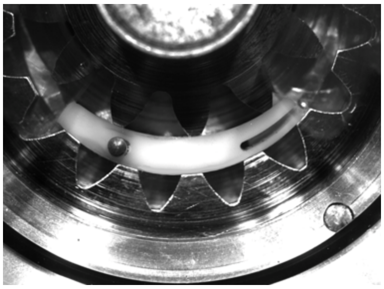

Figure 6. View of the modified insert made of PA – first modification, n = 1000 rpm (source: Towarnicki et al., 2023)

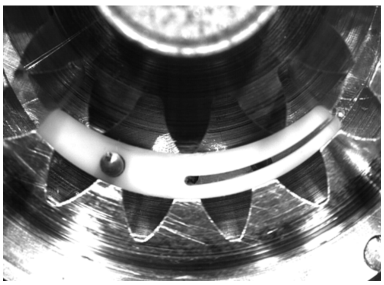

Figure 7. View of the modified insert made of POM – second modification, n = 1000 rpm (source: Towarnicki et al., 2023)

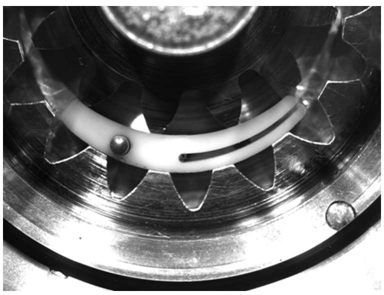

Figure 8. View of the modified insert made of PA – second modification, n = 1000 rpm (source: Towarnicki et al., 2019)

The photos show an internal gear pump with various types of inserts, starting with the classic design made of the typical material of bronze. Further stages of work include using plastic to make a sickle insert, and then making type I and II modifications from various materials. The modification is based on the use of the deformation of the material under the influence of pressure acting on the surface obtained as a result of making the cannal. The longer the canal, the greater the force that causes the elastic tongue of the insert to press against the tops of the teeth, achieving greater tightness. This increases the volumetric efficiency of the pump, but too much pressure causes increased friction, which reduces the mechanical efficiency. Making the appropriate length of the canal incision is very important, developing the optimal length will be the next direction of work on the presented solution. During the experimental studies on a specially designed test stand, the effect of the introduced design change on the pump insert was analyzed, as well as the effect of introducing a new insert material on the change in pump performance and insert weight.

3. The impact of a design change in the pump insert and a change in material on the efficiency and weight reduction of the sickle insert

Measurements of the change in pump efficiency with increasing discharge pressure were made on the measuring station shown below (Figure 9).

The tested pump 1 was installed in the test stand shown in Figure 9. To ensure appropriate suction conditions of the tested pump, feed pump 15 also operated in

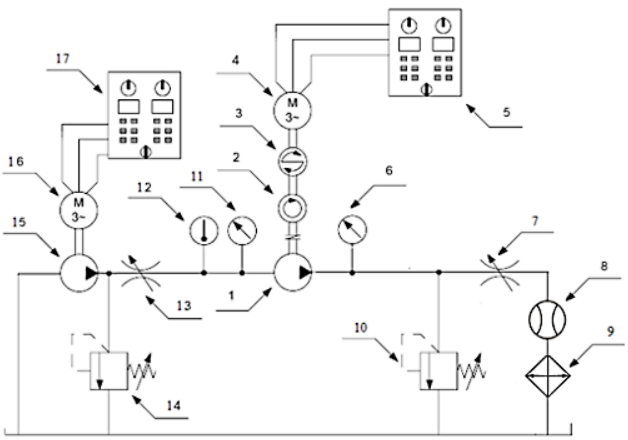

Figure 9. Hydraulic diagram of test system. 1 – tested gear pump, 2 – tachometer, 3 – torque meter, 4 – electric motor, 5 – control cabinet, 6 – pressure transducer, 7 – throttle valve, 8 – flowmeter, 9 – cooler, 10 – safety valve, 11 – pressure transducer, 12 – thermometer, 13 – throttle valve on feed pump discharge line, 14 – safety valve on feed pump discharge line, 15 – feed pump, 16 – electric motor driving feed pump, 17 – control cabinet of electric motor driving feed pump (source: Towarnicki et al., 2023)

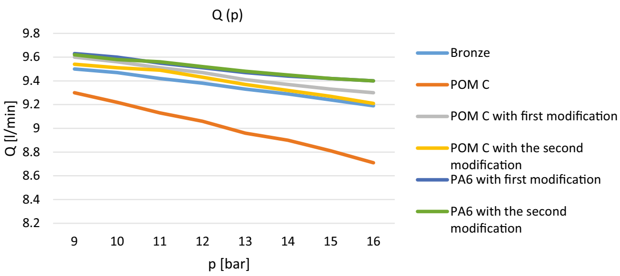

Figure 10. Characteristics of the change in pump performance depending on the change in pump discharge pressure for various materials and with type I and II modifications, n = 1000 rpm

the system. Both pumps were driven by electric motors in which it was possible to change the rotational speed on the shaft. The discharge pressure in the discharge port of the tested pump was changed using an adjustable throttle valve 7. The temperature of the working liquid was stabilized using a cooler 9. The system was protected against overload by save valves 14 and 10. Throughout the testing process, the following parameters were measured and documented: discharge pressure of the tested pump (pressure transducer 6), flow rate generated by the tested pump (flowmeter 8), temperature of the working liquid (thermometer 12), rotational speed and torque on the shaft of the tested pump (tachometer 2 and torque meter 3). During the tests, the safety valve remained closed throughout the entire range of tested pressures.

The measurement results presented below illustrate the variation in pump efficiency as the discharge pressure is altered, comparing unmodified inserts with modifications of type I and II (Figure 10).

During the tests, the changes in pump efficiency depending on the discharge pressure were determined, depending on the structure of the modified sickle insert and the material from which it was made.

The following materials were used for research:

- POM C plastic (natural white);
- PA6 plastic;
- Bronze B101.

After performing the measurements, the mass of the made sickle inserts was measured and compared with the mass of a typical sickle insert made of bronze according to the following formula:

$$\eta_m = \frac{m_{wb} - m_{wt}}{m_{wb}} \cdot 100\%, \quad (1)$$

where: m_{wb} – mass of the sickle insert made of bronze (typical insert), m_{wt} – mass of the sickle insert made of plastic (modified insert).

To measure the mass of the sickle inserts, a RADWAG Model: PS 600.X2 scale was used with a mass measurement accuracy of d = 0.001 [g]. Below is a table (Table 1) with the measurement results.

The introduction of plastic to make the sickle insert instead of the typical bronze resulted in a significant weight

Table 1. Weight comparison of sickle inserts

Type of insert	Mass [g]	η_m [%]
Bronze B 101	26.157	0
POM C	4.144	84.2
POM C with first modification	3.368	87.1
POM C with the second modification	2.694	89.7
PA6 with first modification	2.772	89.4
PA6 with the second modification	2.64	89.9

reduction of over 80%. The introduction of modifications to increase the volumetric efficiency of the pump allowed us to obtain another few percent. According to the information obtained, the introduction of new materials for the construction of hydraulic components is justified due to the reduction of their weight. A pump with a unit capacity of 10.9 cm^3/rev was used in the tests. Pump weight was 3.18 kg. Nominal pump operating pressure was 25 MPa. To be able to take photos while the pump is running, the board was made of PC. For this reason, the pump must operate as shown in Figure 10. The weight of the bronze inserts is approximately 0.8% of the pump weight. When the insert is assembled from the components that are applicable, the mass in the inserts to the mass of the pump is approximately 0.08%. This is a corollary, but the work presented has identified on the inserts that there is not enough data about the material that comes from the pump component assembly. Taking into account the remaining elements, they should be removed.

4. Conclusions

In recent times, there has been notable progress and extensive utilization of hydraulic elements and systems, notably focusing on the trend of downsizing. This trend entails reducing the dimensions or weight of hydraulic elements while preserving their current operational parameters, including nominal pressures, efficiency, and resistance to operating conditions. This is especially important in aviation applications. Due to the growing share of plastics in the production of elements of hydraulic drive systems and the use of new light and high-strength composite materials, the sickle insert was modified from materials with low processing costs. By making the sickle insert from plastic compared to the bronze insert, a weight reduction of over 80% was achieved. To ensure an increase in the volumetric efficiency of the pump, modifications of type I and II were introduced, which allowed to increase the efficiency of the pump and additionally reduce the weight of the insert. The introduced solution allow for the future construction of a hydraulic receiver on which a displacement pump with a drive motor and a set of valves will be mounted. The introduction of new materials with a much lower weight for the production of hydraulic elements allow for the modernization of the existing hydraulic drive system of aircraft. Systems with a central power supply and control system connected to receivers via an extensive pipeline system are mainly used. The flow of liquid through pipeline elements is associated with pulsatile flow resulting from the kinematics of pump operation, activation of valve control elements and vibration of pipes, which may cause cracking of pipeline walls or supports. The extensive pipeline system has considerable weight and increases the response time of the receiver. The introduction of lightweight receivers made of composite materials together with a lightweight drive and control unit allow the replacement of an extended pipeline system, maintaining a similar mass and shortening the receiver's response time.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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