CONTRIBUTION TO THE RESEARCH AND FAILURE ANALYSIS OF THE GEROLER HYDRAULIC MOTOR

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This paper analyses the key aspects of the operation of geroler hydraulic motors, widely used rotary hydraulic motors. The focus is on understanding their performance, efficiency and durability in different working conditions. The work includes a theoretical analysis of the principles of work, supported by modelling. Furthermore, experimental tests conducted to characterize the motors in terms of torque, speed, flow and efficiency are considered. Special attention is paid to the analysis of factors that influence the wear of internal components. The results of the analysis provide deeper insight into the behaviour of geroler hydraulic motors, identify areas for potential improvements in design and application and for optimizing their operation and extending their service life in various industrial and mobile applications. In conclusion, the work contributes to a better understanding of hydraulic motors, which is crucial for engineers and technicians involved in the design, application and maintenance of hydraulic systems.

Keywords:
hydraulic motors,
orbital motor,
geroler,
fault analysis,.
reconstruction

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1 Introduction

Hydraulic components that are used to convert energy are motors and pumps. Hydraulic pumps convert mechanical energy into hydraulic energy, while hydraulic motors convert hydraulic energy into mechanical energy. Hydraulic motors falling into the group of executive elements. The conversion of hydraulic energy into mechanical energy is achieved by the action of the fluid pressure force on the working element of the motor.

The mechanical energy obtained by the operation of hydraulic motors is manifested in the form of rotary or linear (translational) motion [1]. The principle of operation of motors is achieved by increasing and decreasing the volumes filled with fluid, which in the case of motors is associated with high pressure on the suction side and lower pressure on the discharge side. For this reason, these devices are called positive displacement motors, or pumps.

2 Rotary hydraulic motors

Rotary hydraulic motors are motors whose output element moves in a rotary manner, without any limitation of angle or speed. According to the speed of rotation, they can be divided into slow-speed (up to 1000 rpm) and high-speed (over 1000 rpm) motors [2]. Since the power of the motor is equal to the product of the torque and the speed of rotation:

$$P_M = M \cdot \omega \tag{1}$$

for the same hydraulic motor power, the torque must be increased with a decrease in speed or vice versa. That's why slow motors often have a high torque.

Hydraulic motors can be variable and fixed displacement. According to the design and the possibility of the direction of rotation, the motors can be represents as motor that always rotates in the same direction, or aa motor that has the ability to rotate in both directions (reversible), which is achieved by exchanging the sides of the fluid inlet and outlet [3]. Examples of symbols for the configuration of rotary motors are given in Figure 1. The flow of the working fluid through the hydraulic motor is equal to:

$$Q = \eta_V \cdot n \cdot V \tag{2}$$

where:

n - number of revolutions per unit of time,
V - theoretical working volume,
η_V - volumetric efficiency of a hydraulic motor.

The power of the hydraulic motor is:

$$P_M = \eta_M \cdot n \cdot V \cdot \Delta p = \eta_M \cdot Q \cdot \Delta p \tag{3}$$

where:

Δp - pressure drop in the hydraulic motor,
η_M - total efficiency of a hydraulic motor, product of volumetric η_V and mechanical η_m efficiency ($\eta_M = \eta_V \cdot \eta_m$).

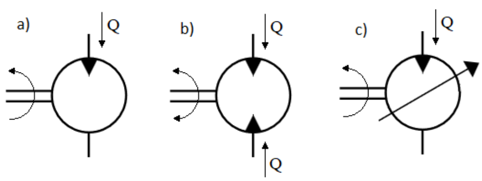


Figure 1: Hydraulic motors configuration symbols.

3 Orbital hydraulic motor

The orbital hydraulic motor developed from studies on rotary piston machines, which are volume displacement machines with chambers between rotor and stator (also known as "star" and "ring"). The epitrochoidal profile is used for the star's profile, while the ring's profile is the envelope, using the same design architecture as the Wankel engine. The previously mentioned design, when applied to hydrostatic machines, leads to increased power density and smaller dimensions of hydraulic motors. The forms of the star and ring are continually changing, allowing trochoidal and hypotrochoidal profiles for the star and encompassing curves for the ring. The key advantage of this design is that it uses fewer components and sealed elements than a traditional gear pump and motors.

Orbital hydraulic motors or in practice known as gerotor motors with a gear ring are mainly used as slow-speed motors with high torque. Compared to other motors with the same torque, they are significantly smaller in size and weight. The advantages of these motors are: simple and compact construction, favourable speed and torque ratios, precise fluid flow distribution, simple change of direction of rotation, relatively low noise production, easy starting under load, high radial and axial load capacity, resistance to external influences, and high mechanical strength and long service life under high pressures [4], [5]. Due to their good working capabilities, orbital motors find their application in industry, mostly in construction with heavy machinery and agriculture with various attached machines.

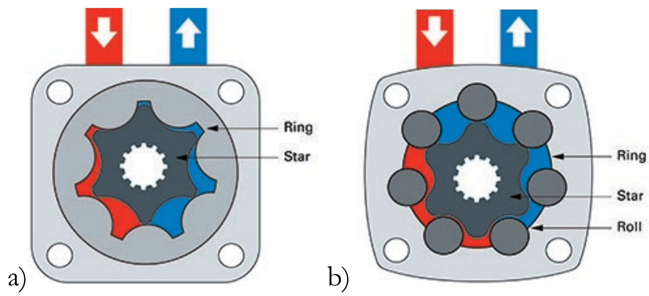


Figure 2: Working principle and basic parts of gerotor (a) and geroler (b) hydraulic motor.

The construction of orbital motors is very simple, the main working element is a star-shaped gear pair composed of one gear with internal teeth that represents the stator and one gear with external teeth that rotates, where the rotor gear always has one tooth less than the stator gear. A decade after the appearance of the first orbital motor, a new concept of the orbital motors was formed and its characteristics were significantly improved. There are two types of orbital hydraulic motors: original orbital hydraulic motor – gerotor type and an improved model of the original - a roller gerotor type (geroler) hydraulic motor. Both variants are shown in Figure 2.

Within this type of motor design, the rotor assembly consists of a stationary ring called the stator and a moving, planetary gear, the rotor. The stator is machined into a star shape within a metal motor housing that houses the rotor, the star-shaped gear, and its walls are used to form fluid chambers to propel the motor. As oil enters the stator-rotor assembly, passing through zones of high to low pressure, it causes the rotor to rotate within the stator and convert the fluid force into torque. Each cavity between adjacent teeth of the moving gear, enclosed by the inner surface between the teeth of the stationary gear, represents a fluid chamber. During operation, these fluid chambers change shape and volume. If these chambers are properly connected to the inlet and outlet ports, during the dynamic change in the volume of the chambers, fluid will gradually be transferred from the inlet to the outlet, while at the same time transmitting torque and power to the shaft [6]. In order to ensure the correct operation of such a hydraulic motor, the openings on the distributor must be correctly positioned in relation to the fluid chambers, otherwise the may malfunction. The distributor can be in the form of a spool or in the form of a disc.

Although the gerotor design can meet the needs of various applications and is an economical option, it has larger clearance tolerances. These clearances allow more oil to pass from high to low pressure than necessary, resulting in greater slip and less torque conversion. The rotor and stator moving relative to each other within a gerotor design can cause them to wear over time, which is why for medium to heavy duty applications at high pressures that require a more robust option, that is a roller gerotor design.

The roller gerotor (geroler) version of the orbital motor functions in the same way as a gerotor motor, i.e. the way the fluid drives the rotor inside the stator, converting hydraulic power into torque [7]. The stator of a geroler motor is constructed slightly differently and instead of using the entire stator wall to form the pressure chambers, roller inserts are also used. It is these roller inserts that eliminate the gaps found in the gerotor design, which leads to a smaller clearance tolerances between the stator and rotor, allowing less oil flow and therefore more torque. These rollers also act as a roller bearing, reducing friction when the rotor rotates, increasing mechanical efficiency and reducing wear in hydraulic systems using low-viscosity fluids.

Motors with this design are more robust and perform better, especially at low speeds, however, there is an additional cost associated with these benefits. Depending on the position of the stator and rotating elements, several types of geroler hydraulic motors have been developed as shown in the Figure 3.

Figure 3: Types of geroler hydraulic motors.

3.1 Geometry of orbit hydraulic motor

In the gerotor design process, two types of curves are used: epicycloids and hypocycloids. These forms of tooting are commonly used due to their excellent meshing properties, endurance to shock load, low noise, etc. Figure 4 illustrates uncorrected and corrected gear profiles [8].

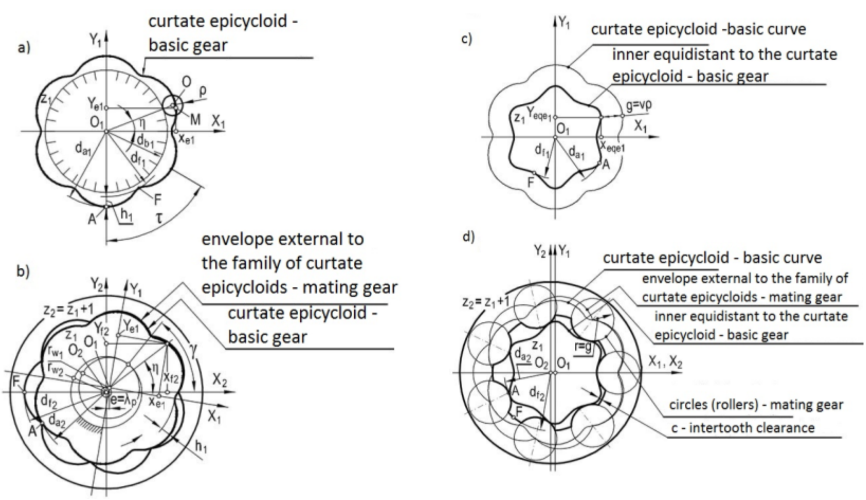


Figure 4: Designing epicycloid gears: a), b) uncorrected gears: internal and external; c), d) corrected gears: external and internal [8].

Figures 4a and 4b present the principles of designing a system of uncorrected epicycloid gears. In Figure 4 the following parameters are shown: z_1 - number of teeth identical to the number of the epicycloid's or hypocycloid's arcs present in the entire closed cycloidal curve, m - a module which in accordance with the principle of constructing cycloidal curves is equal to the diameter of the moving wheel $m = 2\rho$, λ - tooth depth factor $(\lambda = OM/\rho)$, η- the angle of the cycloidal curve, v - correction coefficient of the cycloidal profile, g - shift of the profile ($g = v\rho$), b - tooth width.

Using these variables, the geometry and kinematics of cycloidal gears may be characterized, as well as machine hydraulic parameters such as delivery and delivery pulsation. It shows the adaptability of the selected parameter system and its utility throughout the design process. The parametric equations describing the family of wheels with an epicycloid outline have the following form:

$$x_{f2} = \frac{m}{2}\left[\lambda cos\gamma + (z_1 + 1)cos\frac{z_1\eta-\gamma}{z_1} - \lambda cos\frac{(z_1+1)z_1\eta-\gamma}{z_1}\right] \tag{4}$$

$$y_{f2} = \frac{m}{2}\left[\lambda sin\gamma + (z_1 + 1)sin\frac{z_1\eta-\gamma}{z_1} - \lambda sin\frac{(z_1+1)z_1\eta-\gamma}{z_1}\right] \tag{5}$$

Equations (1) should be supplemented with a condition of the envelope which connects angle of rotation γ of the basic wheel relative to the collaborating wheel with angle of the epicycloid η:

$$d_{a2} = 2(z_1\rho + \rho - \lambda\rho + \lambda\rho) = m(z_1 + 1) \tag{6}$$

$$d_{f2} = 2(z_1\rho + \rho + \lambda\rho + \lambda\rho) = m(z_1 + 1 + 2\lambda) \tag{7}$$

Figure 4b shows that formulas for finding the contour of internal gears are difficult to apply directly. The teeth of both gears have incorrect proportions between the head and foot, resulting in excessive contact pressures. Additionally, creating an internal gear with a complex design is difficult and costly. In such a situation, the gears and gear systems are corrected [9]. First, basic external gear is corrected.

Figure 4c illustrates that the correction involves forming an internal equidistant relative to the curate epicycloid and shifting it by $g = \nu\,\varrho$. The parametric equations that describe the equidistant have the following form:

$$x_{eqe1} = \frac{m}{2}\left[(z_1 + 1)cos\eta - \lambda cos(z_1 + 1)\eta - \nu\frac{cos\eta - \lambda cos(z_1+1)\eta}{\sqrt{1 - 2\lambda cosz_1\eta + \lambda^2}}\right] \quad (8)$$

$$y_{eqe1} = \frac{m}{2}\left[(z_1 + 1)sin\eta - \lambda sin(z_1 + 1)\eta - \nu\frac{sin\eta - \lambda sin(z_1+1)\eta}{\sqrt{1 - 2\lambda sinz_1\eta + \lambda^2}}\right] \quad (9)$$

The formulas for calculating the outside diameter and the root diameter in the corrected gear are:

$$d_{a1} = 2(z_1\rho + \rho + \lambda\rho - g) = m(z_1 + 1 + \lambda - \nu) \quad (10)$$

$$d_{f1} = 2(z_1\rho + \rho - \lambda\rho - g) = m(z_1 + 1 - \lambda - \nu) \quad (11)$$

Next, the collaborating internal gear is corrected. As shown in Figure 4d, circles of a radius equal to the equidistant shift of $r = g$ are drawn from the vertices of the envelope, and then those circles are connected to each other by arcs of the r_{f2} radius circle, which rotates from the centre of the collaborating gear O_2. The characteristic diameters of the collaborating gear after correction are derived from the formulas:

$$d_{a2} = 2(z_1\rho + \rho - \lambda\rho - g + \lambda\rho) = m(z_1 + 1 - \nu) \quad (12)$$

$$d_{f2} = 2(z_1\rho + \rho + \lambda\rho - g + \lambda\rho) = m(z_1 + 1 + 2\lambda - \nu) \quad (13)$$

It can be following defined:

- the formulas for calculating the gear outlines are simple and easy to use in the design process,
- the teeth and gears are proportional,
- manufacturing of the gears is much simpler and cheaper compared to the uncorrected gears, particularly in the case of the collaborating internal gear.

3.2 Hydraulics motor delivery and pulsation

Using the characteristic parameters of the teeth and the mesh, it is possible to make formulas for calculating of the hydraulic parameters of the machines.

The delivery of gerotor machines is determined by the formula:

$$\frac{q_{st}}{\pi bm} = \frac{1}{4}\left[(z_1 + 1 + \lambda - \nu)^2 - \frac{z_1}{z_1+1}(z_1 + 1 - \nu)^2 + z_1\lambda^2\right] \tag{14}$$

and the pulsation of delivery from the formula: $\delta = f(z, \lambda, \nu)$.

In the case of orbital machines, which, by principle, work only as motors, the delivery is determined by the formula:

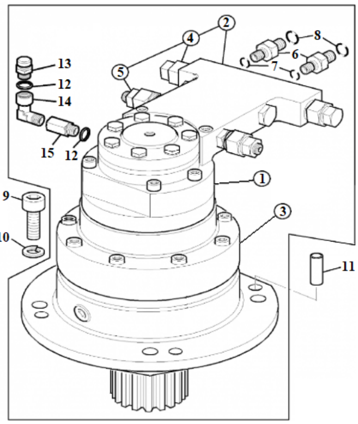
$$q_{or} = z_2 q_{st} \tag{15}$$

4 Model and analysis of geroler hydraulic motor

Geroler hydraulic motors come in many types and versions. In order to be able to show all the elements, CAD model of the geroler hydraulic motor is created. For the analysis is used is used hydraulic motor installed in the excavator JCB mini backhoe (Figure 5), where in the assembly with the valve block and the planetary gear it served as the rotation drive of the upper part of the hydraulic excavator. Hydraulic motor has newt characteristics: volume: 51.5 cm^3, maximum speed: 775 rpm, maximum torque: 100 Nm to 130 Nm, maximum power: 8.2 kW to 9.7 kW, maximum flow: 80 l/min, maximum oil pressure: 140 bar to 175 bar.

Figure 5 shows a CAD model of a hydraulic motor housing. On a hydraulic motor, inside the oil inlet and outlet openings there is a thread whose type and size also determines the type of coupling. Inside the housing walls there are openings and channels through which oil is supplied and discharged under pressure to the orbital part of the motor. Housings are generally symmetrical in structure and made of hard steel resistant to many external influences. Between all parts of the housing (body and covers) there are seals that enable complete sealing and prevent fluid flow at very high pressures.

Figure 6. shows a model of the stator: before inserting the rollers and with the rollers. This parts, together with the rotor, forms the orbital part of the motor. The inner part of the stator is made to a size and shape that depend on the dimensions and shape of the rotor. Like the interior of the stator, the rollers are made by fine machining so that the friction between the stator and the rotor is completely eliminated or reduced to a minimum.



(1) Geroler hydraulic motor
(2) Valve block
(3) Planetary transmission
(4) Flow valve
(5) Safety valve
(6) Hose fittings
(7) (8) O-ring seal
(9) (10) Screw
(11) Wedge
(12) Sealing
(13) Breather
(15) (16) Pipe connections

Figure 5: Geroler hydraulic motor with planetary reducer [12].

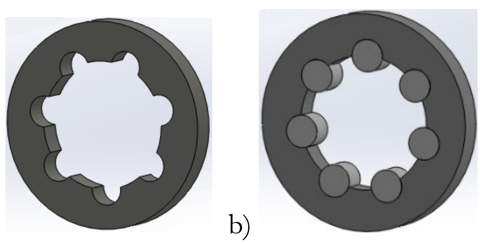
a)  b)

Figure 6: Stator model of geroler hydrauli motor without and with roller elements.

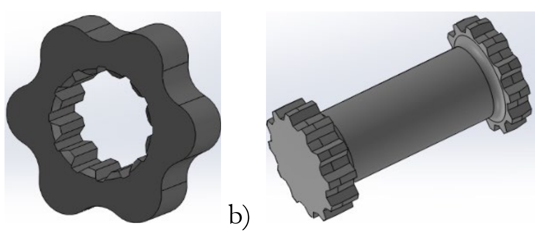
a)  b)

Figure 7: Rotor (star gear) and shaft model.

In Figure 7a, model of the drive gear in the form of an epitrochoid star is shown. This gear represents the rotor of the motor, which, together with the inner shape of the stator, forms fluid chambers. The rotor is made of hardened steel and subjected to thermal and chemical finishing treatments such as hardening and cementation. In Figure 7b, a model of a toothed/splined shaft is presented, which is used to transmit movement and torque from the rotor to the output shaft. The toothed part of this shaft is bevelled at a certain angle because one side of the shaft that is connected to the rotor performs both rotary and planetary motion, while the side that is connected to the spool valve performs only rotary motion.

5 Analysis of geroler hydraulic motor

During work and before the hydraulic motors stopped working completely, it was noticed that the motor was running rough, the rotation speed was reduced. The overhaul was done after the motor stopped working completely and upon removing the upper motor cover, a defect was found. In Figure 8. the rotor of the hydraulic motor is shown, where one can notice an almost uniform way of cracking and damage on the individual segments of the rotor and severe wear of the internal teeth through which the rotational movement is transmitted to the toothed shaft. A visual inspection concluded that the motor stator and the rollers inside the stator were not damaged.

a) b)

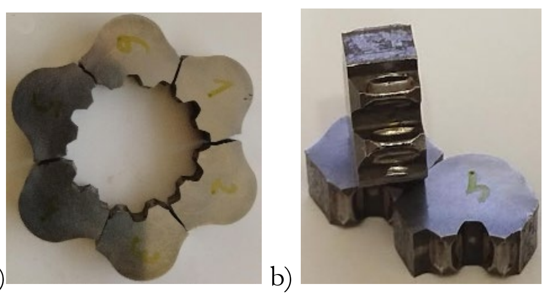


Figure 8: Motor rotor condition: a) damage; b) signs of wear on the internal teeth.

Furthermore, damage was observed to the teeth of the toothed shaft that enter the assembly with the motor rotor. The condition of the teeth on the shaft is shown in Figure 9.

In order to restore the hydraulic motor to working condition, it is necessary to manufacture a new rotor and shaft. Manufacturing the new shaft was not very demanding because most of the dimensions could be determined based on the current condition and considering that the teeth on both sides of the shaft are identical. While the reconstruction of the rotor was quite demanding due to the decomposed condition of the rotor. Based on precise measurements of all rotor segments, the inner stator ring and the rollers on which the rotor moves, a rotor model was manufactured. According to model and designed model in CAD software, a new rotor was manufactured by machining (Figure 10a).

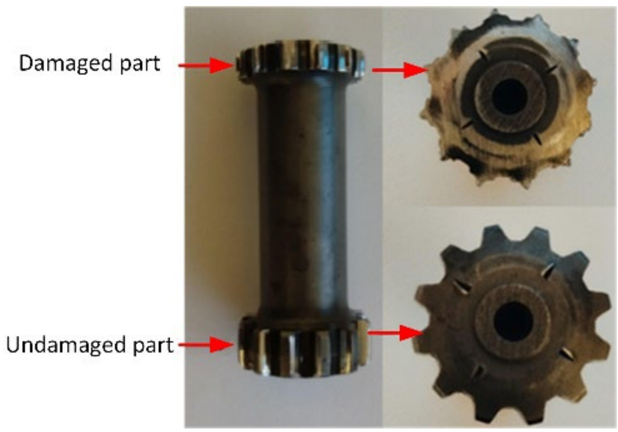


Figure 9: The condition of the teeth on the shaft.

The hydraulic motor was then assembled and put into operation. During the operation of the motor, a major error was found, namely, the motor did not rotate properly. When the motor gave rotational motion in the counterclockwise direction, i.e. when the turret of the excavator turned to the left, the rotation torque was too great, and the rotation happened too fast.

After the analysis, it was concluded that there was an error during the manufacturing of the rotor. The inner teeth of the rotor on which the shaft was supported were not correctly arranged in relation to the outer shape of the rotor. Due to that, a new rotor was made. In order for the hydraulic motor to work properly, Φ must be equal to 0, i.e. the axis of the inner tooth must coincide with the axis of the star arm of the rotor.

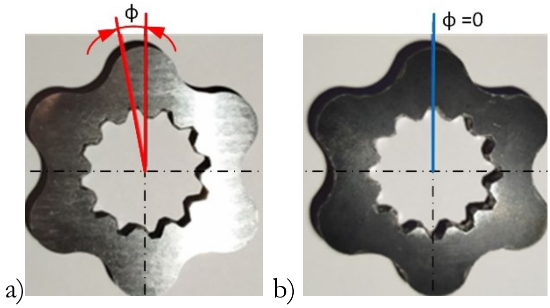


Figure 10: Comparison new rotors: a) rotor with error, b) rotor without fault.

After replacing the faulty rotor with a new rotor, the hydraulic motor was put into trial operation to check for any errors. During the trial operation, the hydraulic motor performed all its functions correctly, rotated at normal operating speed and provided the required torque equally on both sides.

However, the grinding sound during rotation of the turret was still present, i.e. the cause that led to the motor failure had not been eliminated. Further analysis of the entire upper part drive assembly concluded that it was necessary to replace the tapered bearings (Figure 11.) located in the planetary gear. At first glance, the bearings were not particularly damaged, but during operation under load, the high torque caused a small instability in the bearings to lead to large vibrations inside the orbital hydraulic motor. It was precisely this constant exposure of the hydraulic motor to these vibrations that led to the complete failure of the rotor and the cessation of operation of the hydraulic motor.

Figure 11: Tapered roller bearing.

6 Conclusion

The aim of this paper was to analyse the hydraulic motor used in hydraulic systems. It should be emphasized that hydraulic motors in hydraulics play a very important role in converting energy. Choosing the right type of hydraulic motor is a very important factor for hydraulic systems. With the correct choice and installation of the hydraulic motor, the output torque and the number of revolutions can be properly controlled on the external actuators, which as such are used for lifting and lowering loads or for moving large masses. If the hydraulic system needs to perform mechanical work in the form of large torques at low rotation speeds, then orbital hydraulic motors are used. The orbital hydraulic motor of the geroler type represents an improved version of the original orbital motors. The created CAD model in work of the orbital hydraulic motor shows its components and assembly, the connection between individual components, and as such the model was used as a basis for reengineering and subsequent production of the damaged parts of the hydraulic motor. The aim of the paper was to analyse an orbital motor during its work to show the great importance of synchronizing all working elements of the motor. Given that if synchronization is not performed according to, it can lead to damage and permanent deformation of individual parts of the hydraulic motor.

Particular attention must be paid to their mutual compatibility during manufacture and assembly, because even very small deviations can lead to improper operation of the motor. Geroler hydraulic motors are ideal for applications that require high torque and low speed. It should be emphasized that their reliability, compactness and efficiency make them indispensable in a wide range of industrial and mobile applications.

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