APK – A Pneumatic Kaplan Blade Adjustment System for Oil-Free Hydropower Applications

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Kaplan turbines play a key role in low-head hydropower generation, where high efficiency is required over a wide range of operating conditions. Conventional oil-based blade actuation systems, however, involve environmental risks associated with oil leakage, as well as complex auxiliary systems and maintenance. This paper presents APK (Azionamento Pneumatico Kaplan – Pneumatic Kaplan Blade Adjustment System), a patented solution that eliminates oil from the blade actuation system while maintaining reliable and precise blade adjustment. The system combines a ball-screw mechanism for blade displacement with a pneumatic motor integrated into the turbine shaft. Compressed air is supplied through a rotating joint, enabling continuous blade adjustment during operation, while a non-contact sensing system provides accurate blade-position monitoring. A dedicated test bench was developed to assess actuation performance, force transmission, and positioning reliability. The experimental results demonstrate stable and repeatable operation, confirming the feasibility of pneumatic blade actuation as a sustainable alternative to conventional hydraulic systems for Kaplan turbines.

Introduction

The conventional blade actuation system consists of a servomotor, the corresponding oil chambers, oil supply channels, a rotary joint, and the adjustment mechanism, comprising the actuating shaft, crosshead, connecting rod, and lever connected to the blade. The presence of several components containing or conveying pressurized oil makes the system potentially susceptible to fluid leakage and seepage.

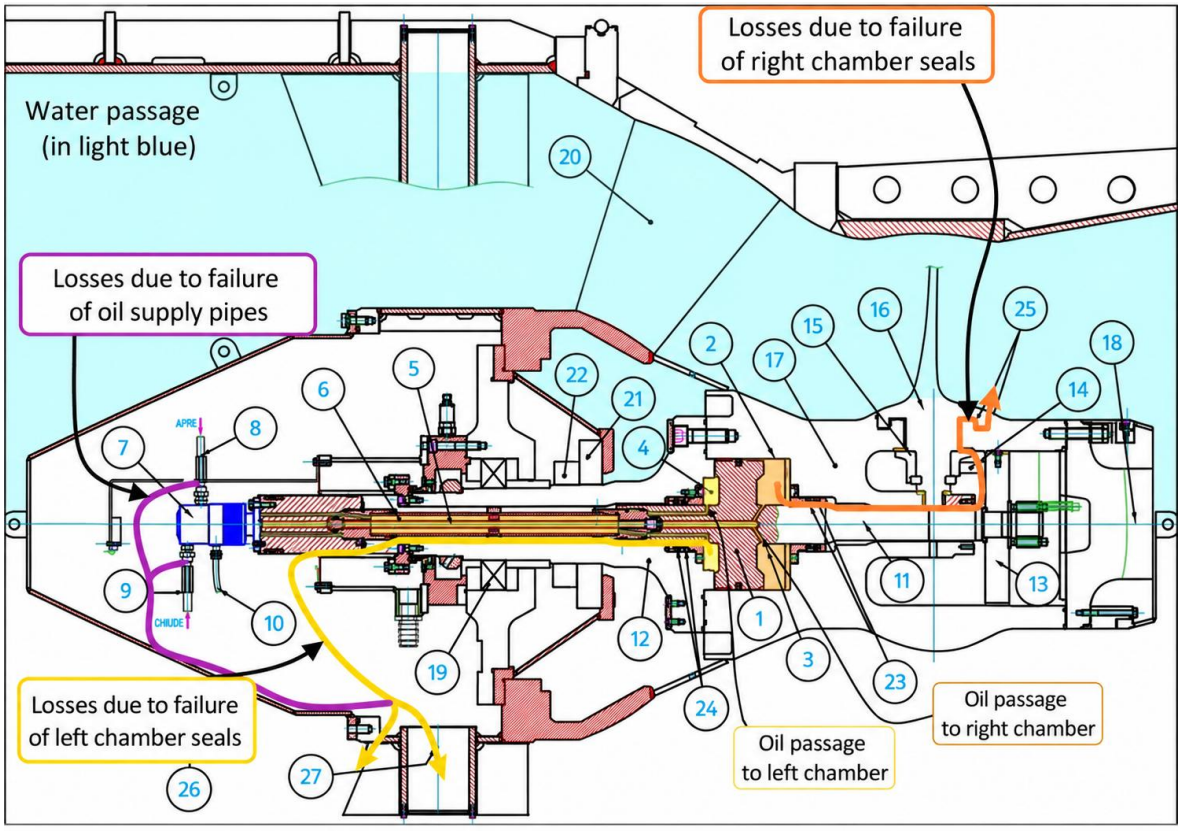


Fig. 1. Illustration of the potential oil leakage paths in an axial Kaplan turbine. The water and oil flow paths are also highlighted.

The main potential leakage paths are associated with the hydraulic seals located around the servomotor cylinder. In particular, damage to the seal corresponding to the right-hand chamber may cause oil to flow through the clearance between the actuating shaft and the hub, resulting in the subsequent accumulation of fluid inside the hub itself. Depending on the extent of the leakage and the amount of oil accumulated, the phenomenon may develop to the point of causing leakage at the interface between the blade and the hub.
A second potential leakage path is associated with the seal of the left-hand chamber of the servomotor. In the event of seal failure, the oil may flow through the clearances and cavities between the actuating shaft and the non-drive-end shaft, subsequently reaching the surrounding metal structures. From this point, the fluid may follow different paths: it may penetrate through the porosities present in the welds and come directly into contact with the water flow or, alternatively, be conveyed through a dedicated pipe and accumulate on the power plant floor.
Further leakage may result from damage to the oil supply pipes. In this case, the leaked fluid may reach the structural components surrounding the machine and follow paths similar to those associated with leakage from the left-hand servomotor chamber. The rotary joint also represents a potential leakage point. In this case, however, any internal leakage is collected through a dedicated drainage channel and subsequently conveyed to a collection tank, thereby limiting its dispersion within the power plant.
Among the different leakage mechanisms investigated, particular attention must be paid to those that may result in the direct entry of oil into the water flow, as they represent a potential source of contamination of the rivers and streams in which the turbines are installed. Since permanent sealing of a hydraulic oil circuit cannot be guaranteed over the entire service life of the system, alternative solutions capable of eliminating oil from the blade actuation system must therefore be investigated.
This requirement has led to the study of different OIL-FREE blade actuation systems, based on actuation principles other than the conventional hydraulic system. The following sections therefore examine four possible solutions: electrical, water-hydraulic, mechanical, and pneumatic actuation, highlighting their operating principles, main components, advantages, and limitations.

1. Analysis of Oil-Free Solutions

1.1 Electrical system

A first alternative involves replacing the hydraulic actuation system with an **electrical actuation system**. The configuration investigated comprises an electrical rotary collector, an electric motor, an actuating rod, a ball screw, and the final blade actuation mechanism.

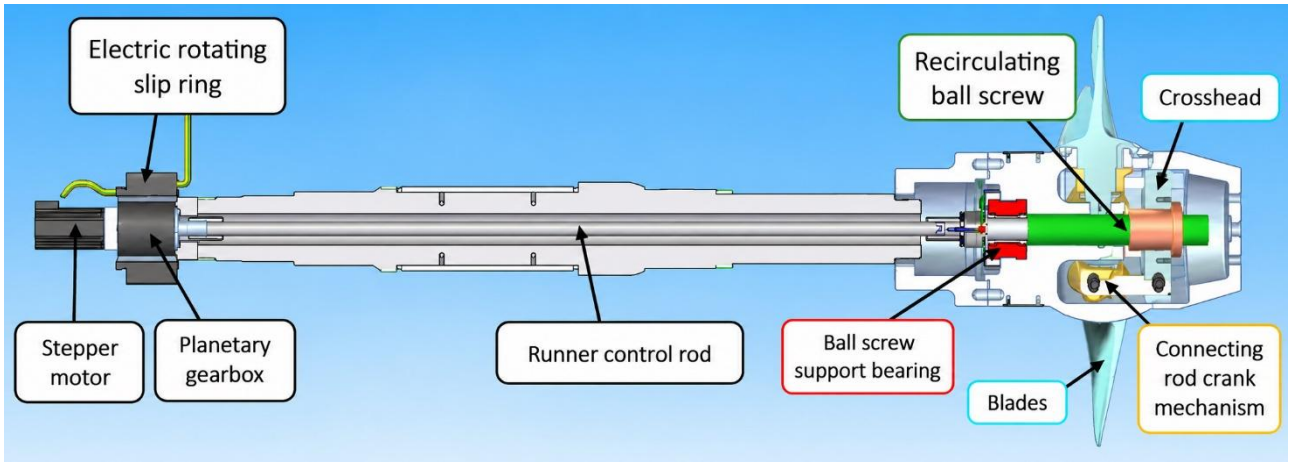


Fig. 2. Schematic of the Electrically Actuated Blade Regulation System

The rotary collector allows electrical power to be transferred from the stationary to the rotating part through a system consisting of rings and brushes. The motor can be either a stepper motor or a torque motor.
The torque motor, in particular, represents a particularly interesting solution for applications characterized by high torque and low rotational speed. The reported values range approximately from 100 to 30,000 Nm, with rotational speeds ranging from a few tens to several hundred revolutions per minute. The high number of poles and the large rotor diameter allow high torque values to be achieved, while also enabling direct coupling to the load without the need for a gearbox. This configuration therefore eliminates the backlash issues associated with geared transmissions.
The conversion of rotational motion into linear motion is achieved by means of a ball screw. The presence of rolling balls allows sliding friction to be replaced by predominantly rolling friction, resulting in average efficiencies of approximately 90%.

The electrical system therefore offers advantages such as simple control and reduced friction due to the use of a ball screw. However, several critical issues have been identified. The maximum force that can be developed is approximately 80–100 kN, whereas some turbines require values of up to 200 kN. In addition, interference may occur between the onboard electronics and the generator magnets. In particular, the service life of the rotary collector represents a significant limitation with respect to the minimum five-year service-life target identified in the study.

1.2 Water-Hydraulic System

A second possibility consists in using water instead of oil, while essentially maintaining the same configuration of the conventional hydraulic actuation mechanism. This solution offers the advantage of exploiting the existing know-how developed for hydraulic systems while maintaining a comparable actuation capacity, estimated at approximately 500 kN. However, the use of water requires significant modifications to the system. The components must be manufactured from stainless steel, and a dedicated hydraulic power unit must be provided. The water used in the circuit must be clean and distilled in order to prevent scaling, clogging, and damage to the components. Therefore, river water or water from the mains supply cannot be used directly without appropriate treatment. These modifications result in an increase in the overall system cost, making this solution less attractive than potentially more cost-effective alternatives.

1.3 Mechanical system

The mechanical solution primarily arises from the need to eliminate the issue associated with **rotary joints**. The concept consists of decoupling the actuation assembly from the rotation of the shaft line, keeping the actuation system stationary while the shaft connected to the runner continues to rotate.

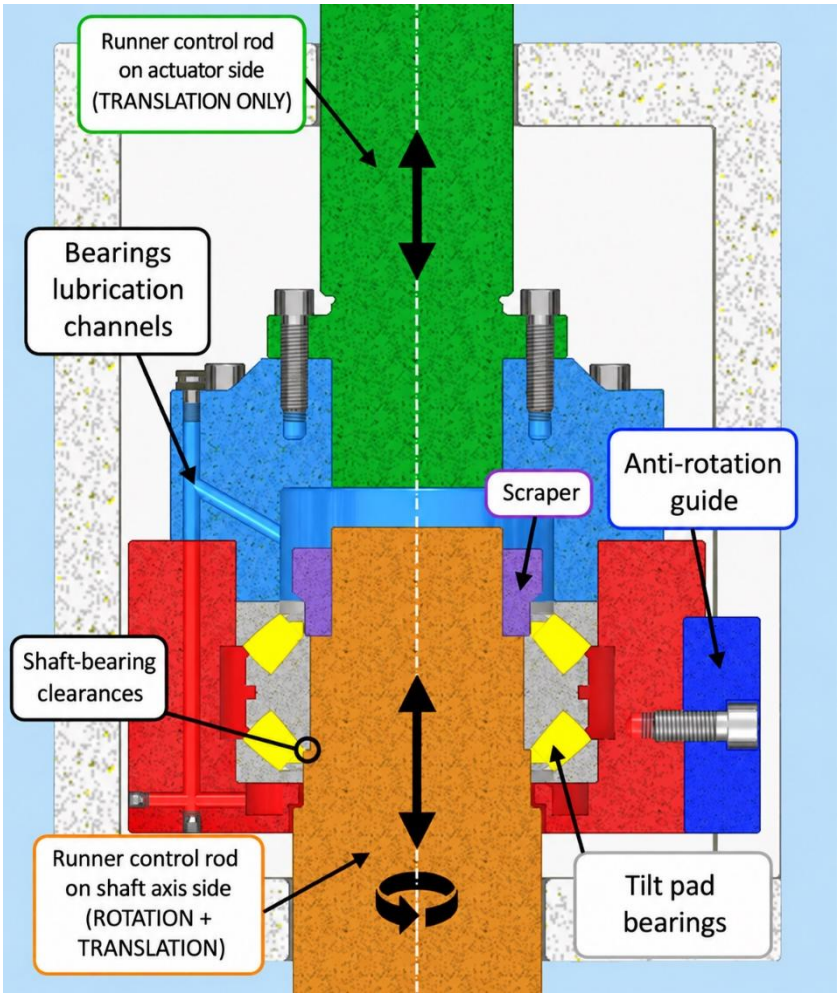


Fig. 3. Mechanical system for decoupling the actuation assembly from the rotation of the shaft line

To achieve this, the actuating rod is divided into two sections: one connected to the actuators and the other rigidly connected to the shaft line. The connection between the two sections is achieved by means of spherical roller thrust bearings.
The bearings must withstand the high axial forces associated with blade adjustment. In the case analysed, for a shaft diameter of 70 mm and an actuation force of 50 kN at 500 rpm, the selected bearing is estimated to have a service life of approximately 125,000 hours, corresponding to approximately 14 years.
The main issue, however, concerns lubrication. The grease tends to accumulate and dry out in the collection area, potentially leaving the bearing without adequate lubrication.

1.4 Pneumatic system

The fourth solution analysed involves the use of a **pneumatic motor for blade actuation**. The system features an architecture similar to the electrical solution, but replaces the electric motor with a **compressed-air-driven motor**. Since the motor rotates together with the shaft line, a **pneumatic rotary joint** is also required to enable the transfer of compressed air to the rotating assembly.

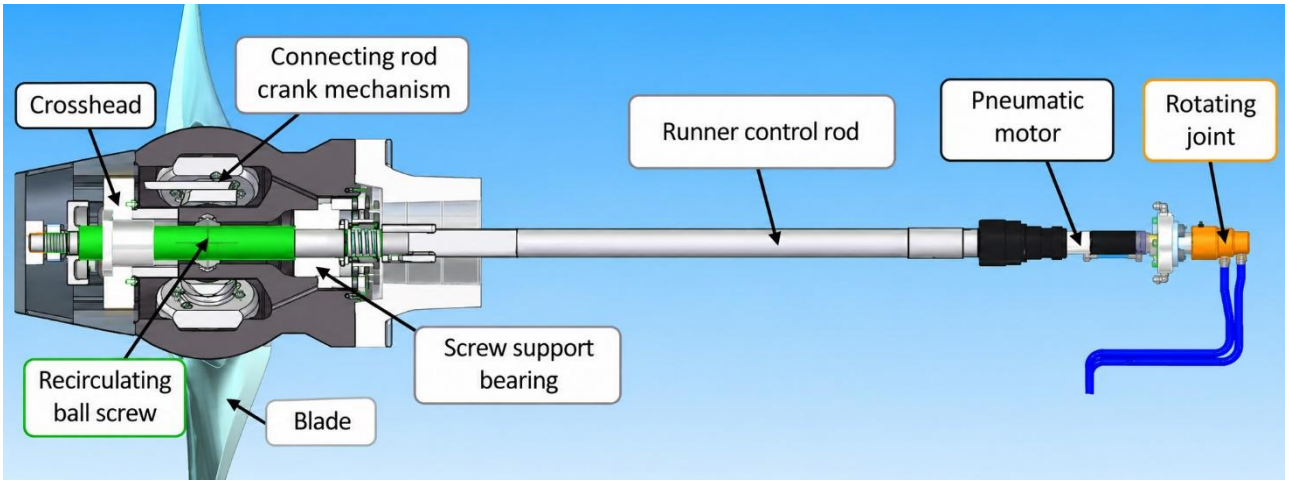


Fig. 4. Pneumatically Actuated Blade Movement System

The main disadvantage of this solution is the need for a compressor.

2. Comparison of the solutions

The comparison of the alternatives highlights significant differences in terms of performance, complexity, and technological challenges.
The electrical system offers simple control and efficient motion conversion thanks to the ball screw; however, the maximum achievable force and the service life of the rotary collector represent significant limitations. The water-hydraulic system, on the other hand, makes it possible to maintain a configuration very similar to the conventional hydraulic system and to achieve high actuation forces, but it requires stainless-steel components and a dedicated hydraulic power unit for water treatment.
The mechanical configuration allows the actuation assembly to remain stationary, thereby eliminating the need for a rotary joint and allowing different types of actuators to be employed. However, the main issue remains the lubrication of the transition bearings.
The hydraulic configuration also requires a dedicated water hydraulic power unit, with all system components manufactured entirely from stainless steel.
The pneumatic system, in contrast, combines a significant actuation force, simple control, the absence of onboard electronics, and the possibility of pressurizing the interior of the turbine. The need for a compressor and the development phase associated with the new kinematic mechanism represent the main challenges.

3. Developed pneumatic system

The detailed design of the A.P.K. system (Kaplan Pneumatic Actuation) is presented below. The components constituting the kinematic mechanism will then be defined. In this process, the system will be divided into two main groups:

- **DTG (Driving Torque Group):** includes all the components responsible for the generation and transmission of torque.
- **LFG (Linear Force Group):** includes the components responsible for converting torque into the linear actuation force and transmitting this force to the blades.

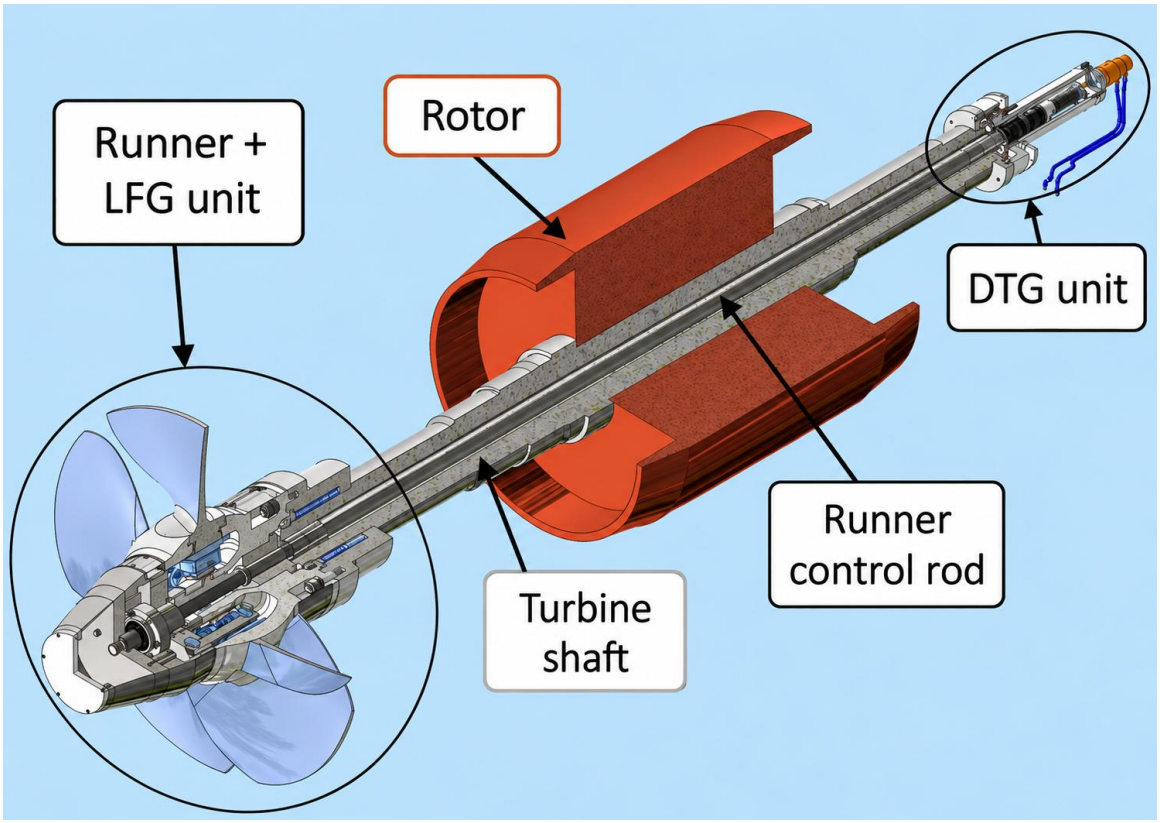


Fig. 5. Three-quarter sectional view of the turbine with the A.P.K. system

3.1 D.T.G. Detail

The acronym DTG (Driving Torque Group) refers to the group of components responsible for providing and transmitting torque to the mechanism. The assembly mainly consists of a pneumatic motor, a rotary joint for supplying compressed air to the pneumatic motor, a blade actuating rod, and a feedback mechanism for monitoring the blade position. The entire assembly is installed on the N.D.E. side of the turbine shaft.
The analysed motor is a vane-type pneumatic motor. It consists of a rotor mounted eccentrically inside a cylinder and equipped with suitable slots in which the vanes are inserted. During rotation, the centrifugal force pushes the vanes against the cylinder walls, generating variable-volume chambers. The expansion of the compressed air within these chambers produces the driving torque.
The motor torque reaches its maximum value with the rotor at standstill and decreases as the rotational speed increases. Power, on the other hand, follows a parabolic trend and reaches its maximum at a speed corresponding to approximately half the stall torque. The motor can also be reversible, a feature required to allow blade adjustment in both directions of rotation.
The motor performance can be adjusted by means of a throttle valve or a pressure-regulating valve. The throttle primarily allows the no-load speed to be adjusted, whereas varying the supply pressure makes it possible to modify both the rotational speed and the stall torque.

The pneumatic circuit also includes a filter, a pressure-regulating valve, a silencer, a 5/3-way valve for controlling the direction of rotation, and a throttle valve. Although pneumatic motors are normally lubricated using an oil mist, the system under consideration adopts a lubrication-free configuration, incorporating low-friction components and sealed bearings in order to maintain the oil-free objective.
The main advantages of the pneumatic motor include its high power-to-weight ratio, reversibility, continuously adjustable power output, and resistance to overloads. The overall system also provides simple control, can achieve actuation forces of up to approximately 330 kN, does not require onboard electronics, and potentially allows the compressor to be used to pressurise the interior of the turbine, thereby improving its sealing performance.

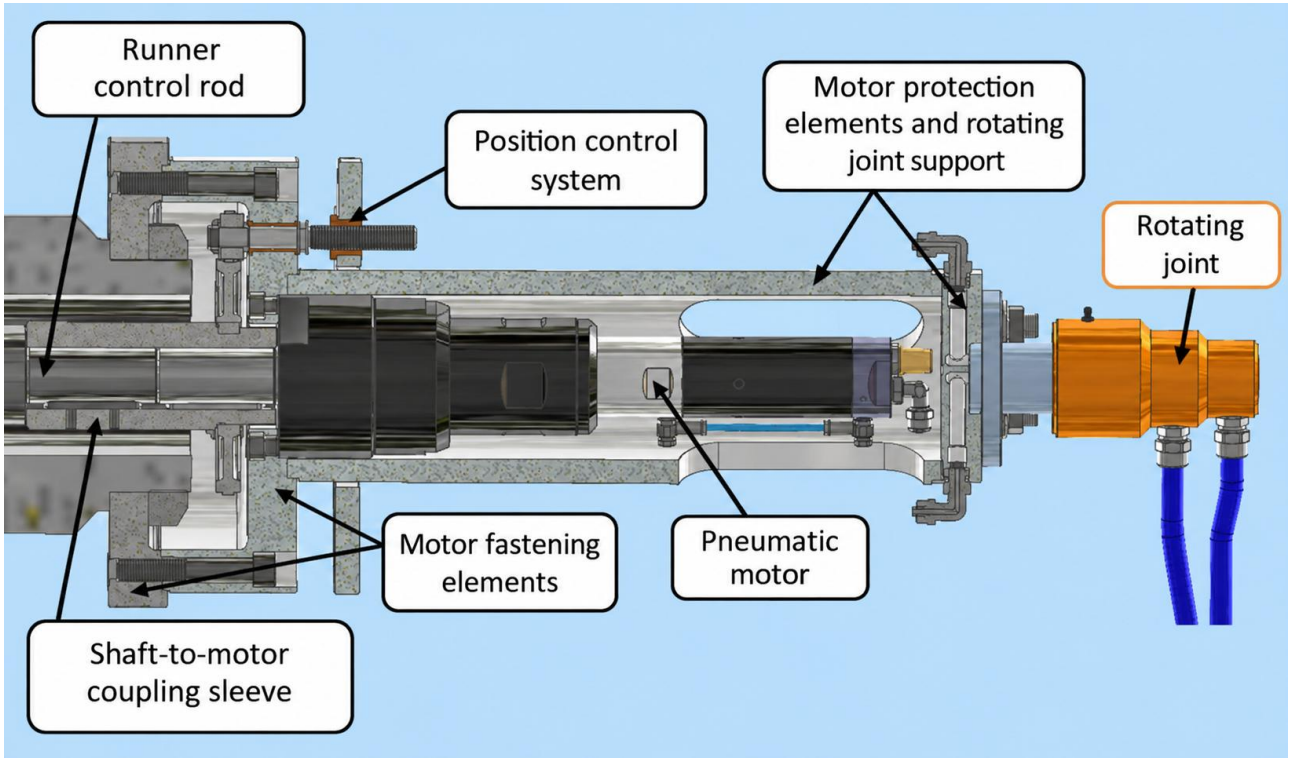


Fig. 6. Detail of the DTG components

3.2 L.F.G. Detail

The LFG (Linear Force Group) is now presented. This term refers to all the components that enable the conversion of the torque generated by the pneumatic motor into an axial actuation force and its subsequent transmission to the blades.
The assembly employs the crank-slider mechanism currently used for blade actuation in the conventional hydraulic system, and also retains the crosshead, which mechanically links the blades to one another. The main difference lies in the method used to actuate the crosshead. Its translational motion is driven by a ball screw, which converts the rotational motion generated by the pneumatic motor into the linear motion of the crosshead.

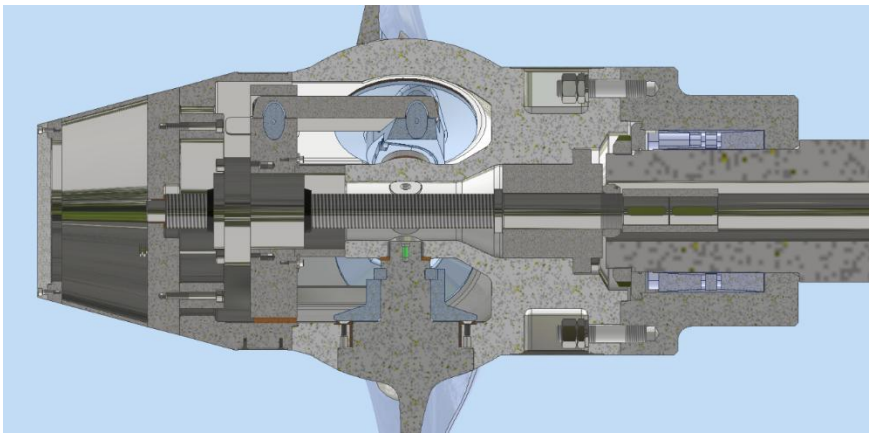


Fig. 7. Detail of the LFG components

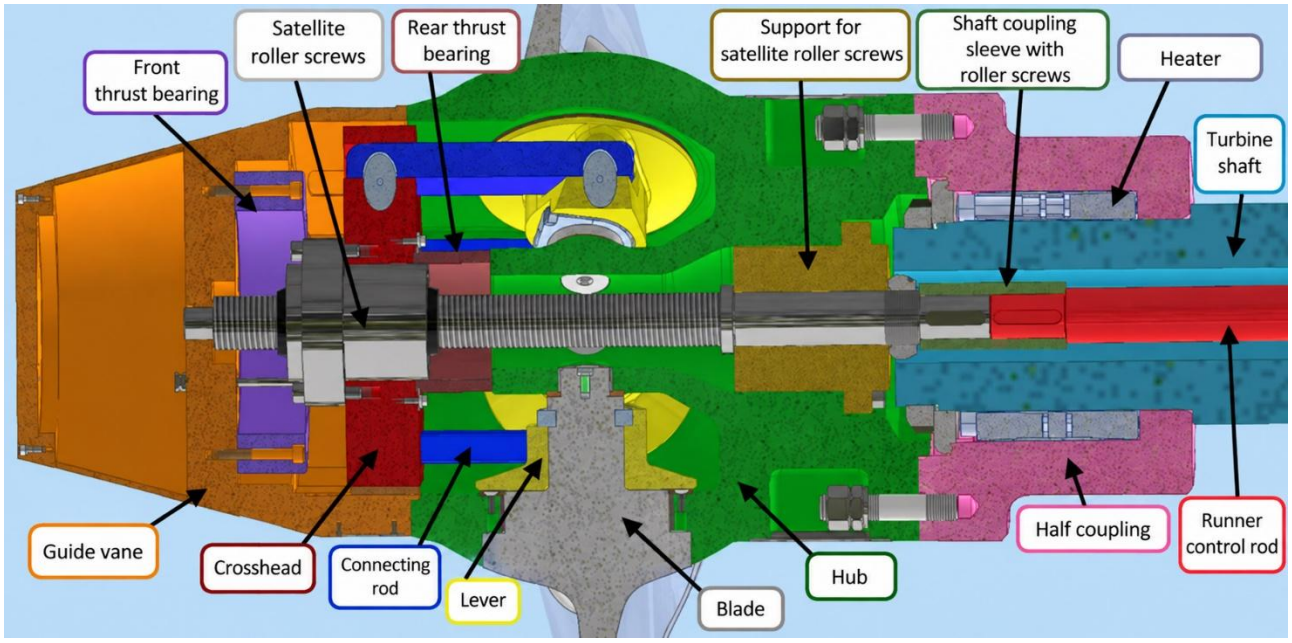


Fig. 8. Detail of the components comprising the LFG

3.3 Blade Position Detection System

The system consists of a planetary gear train, with the sun gear keyed to the blade actuating rod. The planet gears, on the other hand, are mounted on shafts to which a disc is connected by means of threaded connections. When the blade actuating rod rotates, it drives the gears, which in turn rotate the threaded shafts. Consequently, the disc begins to translate along the threaded shafts, while its position is continuously monitored by a sensor. The sensor then transmits its signal to the motor control circuit, which processes the feedback signal and adjusts the actuators accordingly.

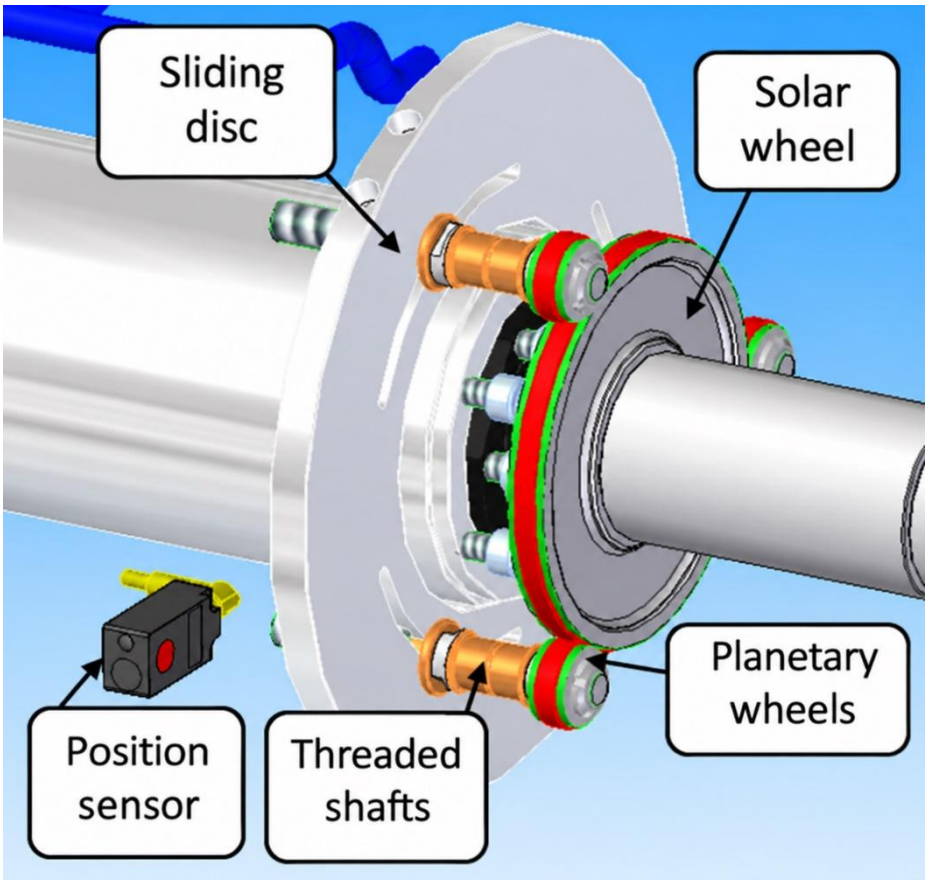
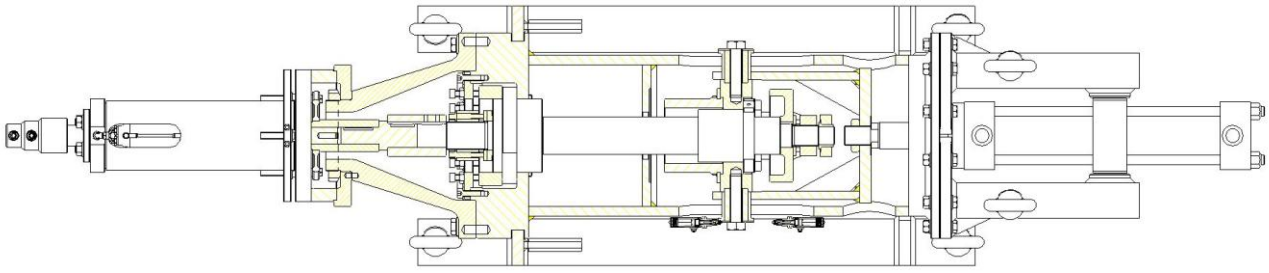


Fig. 9. Blade Position Detection System

4. Test bench

The APK system, as designed, was tested on a dedicated test bench. The test was carried out using a servomotor that, by controlling the throttling of the oil flow in the two chambers, reproduced the resisting force acting on the blade-adjustment crosshead. The test was conducted for a duration corresponding to five years of actual operation, assuming 10 adjustment cycles per day.



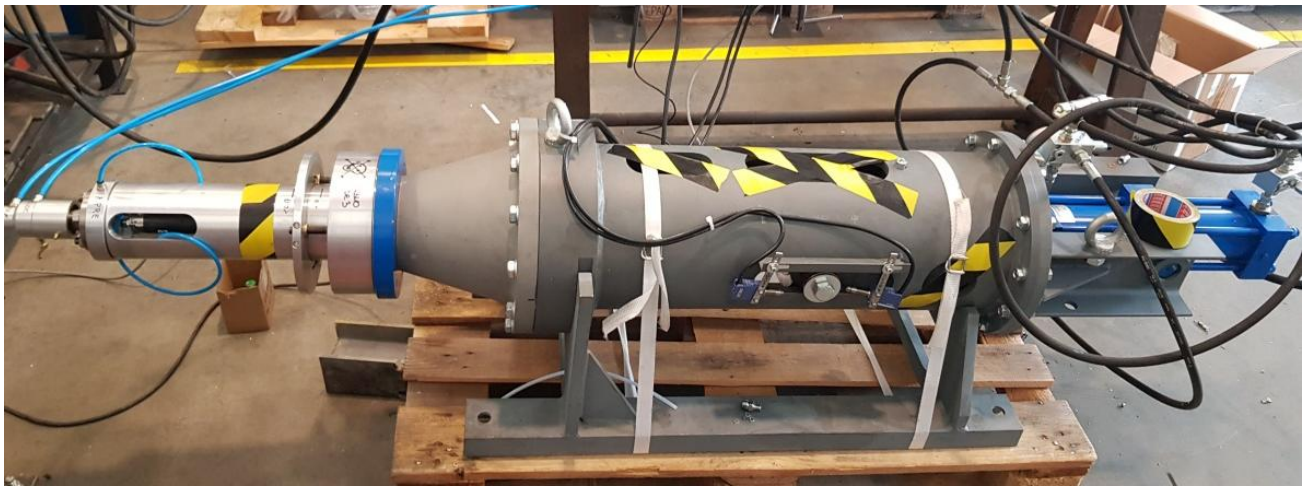


Fig. 10. Test bench

5. Conclusions

The study presented in this paper investigated several alternative solutions for the actuation of Kaplan turbine blades, with the main objective of eliminating the use of oil from the conventional hydraulic system and reducing the associated risk of environmental contamination. Four different configurations were analysed, namely electrical, water-hydraulic, mechanical, and pneumatic actuation, considering their operating principles, achievable actuation forces, complexity, and main technological limitations.

The comparison of the proposed solutions highlighted specific advantages and critical aspects for each configuration. The electrical and mechanical solutions presented limitations related, respectively, to the rotary collector and bearing lubrication, while the water-hydraulic solution required dedicated water-treatment equipment and stainless-steel components. The pneumatic solution was therefore selected for further development, offering a combination of significant actuation force, simple control, absence of onboard electronics, and the possibility of pressurising the turbine interior.

Based on these considerations, the APK (Pneumatic Kaplan Blade Adjustment) system was developed. The proposed architecture combines a vane-type pneumatic motor, a pneumatic rotary joint, a ball-screw mechanism, the existing crank-slider blade actuation mechanism, and a dedicated blade-position feedback system. The resulting configuration enables the conversion of pneumatic motor torque into the axial force required for blade adjustment while maintaining an oil-free actuation system.

Finally, the developed APK system was experimentally tested on a dedicated test bench. The test reproduced the resisting force acting on the blade-adjustment mechanism and was conducted for a duration corresponding to five years of operation, assuming ten adjustment cycles per day. The experimental activity demonstrated stable and repeatable operation, supporting the technical feasibility of pneumatic blade actuation as an oil-free alternative for Kaplan turbines.

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