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DESIGN AND PERFORMANCE OPTIMIZATION OF A CAM-DRIVEN CONSTANT PRESSURE HYDRAULIC ACCUMULATOR

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ABSTRACT

A Cam-Driven Constant Pressure Hydraulic Accumulator (CPHA) that can keep the fluid pressure near constant even when the gas compression is nonlinear is designed and optimized for performance in this research. A groundbreaking cam mechanism is used to convert nonlinear pressure fluctuation into a regulated and constant pressure output, providing a space-saving and mechanically efficient option. One hydraulic fluid cavity and two gas cavities, arranged symmetrically, make up the CPHA's split-structure design. A gas chamber is compressed by the translating cam's interaction with the cam rollers, and friction and wear are minimized by an extension spring's reduction of radial forces. The friction between the piston and cylinder is reduced or eliminated by using a bladder. In order to reduce the radial force on the piston rod of the gas cavity, a genetic algorithm was used to optimize six critical design parameters. Results from simulations show that the CPHA can keep pressure constant and reduce energy losses better than traditional accumulators, suggesting that it might be useful for small, efficient hydraulic energy storage systems.

I. INTRODUCTION

When it comes to fluid power systems, hydraulic accumulators are vital for storing energy, absorbing shock, and stabilizing pressure. Each of the several accumulator designs—bladder, diaphragm, and piston-based—has its own set of pros and cons. A major step forward in guaranteeing system stability, efficiency, and responsiveness is the notion of a constant pressure hydraulic accumulator. However, owing to constraints in their mechanical design and fluid dynamics, conventional accumulator systems often have difficulties in maintaining a constant pressure level throughout operation. One potential solution to these limitations is to include a cam-driven mechanism into the accumulator design. This would allow for more accurate control over pressure fluctuations, better system responsiveness, and increased energy efficiency.

A common mechanical system component, cam mechanisms allow for the regulated translation of rotational motion into linear displacement. Despite their unconventional application, they have recently arisen as a novel strategy for addressing persistent problems associated with pressure variations in hydraulic systems. It is possible to control the piston's or membrane's movement inside the accumulator chamber and keep the pressure profile constant by including a cam-driven system into the hydraulic accumulator's functioning. Industrial automation, aircraft hydraulics, and sophisticated manufacturing systems are just a few examples of the kinds of applications that benefit greatly from this integration because of the high degree of accuracy and dependability it demands. Designers may modify the accumulator's behavior to meet particular operating needs by engineering the cam profile to provide predictable, repeatable, and adjustable motion.

The importance of keeping the pressure in a hydraulic system constant is immense. Unwanted system behavior, increased component wear, and inefficiency may result from hydraulic pressure fluctuations. The capability to maintain a constant pressure, for instance, has a direct consequence on precision, load-bearing capacity, and general safety in machine tools, hydraulic presses, and flight control systems. Gas compression, the mainstay of conventional accumulators, is intrinsically non-linear and subject to performance loss over time as a result of gas leakage or temperature changes. To minimise output unpredictability and reliance on gas-based buffering, a cam-driven mechanical technique is preferable since it provides a more predictable and controlled means of managing energy storage and release.

Complex mechanical, fluid dynamic, and control system factors must be considered during the design of a cam-driven constant pressure accumulator. The cam profile, which controls the piston's displacement in relation to the rotational input, is a crucial component of the design. The pressure-volume relationship inside the accumulator chamber may be engineered by meticulously choosing or optimizing the cam design. For maximum performance, it is necessary to precisely describe the hydraulic fluid dynamics as they interact with the cam, follower mechanism, spring elements (if any), and other components. Due to the interdisciplinary character of the issue, a mixed method approach is required to guarantee robustness and dependability, including theoretical modeling, computational simulation (using tools like computational fluid dynamics and finite element analysis), and experimental validation.

More complicated cam profiles may now be realized with great accuracy because to recent advancements in materials science, CAD, and manufacturing technology. It is now more feasible to create small, efficient cam-driven systems that can operate under harsh circumstances thanks to additive manufacturing, CNC machining, and high-performance lubricants. The design options are expanded and the operating life and maintenance profile of such accumulators are improved by these technical improvements. Intelligent hydraulic systems that can adapt to changing operating needs may be realized via the integration of sensors and smart control systems into the design of the accumulator. This integration paves the way for real-time pressure monitoring and adaptive cam motion control.

A cam-driven hydraulic accumulator's performance may be optimized by focusing on four main areas: reaction time, mechanical durability, energy losses, and pressure stability. Optimization algorithms like evolutionary algorithms, gradient-based approaches, or machine learning techniques may be used to iteratively analyze performance measures and design parameters in order to accomplish these aims. Cam lift, dwell angles, follower stiffness, fluid viscosity, piston diameter, and overall parameter balancing are all crucial to get the desired results. The optimization of the design also has to take into account the trade-offs between mechanical complexity, system cost, and maintenance needs.

A cam-driven constant pressure accumulator's potential uses are almost endless. These accumulators may help wind turbines and wave energy converters smooth out their hydraulic outputs, which is a common problem in renewable energy systems. Excavators and other mobile hydraulic machines may enhance their fuel economy and lessen their environmental effect by maintaining constant pressure. Accurate and responsive actuator performance is possible in robotics with the help of precise motion control made possible by constant hydraulic pressure. Hydraulic accumulators, particularly when improved with cam-driven pressure management, provide an additional or alternative option to electrical energy storage (e.g., batteries) in situations where the former is impractical owing to dimensions, temperature sensitivity, or charge duration.

Although there are many benefits, there are also some difficulties that need to be considered. Adding mechanical cam mechanisms raises the possibility of wear and mechanical failure due to the increased number of moving components, which may not be well designed or maintained. The cam and follower system's alignment and the need for high-tolerance manufacturing might drive up production costs. Furthermore, problems with lubrication, vibration, and noise may be solved by using the right materials and procedures for dampening. To guarantee the suggested accumulator system satisfies the operational and durability criteria of its target application, it is crucial to conduct a thorough design and testing process.

Efforts to enhance the performance and dependability of fluid power systems are in line with the development of cam-driven constant pressure hydraulic accumulators, which falls within the larger framework of sustainable engineering and energy efficiency. Operating closer to their optimal performance range, such systems may reduce waste, energy losses, and maintenance frequency by lowering pressure fluctuations. In the long run, this helps hydraulic-powered processes be more cost-effective and environmentally friendly. Because it is mechanical, the cam system may be made to work without electrical controls, which makes it ideal for use in places that are hard to reach, dangerous, or have little power.

Hydraulic accumulators that use cam mechanisms to maintain a constant pressure are a major advancement in the field of fluid power. It provides an encouraging answer to the age-old problem of keeping hydraulic pressure constant under changing load circumstances. It is feasible to build an accumulator system that improves operational dependability, energy efficiency, and system intelligence while meeting technical requirements by using rigorous design process, computational modeling, and experimental validation. Engineering research and innovation in this field is captivating because it has the potential to reshape the design and implementation of hydraulic systems in many different sectors.

II. REVIEW OF LITERATURE

Pace, Anna et al., (2025) Commercial and experimental prostheses suffer from an inability to imitate the energy-recycling behavior of a natural ankle, leading to subpar walking performance for those who rely on lower-limb prostheses. To address this, a cam-driven hydraulic prosthetic ankle was developed. A hydraulic accumulator stores the negative effort done during stance before push-off, and this innovative mechanism uses that work to propel the body forward at push-off. The experimentally-derived intact ankle torque patterns are reproduced using two cams. A MATLAB-based design software that simulated the primary components of the prosthetic ankle was utilized to develop the new prosthesis. As a result, we detail the design software and its usage in sizing the cam follower return springs and determining the cam profiles needed to simulate intact ankle torque in this article. In addition, the article details a preliminary design analysis that was carried out using constraints to determine the sizes of other critical components that impact the device's size, performance, and energy efficiency. Last but not least, the optimal design that minimizes energy losses and device size is found by comparing the possible design choices according to their energy losses. In conclusion, this method of design not only records the creation of a unique prosthetic ankle, but it also offers a better alternative to heuristics by providing a structured framework for breaking down difficult design problems into smaller ones.

Costa, Gustavo & Sepehri, Nariman. (2023) The usage of hydraulic accumulators in hydraulic circuits dates back many years. Uses range from preserving load energy to maintaining pressure inside a circuit branch. The need for efficient circuits in recent years has brought more focus to one of these applications—the storage and release of energy. To put it another way, accumulators function similarly to electrical circuit components like capacitors and batteries, but in a hydraulic context. There have been several reports of substantial energy gains from the use of accumulators in hydraulic hybrid cars and other complicated agricultural equipment. Typical uses of accumulators for this purpose are reviewed in this article, along with the obstacles that still need to be addressed in each case.

Ven, James. (2013) In order to store energy and reduce pressure variance in hydraulic circuits, hydraulic accumulators find several uses. Two fundamental drawbacks of traditional hydraulic accumulators are the energy density being much lower than in other energy domains and the fact that the hydraulic system pressure changes as the amount of energy stored increases. This work introduces a new kind of hydraulic accumulator that can keep the hydraulic system pressure constant even when the gas pressure fluctuates by using a piston whose area changes with stroke. A rolling diaphragm strengthened with fabric seals the variable area piston. The work builds the piston radius profile from the displacement of the piston and then transforms it into a function of the piston and diaphragm's axial contact point. The geometric design trade-offs were shown by numerically solving the piston profile for a number of situations using both transformation approaches. The highest gas volume ratio achieved was 1.8:1 when a gas piston with a variable area was used in conjunction with a constant cylinder area. By comparing the energy densities of the two designs, we find that the constant pressure accumulator outperforms the traditional accumulator at both the 2.71:1 volume ratio and the lower 1.8:1 ratio, an increase of 16% in energy density. In addition to increasing the density of energy storage, this novel and promising technology keeps the hydraulic system pressure constant regardless of the amount of energy stored, which simplifies system operation and allows for the downsizing of other circuit components to meet the same power needs.

Filipi, Zoran et al., (2004) One of the key technologies that will be used in future ultra-efficient vehicles is hybrid propulsion systems. While many studies have focused on hybrid passenger vehicles and small commercial trucks, many questions remain on how to best hybridize larger trucks that are used for both on-road and off-road conditions. This study provides answers to such issues by conducting a thorough evaluation of the FMTV's planned parallel hydraulic hybrid engine. Based on data on the usual purpose of the vehicle, an FMTV representative duty cycle is produced. A hydraulic hybrid setup with the motor placed after the gearbox makes use of a technique for optimizing the power management and propulsion systems in a sequential fashion. In order to assess the hybrid propulsion system's fuel economy and mobility potential, and to better understand the factors that contribute to expected fuel economy values, this study is crucial.Hybrid propulsion systems, heavy vehicles, power management, optimization of vehicle systems, and propulsion optimization are all related terms.

III. DESIGN AND OPTIMIZATION OF THE CPHA

With a given starting point, the state equation may be used to determine the compressed inner gas pressure of the accumulator. A constant pressure may be obtained by use of an additional nonlinear transformation, even when the pressure change is not linear. It is possible to do the typically nonlinear transformation utilizing the link mechanism, crank shift, and cam mechanism. We opted on a cam mechanism as a compact structure to accomplish this constant pressure accumulator, taking into account the size and quantity of parts. Here we provide a CPHA model that is much less complex than what would be needed for a final design validation.

Structure Design of the CPHA

The novel accumulator's design is a split-type accumulator, with a single fluid cavity and two gas cavities, rather than a conventional accumulator. Because of the physical separation between the gas and hydraulic fluid cavities, the two media might have differing pressures. The three compartments are securely fastened to the foundation, as shown in Figure 1. Piston rods for the fluid and gas cavities are built differently; the former uses a translating cam mechanism, while the latter uses a cam roller. In response to hydraulic oil entering the fluid chamber, the translating cam will compress the gas chamber by moving along the x-axis and pressing the cam roller and piston, respectively. Two gas chambers, one on either side of the fluid chamber's axis at a constant angle, counteract the radial force acting on the translating cam. A radial force acting on the piston rod inside the gas chamber may be broken down by the reaction force between the translating cam and the cam roller. An extension spring that is preloaded is used to link the piston rods of two gas cavities, thereby reducing this affect. Using a bladder as an inner container in the cavity helps to reduce the contact pressure and friction of the seal ring. In this approach, the cylinder-piston friction may be disregarded. The following is the method for calculating the system parameters, such as the starting gas volume, initial gas pressure, fluid pressure, etc.

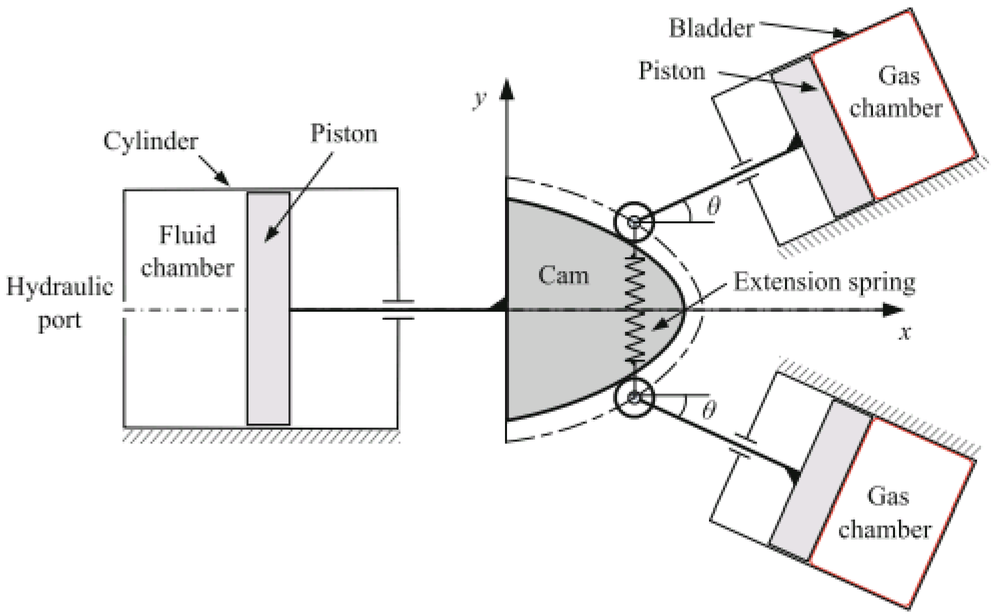

Figure 1A schematic diagram of the CPHA

IV. OPTIMIZATION OF THE DESIGN PARAMETERS OF THE CPHA

Reducing the radial force of the gas cavity piston rod Frad, which increases the friction between the seal ring, is important since friction is a dissipative force. The six design parameters are optimized using the given CPHA mathematical models. The optimization's methodology and outcomes are detailed here.

The optimization objective of the CPHA

Using Eq., we can determine the radial force Frad of the CPHA once all design parameters have been specified. For each point throughout the full compression cycle, the radial force equals as $F_{rad}(i)$, the optimization objective for the CPHA can be expressed as:

$$fval = \min \sum_{i=1}^{n} |F_{rad}(i)|$$

Where n is the number of positions in the compressing cycle (n = 40).

The constraints of the six parameters

For the first two hydraulic property parameters, we establish lower constraints to guarantee that the CPHA and a standard accumulator are of same size. The geometrically impossible solutions are avoided by defining lower constraints of h and y0. By defining lower constraints for the extension spring parameters k and F, we can guarantee that the spring force Fs and the radial force Frad are of equal magnitude. To make sure the CPHA isn't too big or too little, we set maximum values for all six design parameters. Eq. lists the minimum and maximum values for all eight design parameters in relation to the dimensions of the Rexroth 1L bladder-type amplifier HAB1-350-6X.

$$s.t.\begin{cases} 17.5\text{ MPa} \le P_{g0} \le 35\text{ MPa} \\ 200\text{ cm}^3 \le V_{g0} \le 500\text{ cm}^3 \\ \frac{\pi}{12}\text{ rad} \le \theta \le \frac{\pi}{2}\text{ rad} \\ 8\text{ cm} \le y_0 \le 20\text{ cm} \\ 10000\text{ N/m} \le k \le 300000\text{ N/m} \\ 500\text{ N} \le F_0 \le 5000\text{ N} \end{cases}$$

The optimization method

Optimization techniques based on gradients are not as successful when dealing with the radial force since its optimization function is implicit and quite nonlinear. This research makes use of a genetic algorithm due to its resilience and ease of implementation.

V. THE RESULT OF THE OPTIMIZATION

Since the gas and fluid chambers of a traditional accumulator share a single container, hydraulic oil cannot fill the whole chamber while the accumulator is in operation. The hydraulic system pressure and the gas precharge pressure determine the fluid oil volume in a typical accumulator. Quan investigates the efficiency of a standard accumulator. The optimal gas precharge pressure, according to both modeling and experiment, is the pressure at which the accumulator's damping ratio is 0.707. According to Quan's experiment, the accumulator works best at a gas precharge pressure of 16.5 MPa and a system pressure of 17.5 MPa. The amount of fluid oil that may be kept in a 1 L bladder accumulator is 57 ml under these conditions.

In contrast to the conventional accumulator that Quan described, the CPHA has a fluid cavity capacity of 57 ml and maintains a fluid pressure Pf of 17.5 MPa. In engineering, the fluid cavity's available internal diameter rf is discontinuous and limited. The cavity's dimensions and mass informed the selection of a 40 mm internal diameter and a 12.56 cm2 cross-sectional area. Furthermore, the gas cavity's interior diameter is set at 63 mm, and the cross-sectional area, Ag, is 31.06 cm2.

A desired hydraulic pressure of 17.5 MPa is shown in Table 1 as the optimization results. Figure 2 shows that even when the axial force on the rod in the gas cavity rises, the hydraulic force on the rod in the fluid cavity remains constant. The gas cavity rod's radial force may be optimized and reduced using an extension spring, allowing it to be far less than both the hydraulic and gas forces.

Table 1. The optimized results of the CPHA

Pg0	**Vg0**	**h**	**y0**	**k**	**F**
18.00 Mpa	224.85 cm3	1.38 rad	12.39 cm	296240.00 N/m	2674.60 N

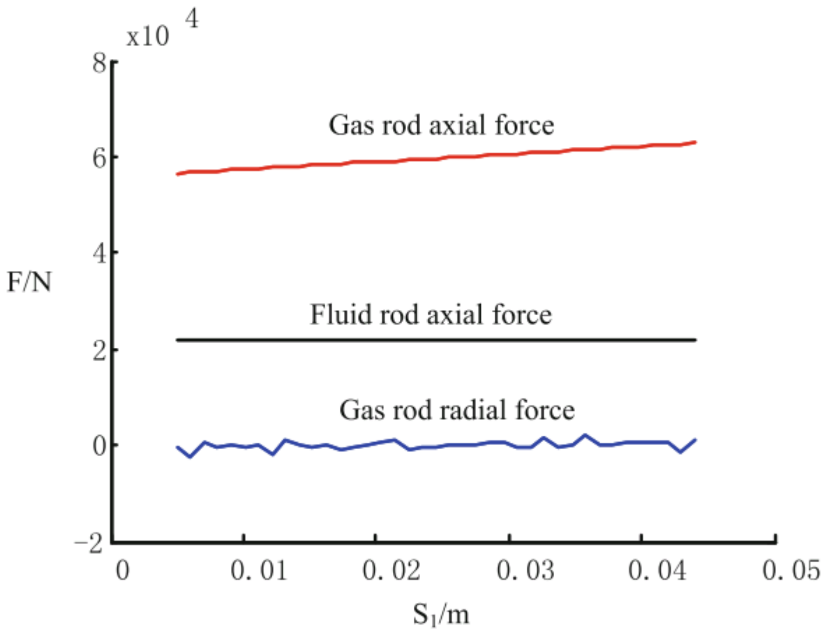

Figure2 The forces on the fluid and gas rod

VI. CONCLUSION

A major step forward in fluid power systems has been the creation of the Cam-Driven Constant Pressure Hydraulic Accumulator (CPHA), which solves the age-old problem of keeping hydraulic pressure constant regardless of the operating circumstances. The device successfully converts the compressed gas's nonlinear pressure behavior into a constant pressure output by using a translating cam mechanism. By separating the gas and fluid cavities and positioning the gas chambers symmetrically, the split-structure design improves mechanical balance and lessens the impact of radial stresses on the piston rods. The use of an extension spring and a bladder further reduces wear and frictional losses, which improves operating efficiency and increases durability. By optimizing six critical design parameters using a genetic algorithm, we have shown that the CPHA may potentially outperform conventional accumulators, especially with regard to energy consumption and pressure stability. Findings from the simulations confirm that the design is successful in reducing radial stresses while keeping the hydraulic force constant. In addition to laying the groundwork for future advancements in energy-efficient accumulator designs, this research presents a compact and dependable solution for sophisticated hydraulic systems. Automation, aircraft, and mobile hydraulics are just a few of the sectors that might benefit from the CPHA's consistent pressure and dependable system dependability.

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