Modes of Failure in Zonal Hydraulics for Construction Machinery

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***Abstract*—This paper discusses possible failure modes in zonal hydraulics for construction machinery. The "zonal" or "decentralized" hydraulics is one of the methods first introduced in the aerospace industry and utilized for hybridization of construction machinery. This method is realized with pump-controlled actuators, which are distributed throughout the system. Due to both electric and hydraulic components being involved and tough working conditions, electro-hydraulic systems such as zonal hydraulics tend to be very complex, and where each one of components can fail. If any of the parts of the electro-hydraulic system are damaged, the appearing problems may be hard to diagnose due to the complexity of a multi-domain system. A general description of zonal hydraulic systems and their components are introduced. Then, a review of the possible failure modes related to zonal hydraulics is presented for construction machinery. This paper provides a broad insight into electro-hydraulic systems and their failures, as well as review the current literature available regarding fault studies.**

Keywords—failure modes; electro-hydrostatic actuators; zonal hydraulics; construction machinery;

I. INTRODUCTION

Hydraulics is a traditional application science widely used in industrial, aeronautical, and off-road mobile applications due to its superior power density and mature technology. Construction machinery examples are illustrated in Figure 1.

Fig. 1: Examples of construction machinery: a) excavator, b) skid-steer loader, and c) bulldozer.

Recently, hydraulic technology has mainly developed incrementally. However, the field of construction machinery will benefit from a new architecture with improved efficiency and high performance level during lifetime; in order to achieve this, built-in functionalities, such as fault tolerance and predictive maintenance are required.

Fault tolerance is a demanding topic in case of off-road and construction machinery. According to [1], 15 % of failures are concentrated in sensors and 10 % in valves, as there are no 100 % fault-tolerant commercial valves in case of off-road machinery. In [2], the failure rate in hydraulic circuits was studied with four different mobile working machines during three years. The authors in [2] found that the hydraulic valves failed 69 times, pumps 34 times, hydraulic motors 237 times, cylinders 318 times and hoses 90 times in 106 hours. Failures were caused by contamination, wearing, external damages, material error, maintenance error or excess load. The off -road machine cases are not so critical compared to airspace, oceanic and other extreme applications, however, faults still create unpleasant financial losses and significant time delays in manufacturing or other performing tasks.

Therefore, valves and sensors are critical components in conventional systems, independent from the type of application. Many applications can benefit from valveless systems, such as pump-controlled systems with "smart" use of electric drive.

Therefore, failure modes of zonal hydraulics systems are investigated by means of review of the current literature. First, this paper introduces zonal hydraulic concepts in detail, demonstrates examples of pump-controlled systems, highlighting the effects of the components. Secondly, the review was designed to cover hydraulic and electric system components. As a result, conclusions are drawn considering designed pump-controlled systems and their benefits for the construction machinery.

II. ZONAL HYDRAULICS

Simplifying conventional systems and enhancing the presence of electric systems can be realized by switching to zonal hydraulics. The zonal hydraulics trend is inspired by the More Electric Airplane program (MEA) (for instance, CleanSKY-Horizon 2020 program). Figure 2 illustrates examples of a conventional excavator and introduces concept of zonal hydraulics.

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Zonal hydraulics also known as decentralized hydraulics and realized with pump-controlled or Electro-Hydrostatic Actuators (EHAs), as in the electrification approach for aircrafts. These systems, such as pump-controlled actuators, are powered directly by the electric drives. In the context of this paper, an electric drive refers to the combination of the electrical machine (motor) and a frequency converter

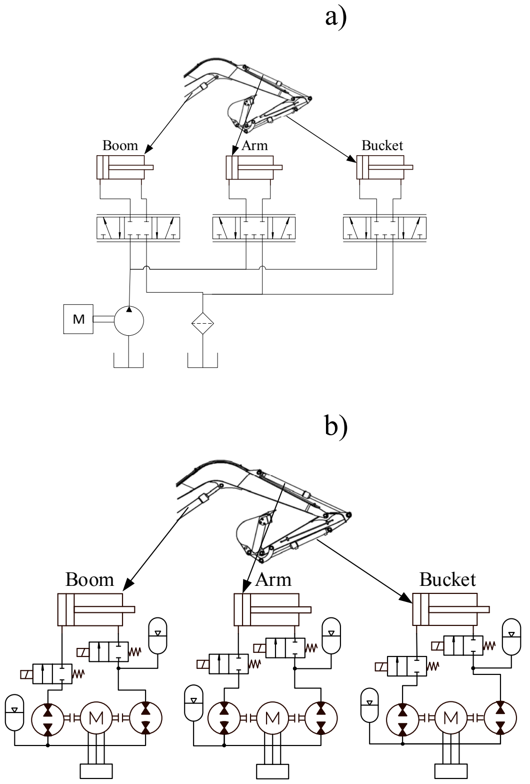

Fig. 2: a) example of the conventional excavator, b) example of the excavator with zonal hydraulics.

Following Figure 3 illustrates examples of pump-controlled actuators. According to Figure 3 and [3], a pump controlled system can be utilized as a combination of a variable displacement pump with fixed speed motor, or fixed displacement pump with variable speed motor or a combination of these two.

Authors in [10] provide an overview of a pump-controlled differential cylinder system. In general, pump-controlled actuators provide the most benefits for applications where seldom use is required. However, this paper investigates the use of pump-controlled units for construction machinery. Analysis of presented topologies in Figure 3 demonstrates that the use of components in a closed system is narrowed down to pump/motors, simple valves, and accumulators as replacement of tank. In contrast to conventional systems, a variable speed electric motor is utilized instead of a constant speed source. In these closed systems, actuation of the hydraulic cylinder is proportional to actuation (position, speed and torque) of the electric motor.

There are a number of recent developments, which may supplant the existing electro-hydrostatic actuator (EHA). For instance in [11], the authors apply the EHA to create electro-hydraulic flexible joint robot system. In [12], it was shown that the EHA system performance in the case of excavator achieved a higher efficiency compared to a conventional load-sensing system. Overall, pump-controlled and EHA developments eventually will lead to a greater use of electric power in support of the environmental EU policies.

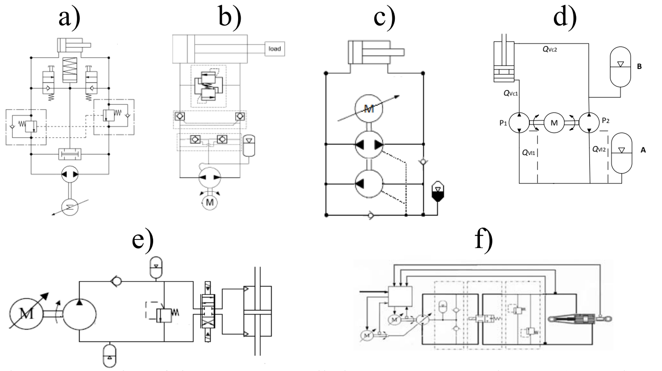

Fig. 3: Examples of the pump-controlled actuators a) [4], b) [5], c) [6], d) [7], e) [8], f) [9].

Conventionally, EHA is considered unreliable compared to conventional fully hydraulic systems (e.g. in aircrafts), and works mostly as backup in case of failure of the primary flight control units [13]. In general, both hydraulic and electric systems are prone to fail; therefore, following section summarizes common failures of pump-controlled actuators.

III. MODES OF FAILURE

In general, both hydraulic and electric systems are prone to fail [14]. Common failure modes for hydraulic and electric systems are summarized in the following sections.

A. Hydraulic failure modes

Typical valve faults are broken seals and spool malfunction due to contaminated oil [15]. Pumps and hydraulic motors have various basic failure modes: wear can occur for improper fluid selection or an incorrect installation, water and particulate contamination, fluid oxidation, cavitation, and overload. Misalignments of the shaft and excess payload can cause premature failure due to high stress in the bearings. A detailed classification of possible system faults has been summarized in [16].

To convey linear movement a cylinder is applied. Normally non-symmetrical and double acting is utilized for construction machinery. The major contribution to cylinder failures comes from seal failure, which will lead to internal and external leakages and wearing. These three types of failures will lead to other failures such as blocked elements, clogging or sensor damage. [17] Common faults in cylinders are seal wear, faults in the electronics-position measurement system, and backlash at actuators ends.

Hydraulic accumulator failures are spring or valve failure, and for piston type of accumulator, the failures are identical to a cylinder.

Hydraulic hose failures, for instance, are erosion, fluid incompatibility, improper assembly, heat aging, and abrasion.

Movement in machine joints and environmental reasons can accelerate these failures.

B. *Electric failure modes*

Common failure modes in electric drives are broken rotor bars [18], stator winding faults [19], air-gap eccentricity [20] and load faults. Some failure modes are specific to the motor type. For instance, broken cage due to manufacturing defects or mechanical damage is typical to induction motor, where broken magnet and demagnetization are related to permanent magnet synchronous machines.

Regardless of motor type, following faults can occur such as damaged bearings, damaged shaft and shaft misalignment. Overload on the shaft, harsh environment or undesired vibrations can damage or accelerate aging of the electric machines rotor. Overheating or overcurrent can damage the insulation of the motor winding, creating partial short circuits, which rapidly will continue to full short circuit.

Overcurrent fault, high starting-load current and contamination failure are frequency converters common failures. Temperature failure among many other faults is caused by wrong application of the frequency converter. Process changes related to load and/or speed variation or changes in environmental operating conditions can be a major contributor to frequency converter failure.

Battery failures are related to manufacturing or uncontrolled operating conditions such as high or low ambient temperatures (which accelerate aging). Lack of cooling, and physical damage are also a significant contributing factor. For battery failure, external factors are sensor failure, cooling system failure, BMS failure, and charger failure (overcharging).

C. *System failure modes*

Due to nature of EHA being a closed system with limited amount of oil, it is more sensitive to leakage related failures. System temperature related failures are also important, due to compact nature of the EHA designs.

Utilization of zonal hydraulics in multi actuator systems (series and parallel from kinematic point of view) can lead to control mode failures. For instance, loss of the synchronization of actuators, which may result in mechanical failure or wrong trajectory of motion.

Moving joints and outside extreme temperatures will accelerate degradation of cables, and can lead to premature cable failures. Apparently, location of EHA next to actuator is reducing amount of hydraulic tubing needed between actuator and the EHA unit, however, the EMC created by cabling and frequency converter, can cause noise in sensors and other control signals resulting in failures. Due to location of EHA being outside the protective enclosure of the machine, it is more vulnerable to physical damage, temperature changes, dust, and moisture.

IV. DISCUSSION

To ensure reliability and fault-tolerance in a system, in some cases, components are duplicated for redundancy. Multiple redundant architectures for hydraulic and electrical systems are considered as well as multiple redundant lanes or channels of computing and actuation for control purposes. Duplication and redundancy obviously increases weight and cost. Examples of components are multiphase electric machines. Typically, the utilization of these machines is limited to special cases of applications like aircrafts, ship propulsion, locomotive traction, electric vehicles, high power machines, or energy generation due to their ability to support the required performance in high tolerance operation. However, in construction machinery for cost and space related reasons, duplication is not possible and similarly, for cost and reliability related reasons, complicated control systems with many sensors are usually not possible.

Therefore, the industry strives for fault-tolerant components. In the literature, we can find some examples of fault-tolerant components for hydraulic and electric applications. The majority of these examples only concentrate on single components. The authors in [21] proposed a digital hydraulic valve that can accommodate a fault and re-configure the valve parameters according to the detected fault. As the authors admitted, this digital valve is not protected from valve problems. However, it improves the overall fault resistance of the system. The authors in [22] proposed a fault-tolerant multilevel converter topology for switched reluctance machines. The results of the power losses analysis show that the proposed converter inherent fault tolerance does not have to dramatically decrease the overall efficiency. However, the major disadvantage is the increased number of switches in comparison to the conventional solution using redundant asymmetric bridge converters.

While there are ultimately no 100% fault-tolerant components nor a general method to monitor, detect, diagnose, or prevent a failure, measurements are needed to see what is happening in the system in order to prevent failure. Conventionally, modern control methods contain information that characterizes the normal and potentially degrading performance of a system and its components. Knowledge of information such as flow rates, pressures, actuator position, and elapsed operating time is obtained from sensors. Afterwards, measurements are compared with input data of known wear characteristics to form the basis of an analysis of degrading performance, therein detecting and diagnosing faults. Due to these potential problems, condition monitoring and fault detection for hydraulic systems are highly demanded to reduce the cost of maintenance and to prevent the system from deteriorating by detecting a fault in its incipient stage. However, due to inherent nonlinearities, fault detection in hydraulic systems is difficult to implement in practice. Compare to electric systems where fault detection is more achievable due to the nature of the systems. The state-of–the–art established methods for detecting common faults in hydraulic and electric systems are based on physical monitoring methods, model-based or frequency spectra analysis. The state-of –the –art demonstrates established methods for detecting common faults in hydraulic and in electric systems separately, however it has not been extended across both domains. It should be noted that conventional monitoring solutions use conventional standalone sensors.

These sensors, as a basic part of the monitoring systems, help to detect and diagnose failures. However, sensors add potential points of failure to the system and, therefore, can make the system more fault sensitive. Lower "malfunction sensitivity "can be achieved with a Virtual sensor. Virtual sensors utilize other sources of information to replace missing required information. Virtual sensors are widely explored in the literature for various applications. The authors in [23] demonstrated the implementation of a virtual sensor, which utilized an artificial neural network (ANN) in an FPGA system, which estimated the speed of a DC motor based on voltage and current signals. The behavior of the virtual sensor was analyzed in normal operating conditions and the error margin was less than 5% in real time. However, the method failed to show acceptable results in abnormal operating conditions. Another solution is to use a component as a source of information and utilize sensor fusion for monitoring purposes. This will potentially extend normal operation and prevent degradational and catastrophic failures in construction machinery.

V. CONCLUSION

Paper investigates a proposed method for hybridization of construction machinery by zonal hydraulics from failure point of view. Zonal hydraulics are suggested to be realized with pump-controlled actuators, which are distributed throughout the system. Due to both electric and hydraulic components being involved and tough working conditions, electro-hydraulic systems tend to be very complex, and where each one of components can fail. This paper reviewed possible failure modes in zonal hydraulics for construction machinery application. Due to complex nature of the EHA, new system-level failure modes were pointed out, which were not present in traditional valve-controlled systems.

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