Fault-Tolerance Control Architecture of Independent Metering Control System

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Abstract: Due to the special hardware layout and complex control method, independent metering control systems suffer from the problems of higher faulty probability and more faulty categories, resulting in decreases of safety and reliability. This paper first analyzed typical faults and their adverse effects on the whole system by the simulation and experiment on a 2 t excavator. Then, a fault-tolerance control (FTC) system is presented to deal with three faulty problems: lost function, lost accuracy and lost stability. The preliminary research about this FTC is also simulated on this excavator. The results demonstrate that under different faults of valves and sensors, the system can continue tasks by other available valves and sensors. The safety can be guaranteed with little degradation in motion and energy-saving performances.

Keywords: mobile hydraulic system, independent metering control, fault-tolerance control

1. BACKGROUD INTRODUCTION

In the conventional mobile hydraulic system, each actuator is controlled by one signal - the spool displacement of control valve. Therefore, it has disadvantages including weak adaptability, low energy efficiency and poor controllability. To address these problems, a programmable electro-hydraulic controlled way - independent metering control system is utilized. By breaking the mechanical coupling between inlet and outlet, the control degrees of freedom are increased to 2, and the electronic feedbacks are introduced to individually adjust the areas of meter-in and meter-out orifices.

In spite of many advantages such as improved flexibility, high energy efficiency and good controllability, independent metering control systems are still not widely applied in practical mobile machinery. Both Prof. Murrenhoff [1] from RWTH Aachen University and Weber [2] from Dresden University of Technology consider that one of the main obstacles which prohibit the system from industrial applications is the issues of reliability and safety.

Reliability and safety are important features of machines. A series of regulations and standards are set up to estimate them. A technical standard IEC 62061 “Safety of Machinery—Functional Safety of Safety-Related Electrical, Electronic and Programmable Electronic Control Systems” was presented by the International Electrotechnical Commission [3]. The International Organization for Stanrardization issued DIN EN ISO 13849 to focus on safety analyses of control systems, not only for electronic system, but also for mechanical, hydraulic and pneumatic systems [4]. Also, machinery safety has been commanded to laws by the directive 2006/42/EC in European Union [5] . Therefore, it is urgent to take into account the reliability and safety for the design and applications of machines.

On the other hand, the working conditions of mobile machinery are always complex and hazardous. What’s more, they are controlled directly by the operator without enough fences and similar safety measures to separate humans from danger. Therefore, mobile systems have tougher requirements for safety and reliability than industrial systems for achieving similar human safety. Specific to Earth-moving machinery, performance criteria and tests for functional safety are specially issued by ISO 15998:2008(E) [6].

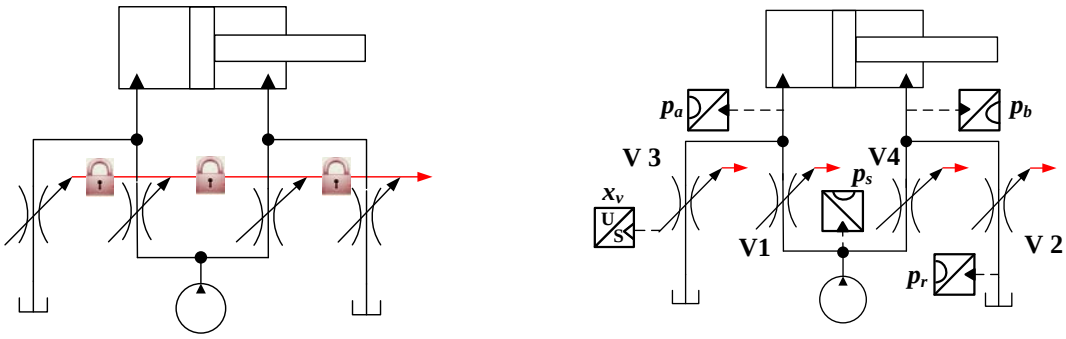
Due to the aforementioned two aspects, this paper aims to improve the safety and reliability of independent metering control system from the aspect of fault issues.

2. RESEARCH MOTIVATION

All hydraulic systems will inevitably suffer from the faults and failures to influence the safety and reliability. However, compared with conventional systems, there are the following distinguished features of faults in independent metering control systems:

(1) Hardware Layout

Fig.1 exhibits the system hardware layouts using conventional systems and independent metering valves (IMV). Because more than one valve are controlled simultaneously for one actuator [7], the system is unable to operate if any one valve encounters failure, such as spool jammed, electromagnet failure. The more valves arranged in hydraulic systems, the higher fault rate for the system will occur. Furthermore, to take advantages of IMV, many functions used to be attained by hydro-mechanical way are move into software with additional valves and electronic sensors. The reputation of electronics and sensors are less reliable than purely hydro-mechanical devices. Therefore, special hardware layouts make the system easier to occur failure than conventional systems.



(a) Conventional system (b) Independent metering control system

FIGURE 1. Comparisons of hardware layouts between conventional system and independent metering control system

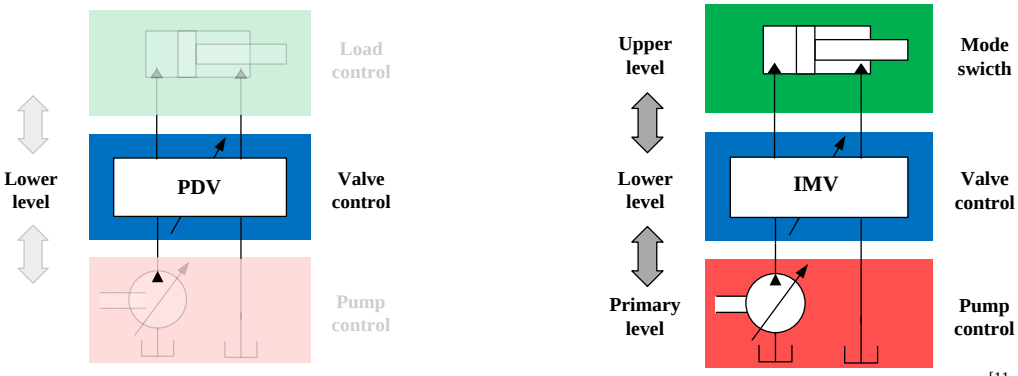
(2) Control method

In conventional systems, the velocities of actuators are controlled by steering the orifice areas according to the operator's command, so its control mode is simple. After breaking the mechanical coupling between inlet and outlet, the control modes increase by introducing the electronic and intelligent ways:

(a) The control degrees of freedom are increased to change the system as a multiple input and multiple output (MIMO) system [9], such that not only the velocity, but also the pressures can be regulated simultaneously;

(b) The control system is expanded to two or three levels, which mode switching is supplemented to save energy by regeneration, recuperation or float modes in terms of load characteristics [10].

Accordingly, it is also easier to confront with more types of faults because more uncertainties are introduced by the complex control algorithm.



(a) Conventional system (b) Independent metering control system [11, 12]

FIGURE 2. Comparisons of control architectures between conventional system and independent metering control system (PDV- Conventional proportional directional valve; IMV- independent metering valve)

According to the analysis of the two aspects, it can be inferred that compared with conventional mobile hydraulic system, the faults of independent metering control system have the features of higher probability and more categories, resulting in the decrease of safety and reliability. Therefore, this paper focuses on the faults issues of independent metering control in mobile applications and aims to build a fault-tolerance control system to deal with these faults in order to first assure the safety and then weak their adverse influence to the system.

3. FAULT DEMONSTRATION

3.1 Normal controller

The faults in independent metering control system are analyzed using a normal control method. The normal controller is a typical three-level control system. The upper level conducts load control to achieve individual fluid paths, such as regeneration and float, so it usually referred to as the mode switch. This control level selects the most efficient operating mode in terms of the current system states and desired motion trajectory, and it controls the transitions between different modes. The lower level conducts valve control under the selected operating mode. It aims to primarily achieve the desired motion characteristic and to attain secondary goal, reducing throttling losses. The pump control is also added as the primary level to adjust the supply flow and pressure.

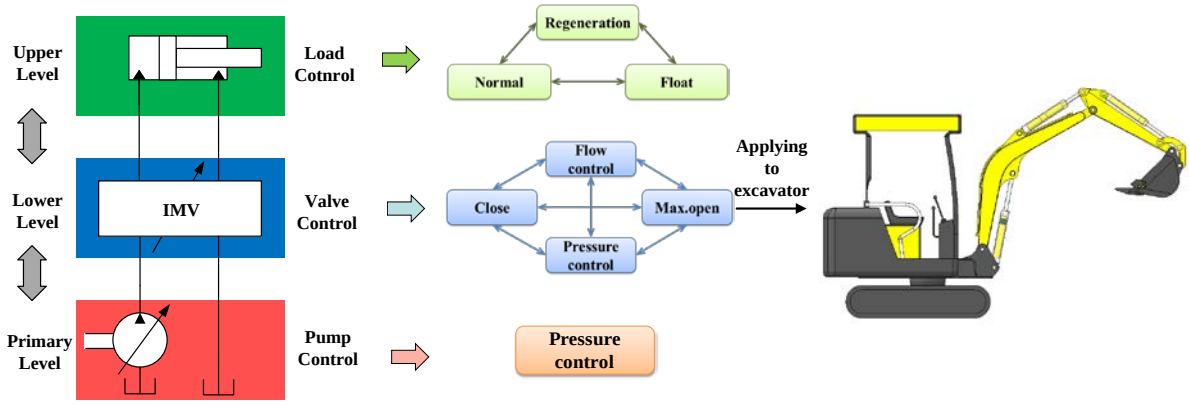
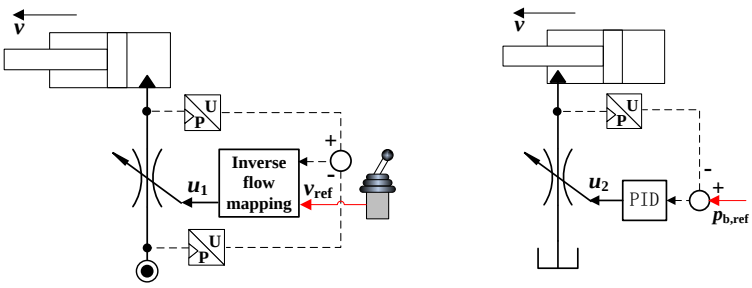


FIGURE 3 Control structure of normal controller for IM system

The schematic diagrams of valve control approaches are depicted in **Fig.4**. Generally, flow control is applied in meter-in valve to distribute the supply flow among multiple actuators. It is conducted by an electronic pressure compensator in terms of the inverse flow mapping of orifice to cancel out the flow dependency of load pressures. Meter-out pressure control is used to diminish the throttling losses across the meter-out valve and then reduce the supply pressure. The pressure is generally adjusted to 0.2 MPa to avoid the cavitation by a pressure feedback loop. The schematic diagram of the pump control approach is depicted in **Fig.5**. This is a close-loop control approach improved from conventional LS systems. It uses pressure transducers to replace complex load-sensing hose and control the pump electronically [13, 14]. Compared to conventional LS systems, the pressure losses in the meter-in valve can be reduced by optimizing the setting of pressure margin p_m adapting to the operating conditions.



(a) flow control (b) pressure control

FIGURE 4. Valve control approach of normal controller

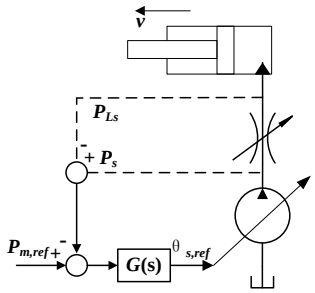


FIGURE 5. Pump control approach of normal controller

3.2 Fault analysis

Using the normal controller, typical faults are analyzed by taking a special application, 2 ton excavator. In this paper, the faults are divided into three categories:

(1) **Function lost:** it is caused by the failure of valve components. Hydraulic valves may encounter with the problems including jammed spool, disabled electromagnet, leakage, etc. Any fault in one valve will makes the actuators disable to track the desired trajectory. Referring to the boom upwards and downwards motions, the influences of the faults are shown in **Fig.5**.

Case 1-(a): During the process of boom upwards, the meter-in valve (Valve 1) is unable to open, then the cylinder is stoppage and the supply flow may overflow, resulting in the energy dissipation;

Case 1-(b): When the boom is lifted from lowering, if the valve which connects the head side and the drain line (Valve 3) cannot be closed, then a bypass leakage appears and the velocity of cylinder decreases. Sometimes the cylinder even moves reversely. This phenomenon is dangerous in excavators.

Case 1-(c): During the process of boom downwards, the cylinder is under overrunning load. IMV is operated in the regeneration mode to save energy. If Valve 3 cannot be diminished due to the spool jam, the cylinder drops rapidly and dangers occur.

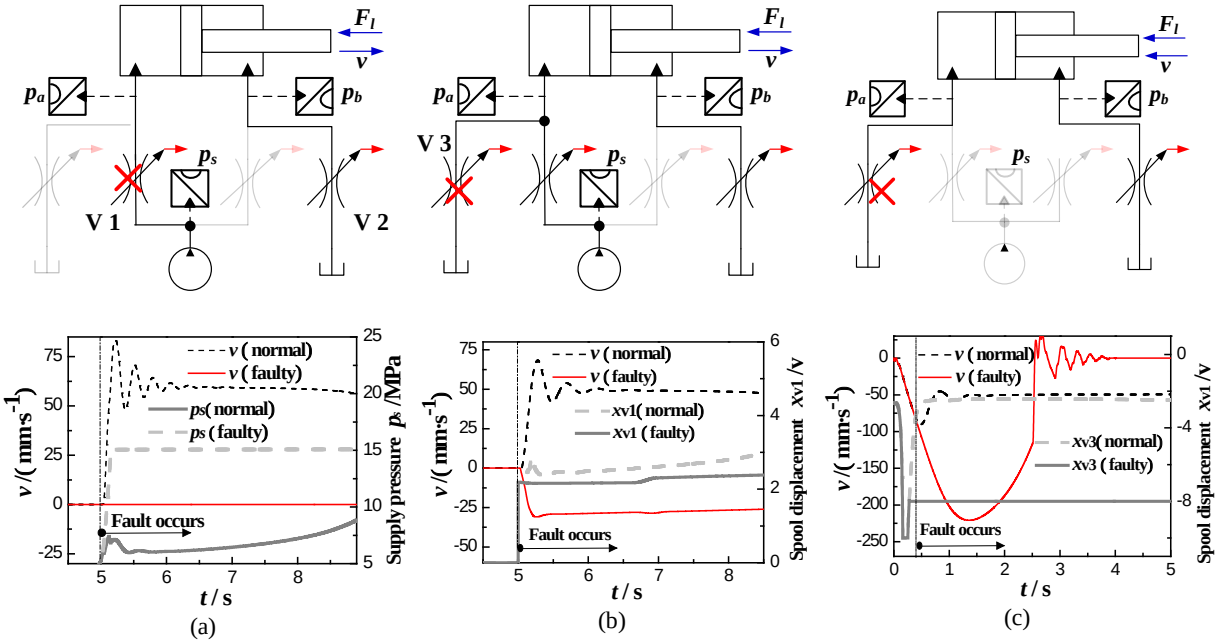


FIGURE 5. The influences of valve faults on the independent metering control system

(2) **Accuracy lost**: The system may be able to achieve required functions without valve faults, but the faults of sensors, including meter-in and meter-out pressure and spool displacement sensors, may cause the degradation of performance, even out of control. Also, some typical faults are simulated in boom of excavator.

When the boom is lifted, the normal mode is selection. The meter-in flow controller receives the feedback signals containing supply and head side chamber pressures (p_s & p_a) and the meter-out pressure controller receives the feedback signal of rod side chamber pressure (p_b). When the boom is lowered, the float mode is selected owing to the overrunning load, and the flow controller receives the feedback signals containing head side chamber and drain line pressures (p_a & p_r). One of pressure feedback signals is broken to simulate the fault of corresponding sensors. The influences of these faults are shown in **Fig.6**.

Case 2-(a): When the supply pressure sensor is faulty, the cylinder stops during upwards motion.

Remark: p_s is forced to 0 such that the calculated pressure difference of meter-in orifice is negative. Therefore, the valve control signal is small that the spool is unable to open, so the cylinder motion is stoppage.

Case 2-(b): When the head side pressure sensor is faulty, the cylinder stops during upwards motion.

Remark: p_a is forced to 0 such that the calculated pressure difference is larger than the actual value. Therefore, the control signal is less than required one, inducing the decrease of orifice area and accordingly the cylinder slows down.

Case 2-(c): When the head side pressure sensor is faulty, the cylinder drops rapidly during downwards motion

Remark: p_a is forced to 0 such that the calculated pressure difference of meter-out orifice approximate to 0. Therefore, the valve control signal is too large that the cylinder drops rapidly and dangers would occur.

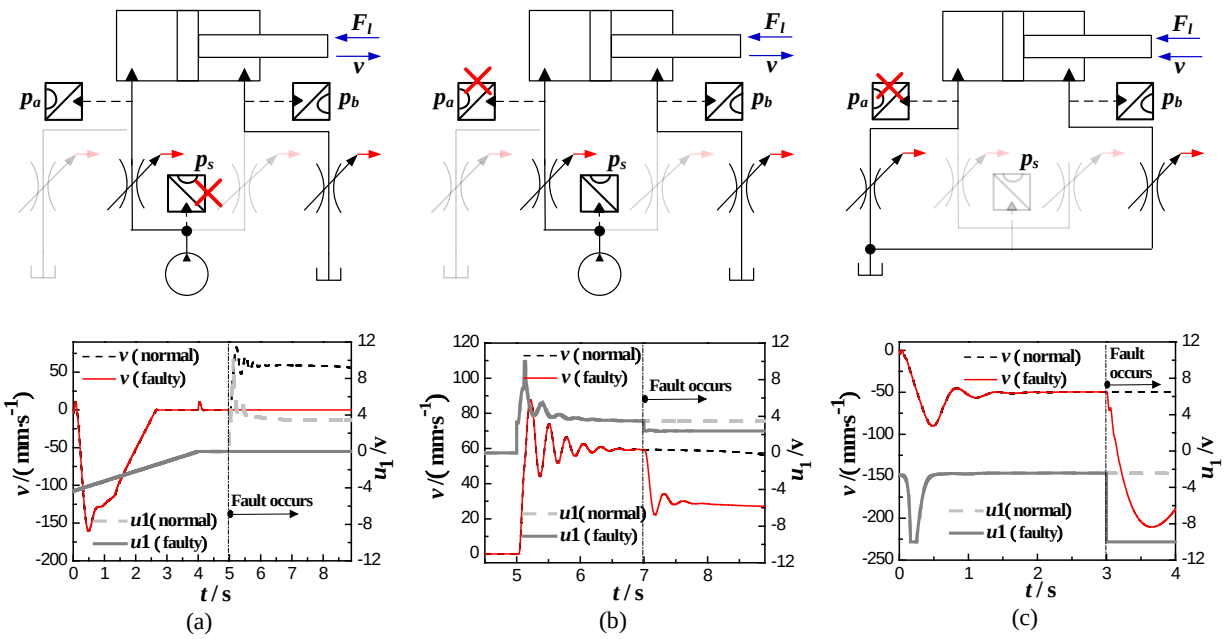


FIGURE 6. The influences of sensor faults on the independent metering control system

(3) **Stability lost**: There are no any faults in the hardware involving valves and sensors, but during the transfer instant of some additional functions using IMV, such as multi-variable control transfer, operating mode switch, the system become instability and it is unable to continue operating.

In the current research, the mode is usually transferred discretely based on the results of mode selection. The arm motion in Fig. 7 is taken as an example to demonstrate the mode switch process. The cylinder keeps extending, but the load force first decreases to zero, and then increases, with the variation from overrunning loads to resistive loads. Therefore, the load quadrant crosses from Qua.IV to Qua.I. For Qua.IV, the system selects the float mode, such that no energy is taken from the pump. When crossing to Qua.I, the system switches to normal mode. Two operating modes can be seen as two different sub-systems.

Fig. 7 shows the experimental results of the discrete switch for the aforementioned arm motion. The cylinder moves steadily until the mode switch occurs. A frequent switch phenomenon appears, and the pressures and velocity continues oscillating. It is a typical instability during the switch instant [15]. It can be inferred that in an integrated system with multiple sub-subsystems, the stability depends on not only the dynamics of sub-systems before and after mode switching, but also the dynamic during the switching instants. If the instability of this instant is difficult to converge, the whole system would oscillate such that the machine cannot continue working.

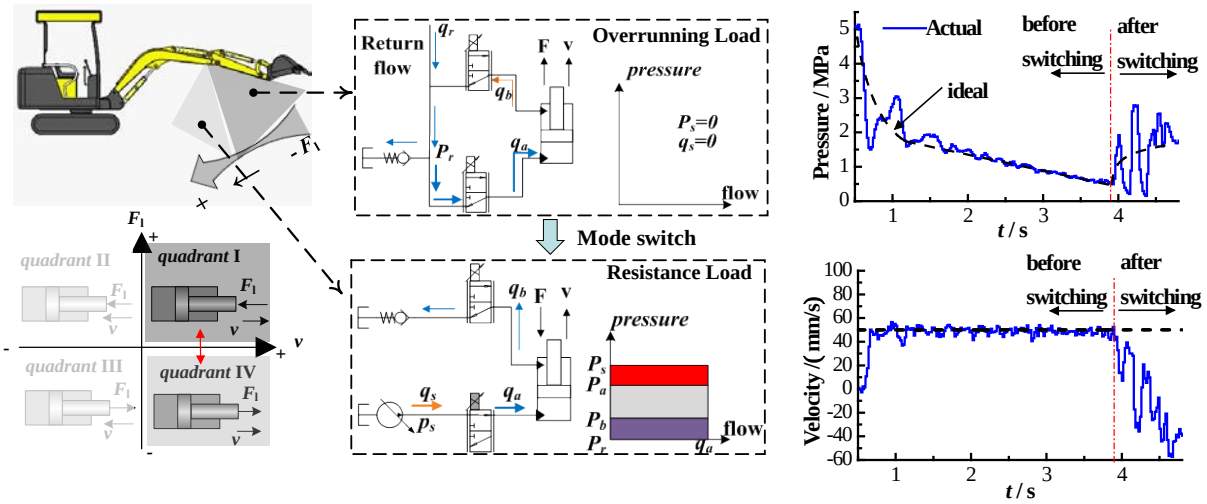


FIGURE 7. The instability fault in excavator by experiments.

4. FAULT-TOLERANCE CONTROL ARCHITECTURE

To address the three types of faults, a fault-operation control (FTC) architecture is built to parallel connect with the normal controller (NC). Considering that the faults have been identified accurately by the fault diagnosis techniques, the information of the fault are captured including its location, category and extend. Based on this information, the fault-tolerance control architecture aims to first assure machinery's safety and then weak the adverse effects on the system performances. It contains three sub-controllers:

(1) Multi-valve coordinates control to recover the system function towards valve faulty;

If one of valves is failure, the control mode in NC should be reconfigured by other available and standby valves. It is benefit from the multi-valve parallel layout using independent metering control techniques. In order to accurately compensate adverse effects by the faulty valve, the model of the faulty system is estimated according to the identified information of the fault, such that the dynamic characteristics under reconfigured modes can strictly match with that of faulty system. Then, reconfigured modes conduct coordinate controls of other valves to deal with the faulty valve.

(2) Multi-variable control with the absence of variable information towards sensor feedback faulty;

The faults of sensor will cause the absence of necessary state feedbacks. The remedy is to indirectly derive the state variable without its feedback. Owing to the coupling relationship between the internal system parameters, an equivalent variable can be constructed in terms of the mapping among different variables. Accordingly, the abnormal sensor feedback can be replaced. Although there exist faulty sensors, the multiple variables still can be controlled simultaneously based on the part of normal sensors.

(3) Multi-mode switch stability online monitoring towards switching transient faulty.

In order to assure the stability of switching transient, the control system considers this stability as a state variable. The key technique is to construct such variable to describe the energy of each sub-system for each instant. Then, this variable is monitored as a feedback to the controller. Based on the Lyapunov theorem of stability for the multi-subsystem, a stabilizing control law is searched such that the instability energy between two modes can be strictly converged.

5. IMPLEMENT OF FAULT-TOLERANCE CONTROL

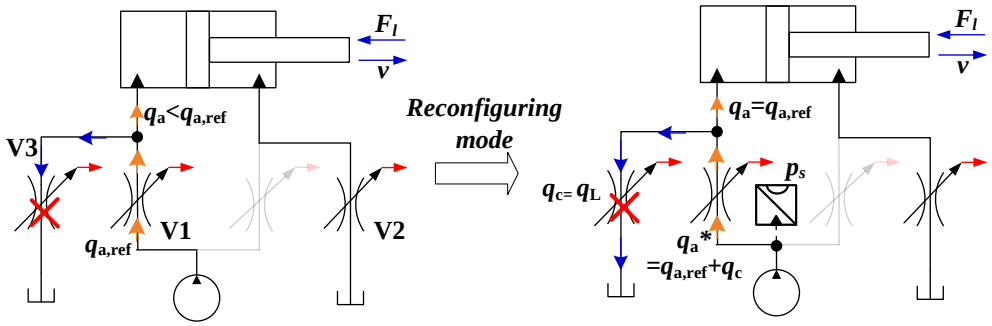
(1) Multi-valve coordinates control to recover the system function towards valve faulty;

Although the different faults should apply distinguished control methods, their common criterions are to compensate the disturbance of the faulty valve according to the estimations of its flow and pressure dynamics. **Figs.8** and **9** show designs of reconfigured modes for aforementioned faults Case 1-(b) and Case1-(c). In **Fig.8**, the flow across Valve 1 should be enlarged to compensate the bypass leakage flows across Valve 3. Therefore, the amended reference flow q_a^* are given by the sum of original reference flow $q_{a,ref}$ and compensation flow q_c:

$$q_a^* = q_{a,ref} + q_c \tag{1}$$

$q_{a,ref}$ is determined by the reference velocity of boom cylinder. q_c should equal to the leakage flow q_L. It is estimated online. In terms of the valve flow control algorithm Fig.4 (a), q_L is solved as an inverse way by the forward flow mapping of valves, as depicted in **Fig.10**. The forward flow mapping is to obtain the flow across orifice with respect to the pressure difference and spool displacement (or input control signal) by Eq.(2):

$$q_L = K_v(x_{v3}, p_a - p_r)\sqrt{p_a - p_r} \tag{2}$$



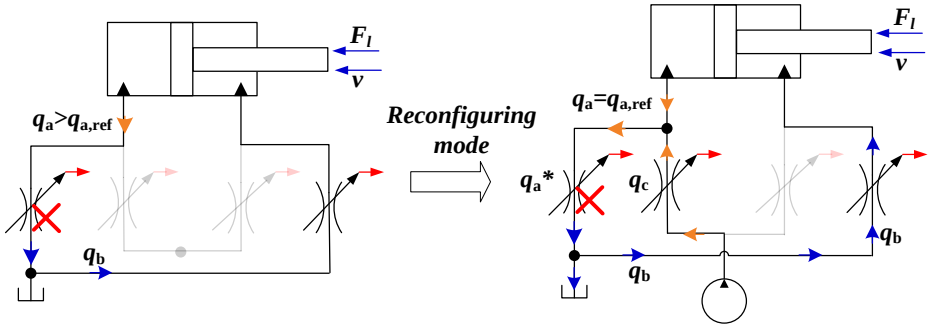
Normal controller (NC) Fault-tolerance controller (FTC)

FIGURE 8. Operation mode reconfiguration by the multi-valve coordinates control in FTC [Fault Case 1-(b)]

With an enlarged flow across Valve 1 in terms of Eq.(1) and Eq.(2), the adverse effect of leakage flow can be matched such that final flow into the head side chamber q_a equals to the reference value and the cylinder is able to track the desired velocity trajectory.

In **Fig.9**, the same control method is used but in this reconfigured mode, the pump and Valve 1 are active to supply flow as the compensation q_c. Faulty flows across Valve 3 are estimated by Eq.(3). It decreases the flow out of the head side chamber (q_a) and then avoids the rapid dropping of actuator.

$$q_a^* = K_{v3}(x_{v3}, p_a - p_r)\sqrt{p_a - p_r} \tag{3}$$



Normal controller (NC) Fault-tolerance controller (FTC)

FIGURE 9. Operation mode reconfiguration by the multi-valve coordinates control in FTC [Fault Case 1-(c)]

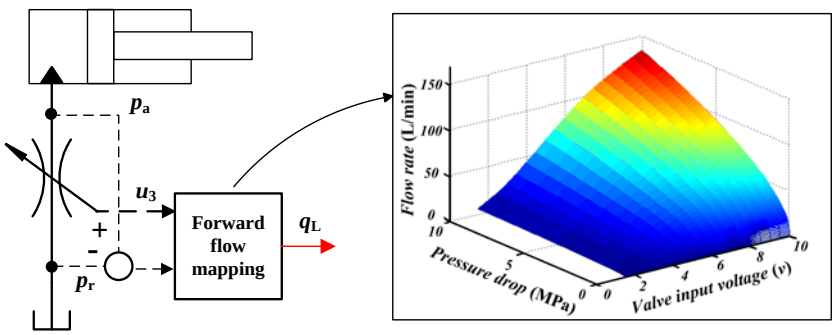


FIGURE 10. Flow disturbance estimation of faulty valve in FTC

Figs.11 and 12 depict the simulation results using proposed FTC for valve faults. **Fig.11** shows that the area of meter-in valve is increased such that more flows are supply to compensate the leakage flows across bypass valve and simultaneously drive the cylinder as the desired velocity. After this reconfiguration in control algorithm, the velocity is modified to approximate to that of the normal condition. **Fig.12** shows that the pump is active in the reconfigured mode and the supply flows are used to compensate the excess flow across the meter-out valve. Then, the flows out of the head side chamber when cylinder is retracted are decreased and the velocity is endeavored to track the desired value.

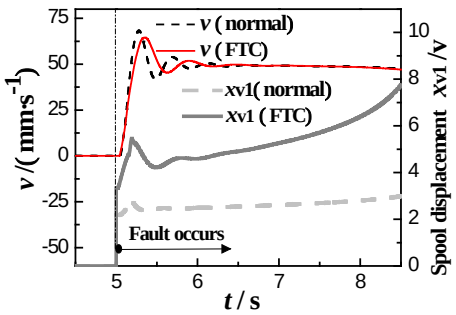


FIGURE 11. Simulation results by FTC[Fault Case 1-(b)]

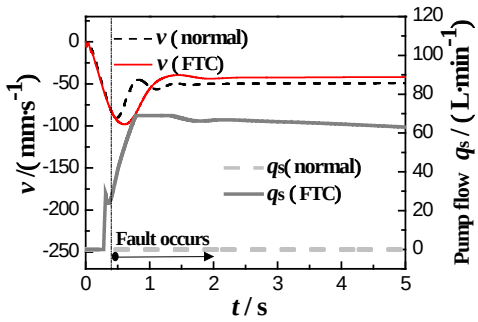


FIGURE 12. Simulation results by FTC [Fault Case 1-(c)]

(2) Multi-variable control with the absence of variable information towards sensor feedback faulty;

For the fault in Case 2-(b), pressure dynamics in the head and rod side chambers of cylinder are given by Eq.(4) and Eq.(5) due to the extension of boon cylinder:

$$\frac{V_a}{\beta_e}\dot{p}_a = (q_a - A_a v) \tag{4}$$

$$\frac{V_b}{\beta_e}\dot{p}_b = (A_b v - q_b) \tag{5}$$

Then, the pressure differential of the head rod side chambers can be by:

$$\dot{p}_{a,ref} = \frac{\beta_e}{V_a} q_{a,ref}(1-\kappa) - \frac{V_b}{V_a}\cdot\kappa\cdot\dot{p}_b \tag{6}$$

where κ represents the area ratio between head side and rod side (A_a/A_b). Therefore, p_a can be indirectly captured by the integral of Eq.(6). It is noted that the initial value of this integral equals to the value just when the pressure sensor fault occurs. With the help of indirect estimation of feedback signal, the velocity can be tracked to the desired trajectory without the pressure feedback of head side chamber by means of the differential of p_b signal.

Figs.13 and 14 depict the simulation results using proposed FTC for pressure sensor faults. Compared with **Fig.6(b)**, the velocity tracking performances are increased and the errors between the actual and reference velocities are decreased by the pressure differential control method. Compared with **Fig.6(c)**, there are no any hazardous movements occurring. There is still discrepancy between reference velocity and that of FTC. They are caused by the deviations of pressure estimations based on the pressure differential.

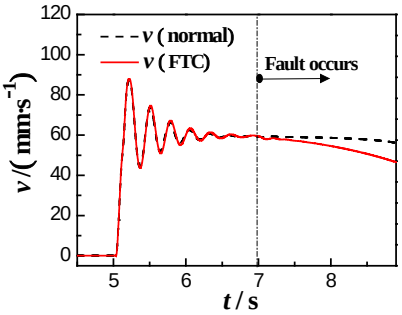


FIGURE 13. Simulation results using FTC [Fault Case 1-(b)]

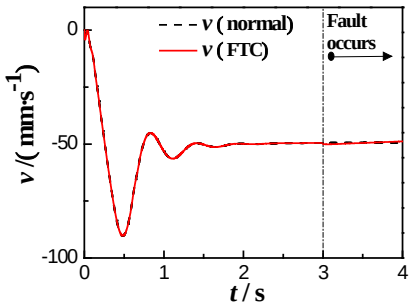


FIGURE 14. Simulation results using FTC [Fault Case 1-(c)]

6. CONCLUSION AND FUTURE WORK

Distinguished faults in the independent metering control system are researched in this paper. Typical faults and their adverse effects on the whole system are analyzed by the simulation and experiment on a 2 t excavator. They are divided into three categories: lost function caused by the faults of valves, lost accuracy caused by the faults of sensors and lost stability by the worsen dynamics between the mode switching. Then, a fault-tolerance control architecture containing three sub-controllers is presented: (1) adaptive reconfiguration of control law by multi-valve coordinate steering; (2) multi-variable control strategy with the absence of feedback signals; (3) stability online monitoring and prediction method. The preliminary research is simulated on a 2 t excavator. Then some typical faults are conducted by the proposed fault-tolerance controller. The results demonstrate that under different faults of valves and sensors, the system can continue tasks by other available components. The safety can be guaranteed with little degradation in motion and energy-saving performances. Future work will concentrate on the complete fault-tolerance control design and its verification by experiments on the excavator.

ACKNOWLEDGMENTS

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