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Aircraft Control System Validation via Hardware-in-the Loop Simulation

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I. Introduction

THIS Note presents experiences from the validation process of an aircraft control system—the yaw damper controller (YDC) with hydraulic actuators. The hardware-in-the loop (HIL) simulation on a hydraulic stand with a revolving platform and a loading force actuator was used in the validation process of this mechatronics system in the first step [1]. This Note extends the previous work by describing the next level of the validation process in which the YDC and actuators have been embedded into the aircraft where the interaction with the mechanical control system is validated by the HIL simulation. The yaw damper controller and the simulator are very briefly described and the practical experiences demonstrating the usefulness of the hardware-in-the loop simulation during detection of errors in the system components are mentioned.

The yaw damper (YD) is a device directly coupled with the aircraft rudder. It senses the yaw rate via a fiber optic gyro (FOG) and compensates oscillations via hydraulic actuators deviating the rudder. Even though it is designed to be fail-safe (it is disconnected from the ruder when a failure is detected) and the direct mechanical coupling of the rudder with the pedals guarantee controllability of the aircraft when the YDC does not work, a malfunction of the YDC could have a serious effect on flight safety. Therefore, the validation of the whole system controlling the ruder must be carefully undertaken.

HIL simulation is a popular validation method in many branches. The HIL simulator for an electrohydraulic flight control system has been described in [2]. HIL simulation has been used for the development of the antiskid braking system of the aircraft in [3] or for the flight-formation system [4]. HIL is also often used for development of control systems of unmanned aerial vehicles [5–9], and missiles [10]. Reference [11] presents a study of the performance of a fuel-cell powered unmanned aerial vehicles using HIL simulation of the aircraft in flight. HIL simulation is irreplaceable in the automotive industry and it is also very useful in power electronic controls, motor control, and energetic-component design and teaching.

The rest of the Note is organized as follows. The YD is briefly described in Sec. II. Section III presents the HIL simulator. The validation process is described in Sec. IV. The concluding remarks are mentioned in Sec. V.

II. Yaw Damper

The yaw damper is a device sensing the yaw rate of the aircraft via a FOG and compensating its oscillations via hydraulic actuators deviating the rudder. The YD actuation is additive to the pilot's commands. The direct mechanical linkage of the pedals with the rudder is maintained and the driving force of the YD actuators is mechanically mixed with the pilot's driving force. The YD fundamental blocks with the basic kinematics scheme are depicted in Fig. 1. The serial actuator (SA) is connected in series with the pedals' movements. Therefore, its deflection is additive to a deflection of pedals. The SA is used to add the YD actuation needed to compensate the yaw oscillations to the rudder deflection. To prevent propagation of the SA driving force to the pedals, the parallel actuator (PA), connected in parallel with the pedals' movements, is used. The YDC measures the force in the pedals via the force sensor (FS) and drives the PA to reach the defined force.

Several HIL tests have been specified to validate the YD functionality. The main goal was to identify the real dynamics and the rate of damping of the yaw rate. It has been accomplished for several points of the flight envelope and for different configurations of the plane. Backlashes, friction, and other nonlinearities in the closed loops can cause undesirable oscillations in the system. The intention of the HIL simulation is to identify the source of these oscillations. The most important issues were the dynamics of the new actuators, nonlinearities of the force sensor and the actuators, and the control law containing a Kalman filter eliminating the drift of the FOG.

III. Hardware-in-the Loop Simulator

The basic principle of the HIL simulation is based on the connection of real hardware devices (YD with electronic, hydraulic, and mechanical subsystems) with a computer-based simulator providing a real-time numerical simulation of the rest of the system (aircraft) in the closed loop. Because of the presence of the real devices in the closed loop, the simulation is as near to reality as possible in this validation phase. Because of the utilization of the model in the closed loop, the simulation is less expensive, easier, and less time-consuming than experiments on the real device; risks of damage to the real device are eliminated; and it is possible to perform simulation of the system behavior in extreme modes of operation that are hard, dangerous, or even impossible to induce on the real device. A measurement and data-logging implementation is much easier and flexible on a stand than on a flying aircraft. All input signals are

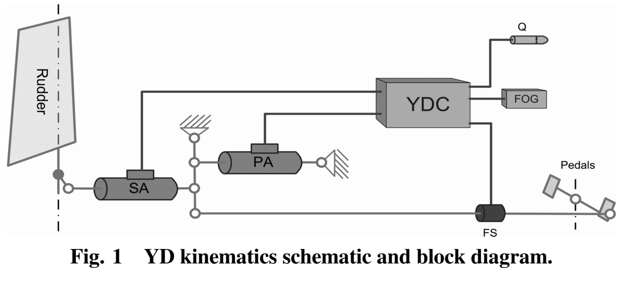

Fig. 1 YD kinematics schematic and block diagram.

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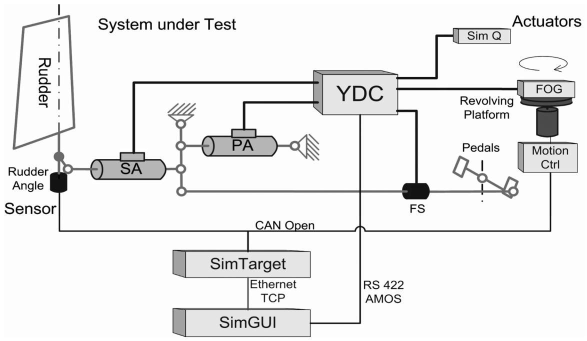

Fig. 2 HIL simulator for YD testing on the plane.

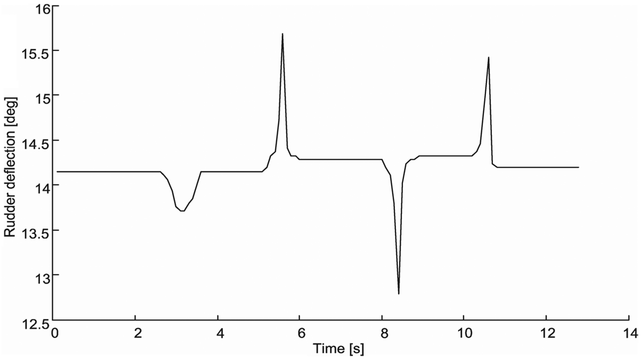

Fig. 4 Rudder deflection caused by PA backlash.

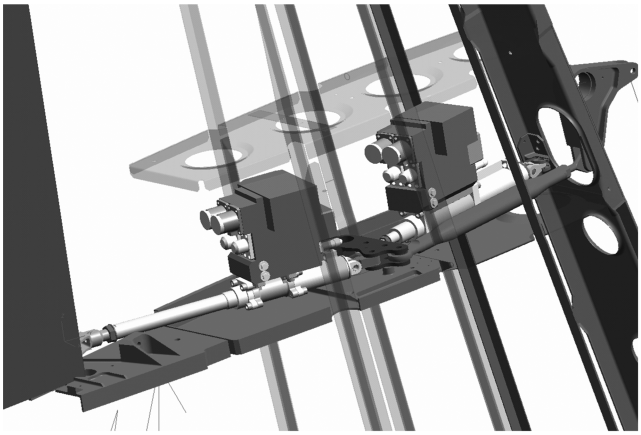

Fig. 3 YD actuators in the rudder fin.

deterministic in the computer-based HIL simulation. The reproducibility of a passed experiment is therefore easy, contrary to flight tests.

At the YD HIL simulator, the system under test is the YDC with actuators (PA and SA) installed in the aircraft (see Fig. 2). The aircraft yawing is simulated by rotating the gyro on the revolving platform, and the angle of the rudder is measured via the sensor. The numerical model of the aircraft is executed in real time by an embedded computer (SimTarget). The graphical user interface (SimGUI) is implemented in MATLAB. SimQ allows one to set the dynamic pressure *Q* manually. Pedals are used for accomplishing maneuvers. The real-time communication between sensors, actuators, and SimTarget and their synchronization is provided via the CAN bus and CANopen protocol. The SimGUI gathers data from the SimTarget via an Ethernet. Additional data are acquired from the YDC via the RS422 port with an AMOS protocol intended for monitoring purposes.

The hydraulic actuators are installed directly in the rudder fin (see Fig. 3). The control loop therefore contains all real components providing any undesirable features as friction, backlash, and other nonlinearities or unknown dynamics that have been omitted or only estimated at the YDC control law design.

IV. Validation Process

In this section, we briefly describe the few main steps of the YD validation process. All components of the YDC and the actuators have been developed by third parties. Aero Vodochody, the aircraft manufacturer, therefore focuses on the integration tests.

YD functionality has been tested via HIL simulation on a hydraulic stand at the first step of the validation process. Since the actuators had not been finished at that time, temporary actuators from different aircraft were used. Even though the temporary actuators have different dynamics and do not allow testing of the YD disengaging in case of failure, these experiments have been very useful. A very simple experiment passed on this HIL simulator proved that there was an error in the YDC SW: the sign of the yaw rate measured by the FOG was wrongly interpreted under race conditions [1]. These experiments have also been very useful for validation and improvement of the test methodology. This later helps us to pass all experiments on the new actuators much faster.

When the new actuators were delivered and installed on the hydraulic stand, a very strong tendency for the oscillations was observed in the closed loop. An experiment in the open loop helps to identify an undesirable backlash of the parallel actuator PA (manual force of about 500 N deflected rudder for more than 1 deg when the current to PA and SA was zero; see Fig. 4). The actuator developer can later isolate and solve the problem caused by an anticavitation valve, based on this result. After the PA correction, the complete YD system has been validated on the hydraulic stand by the set of HIL simulations.

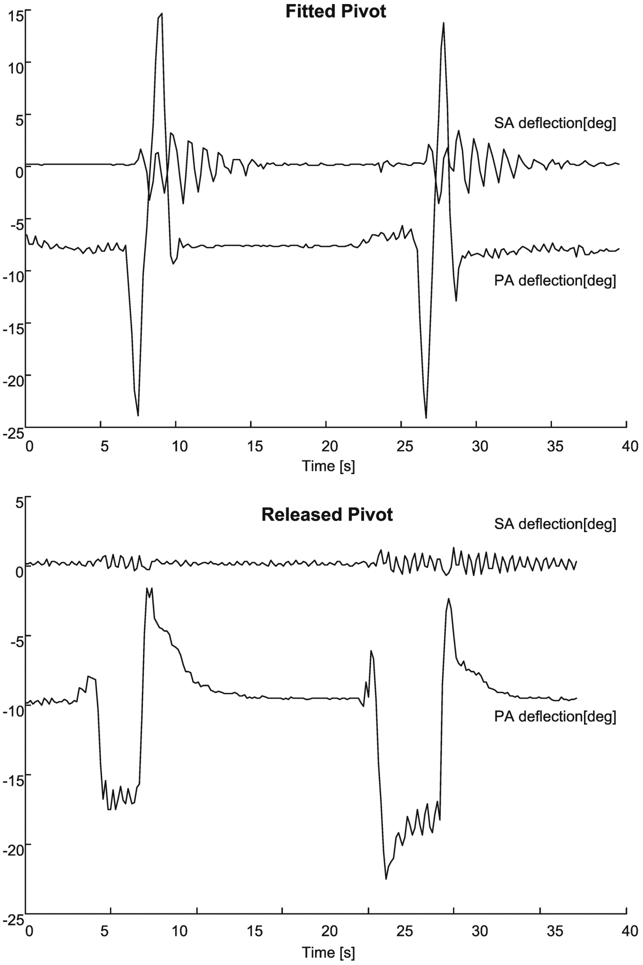

Fig. 5 Effect of the released pivot linking the PA and SA.

The final step of the ground validation was the integration of the complete YD system to the aircraft. The HIL simulator has been used to simulate FOG rotation according to the mathematical model of the aircraft. Since the schedule of the flying aircraft (the only one equipped with the necessary systems) was very tight, actuators have been installed into the tail of the nonflying aircraft and the complete tail prepared for experiments was quickly installed to the fuselage of the flying aircraft at the time scheduled for the experiments.

Contrary to the stand experiments, experiments on the aircraft do not use the actuator simulating the aerodynamic load. Experiments on the hydraulic stand showed that the aerodynamic load does not affect the dynamics too much. Experiments on the aircraft have been focused on the YD interaction with the real mechanical control system, which was substituted by the reduced mass on the stand. The passed HIL simulations have revealed a high sensitivity to the backlashes in the connection of the PA, SA, and control rod (see Fig. 3). When the pivot linking PA and SA is not fitted well, the closed loop has a tendency to oscillate (see Fig. 5).

V. Conclusions

The experiences with the yaw damper validation process via hardware-in-the loop simulation have been described. Since both the key components of the system (yaw damper controller software and parallel actuator) contained an error, the hardware-in-the loop simulation was found to be very useful for error detection, isolation, and its demonstration to subcontractors.

The management personnel responsible for the project had an education and know-how in mechanical engineering. Hardware-in-the loop simulation is therefore more acceptable for them than a numerical simulation. The demonstration of the yaw damper functionality on the real aircraft helps to demonstrate the viability of the yaw damper project, even when it was late (caused by the described errors in components).

From the economical point of view, it is worth mentioning that the effort put into the hardware-in-the loop simulator, stand, and experimental installation to the aircraft has also been reused for the validation of the aeroelasticity.

Acknowledgments

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