BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LXV No. 3/2013	65 - 70	Seria Tehnică

Control Design of a Pipe Testing Facility

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Abstract

This paper presents the model based design of the control structure for hydraulic pipe testing frames. The obtained control structure is tested and evaluated on a software simulator. The simulation results can be used as reference for a future implementation of advanced control to a pipe testing facility.

Key words: *hierarchical control, predictive control, modeling*

Introduction

The pipe testing facilities are used to test full scale tubular goods used mainly in petroleum drilling and production. The testing facility consists in a frame which is designed to simulate the borehole conditions and to allow the online behavior evaluation of the tubular material. For the validation, the tubular material are subject to complex combined loads (axial, bending, torsion), internal or external pressure, and temperature cycles. The magnitude, dynamic and combination of these loads result in various pipe body failures.

Beyond the engineering design problems of the testing frames, a big challenge is to assure a good quality and versatility of the tests. These requirements can be achieved by implementing an appropriate automation system which must fit the standards requirements, in order to offer testing flexibility, to optimize the running procedures and test quality, to allow future improvements, and to add safety and economic benefits.

Based on the actual computing power, the advance of control technologies can be pushed further in the domain of nonconventional control.

The Pipe Testing Facility Setup

In order to test and qualify tubular goods, it is necessary to use a full-scale testing frame able to generate extreme combined loads. The frame must be designed to simulate the borehole conditions and to allow the online behavior evaluation of the tubular material. The measurement system must be able to provide coherent information to the control system and to estimate values that cannot be measured with installed instrumentation. The actual standards [1] require to record the controlled values as the axial load in compression and tension, the internal and external pressure, the bending intensity, and the temperature. The control system must manipulate in real time the process values in order to obtain an accurate position of the states with respect of the sequence and the trajectories between states.

Beyond the standard requirements, the frame must offer customization for testing procedures and, eventually, upgradability in order to carry out tests corresponding to future standards. The versatility of the frame is represented by mechanical construction and also by the control system that must be able to cope both with load and displacement controlled tests on tubular material.

The common features of the testing frames are the actuation principles and the constructive setup. The actuation is based on hydraulic systems that provide advantages over electrical actuators like [2]:

- Are producing large forces at high load stiffness;
- Hydraulic fluid acts as lubricant and cooler reducing the wear and the maintenance;
- High speed response;
- Overloading protection is simple with pressure relief valves.

The issues of hydraulics are represented especially by high dynamic non-linearities and by cost as a result of low tolerance geometry. The tests performed by full scale testing facilities are based on failure principles and are quantifiable by measurements. In order to conduct the test, several variables must be manipulated, measured and controlled.

Model of the Hydraulic Actuation

In this section, the model of a general hydraulic actuation system is derived, containing an unbalanced double way hydraulic cylinder powered by pumps, drained by valves and having an elastic payload. All the actuators contained by testing facility are based on the same principles, and therefore can be analyzed in a general manner. Before approaching every loading system, it is necessary to analyze a standard hydraulic actuation system. Figure 1 shows a typical dynamic system used for force and displacement manipulation.

The double acting asymmetric cylinder reacts on the pressures from both chambers and generates a force on the piston or displaces it. The flow injected by the pumps will build up a pressure that will energize the piston. To withdraw the piston, the chamber pressure is released by a 2-way valve. In this figure, the payload is a spring with a stiffness k that is moved by the asymmetric cylinder having an equivalent mass m of the piston and the rod. In this scenario, considering the direction of the displacement y positive, the lower chamber will be pressurized. The displacement controlled pumps P_1 and P_2 are generating the volumetric flow Q_{P1} and respectively Q_{P2}. The cylinder chambers are drained by the servo-valves V_1 and V_2 with the volumetric flows Q_{V1} and Q_{V2}. The forces in the system are: F_y – the actuation force of the piston created by the pressure, F_f – the friction force on the piston and the rod seals, G – the weight of piston-rod assembly, F_e – the elastic reaction force of the spring and F_d – the external disturbance force. Q_L denotes the volumetric leakage flow between the chambers.

The u_{P1}, u_{P2} denotes the electrical commands for the pump speed, respectively u_{V1}, u_{V2} the electrical commands for control valves opening. The equivalent force generated by the piston is F_P.

The oil volume of the two chambers and the compliant pipes is expressed as:

$$V_1(y) = V_{01} + A_1\, y \tag{1}$$

$$V_2(y) = V_{02} + A_2\, y \tag{2}$$

where: A_1, A_2 – piston active surfaces in the chambers [m^2]; V_{01}, V_{02} – the initial volumes of the piston chambers and the volume of the pipes between pump and valve [m^3].

By evaluation of a single actuator, one can synthesize the multivariable model of the testing frame as multi-DOF (degree of freedom) mechanical system.

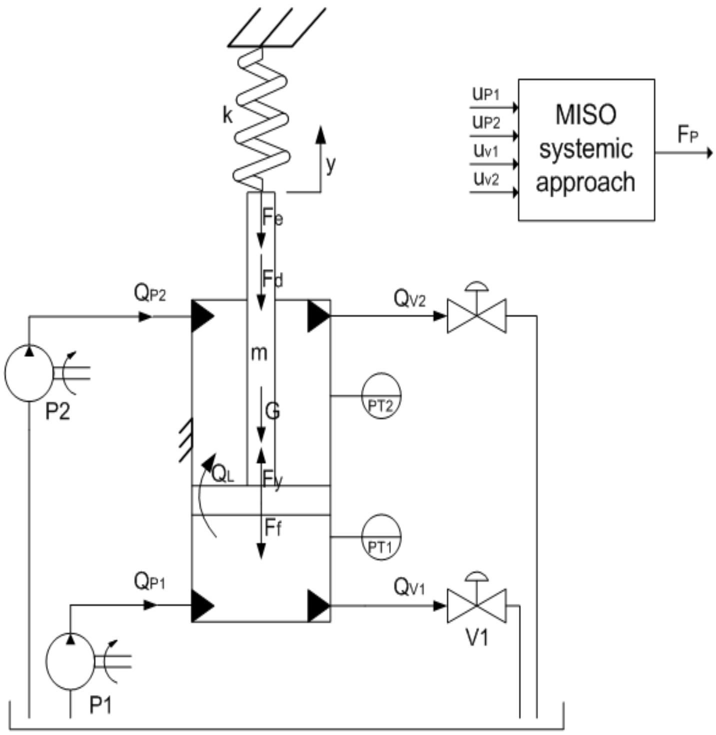

Fig. 1. Typical hydraulic actuation system.

Control Planning and Evaluation

The new demands for tubulars testing accuracy and complexity are difficult to satisfy. The expected new standard becomes even more severe with additional requirements for the testing frames and the appropriate control systems.

The design of a control system can be tested on the simulator prior the implementation in the real process. Based on the actual computing power, the advance of control technologies can be pushed further in the domain of nonconventional control. The primary objective of a testing frame control system is to bring and maintain the primary loads to the desired operating condition in an accurate, safe and efficient way. Unfortunately, not all process values can be measured directly. In this case the missing values have to be estimated. The variables associated with the control system are enumerated in Table 1.

Table 1. The variable associated to the control system

Subsystem / variable	Axial	Internal Pressure	Bending
controlled	F_A	P_i	B_i
manipulated	u_A	u_P	u_B
measured	Axial piston chamber pressures, bending piston chamber pressures, intensifier hydraulic pressure, ΔL, P_i, Temperature		
calculated	B_i, F_A		

The process variables are imposed by the testing procedures. The manipulated variables are applied to control vales in order to create a specific pressure in the hydraulic actuators. The measured variables are provided by sensors, which should be placed physically in points that provide maximum sensitivity and unwanted transient regimes.

Organization of the Testing Frame Hierarchical Control System

The control design has to identify the control strategy and the control structure based on process particularities, issues and requirements.

The multi-loop control issue arises from the controlling process variables due to internal interactions. The most undesirable problem is the system overshoot and instability. The interactions can generate a type of *race conditions* around the steady regime which can lead to oscillation and instability. In the classical approach the problem of multi loop instability is solved by:

- Just one loop is active at a time, in the tracking regime only one variable is controlled;
- Each controller is tuned to be efficient in steady state regime without considering the tracking regime and loop interactions;
- Large tolerances are used for the steady state regime, allowing the system to stabilize and to ignore the interactions.

The enhancement for a new control system to deal with process nonlinearities is the so called *gain scheduling*. This technique is using a series of stored controller settings, specific to every operating zone.

In the classical approach for the actual control system all control tasks are implemented on standard controllers and are supported at a single regulatory level. The unpretentious requirements for the classical control system allowed to implement a multi-loop control without appropriate knowledge of the process.

The proposed control design for the pipe testing facility does consider more complex requirements than the previous implementations, when the process model is available. The obsolete multi-loop control strategy can be replaced by another control structure which should satisfy a wide range of control particularities:

- The process has relatively strong interactions between variables. The problem could be solved by using a multivariable control strategy.
- The process exhibits non-linear behavior. As the process model is now available, it can be explicitly embedded into the control algorithm [3]. This technique is termed Model Based Control.
- The process has measurable disturbances. Because the temperature is a priori known, its influence can be compensated using feed-forward techniques.
- The constrains on process variables should be satisfied. For the pipe testing process the maximal values of internal pressure and equivalent axial load are limited by the limit load envelope. Additionally, the transitions between states (the tracking regime) should be performed at a predefined rate. These requirements can be achieved by implementation of Model Predictive Control (MPC).
- Wastage minimization of the internal pressure fluid. This requirement can be accommodated by implementation of an optimization procedure.
- Lack of measurements for friction force. In this situation the process variable like actuator force should be estimated using the modified LuGre frictional model. This technique is named soft-sensing [4].
- Decision and diagnostic requirements. The key terms of the problem are the safety in operation for personal and facility, and supervision of control sequences. The events like fault detection or constraint violation should generate procedures to bring the process in a

safe state. Tasks of monitoring and supervision should be carried out in order to evaluate and trigger the testing sequences. These requirements can be implemented by an inferential rule based system.

Starting from the overall enounced problems, the challenge in control design of pipe testing facility is to assemble the control functions in layers with specific targets. The proposed concept can be projected as a hierarchical control structure as depicted in Figure 2 [5].

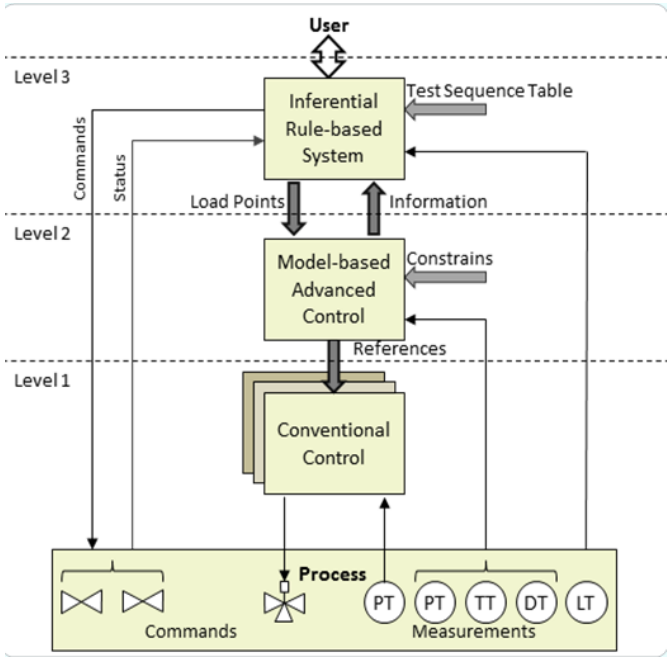

Fig. 2. The layers of the pipe testing process control hierarchy.

The level 1 – the conventional control has a regulatory function on the hydraulic pressures that are provided to actuators. This layer contains instrumentation components which have functions as measurement, actuation, switching and protection. In Figure 1 the transducers are measuring: PT – pressure, TT – temperature, DT – displacement, LT – leakage intensity. The commands are targeted to three-way proportional valves and directional control valves. The directional valves are enhanced to confirm the status by electrical signals. All the three subsystems are regulated at this level by individual feed-back single loop controllers, which references are provided by the hierarchical Level 2. At the regulatory level the control loops should assure the best dynamic response without the knowledge of the process interactions. The mono-variable control systems will be discussed in the next section.

The level 2 – the advanced control has the objectives to elaborate commands which should be delivered as appropriate references for the regulatory level. The controller design for this level should be focused on problems that have a multivariable nature with constrains. Additionally, the designed controller must deal with feed-back and feed-forward variables as well. The input variables are measured by the transducers attached to process or evaluated by additional computational blocks. The references for the advanced control level are provided by the third hierarchical level.

The level 3 – the inferential rule-based system has as objective to schedule the test process sequences based on predefined rules. The rules describe the machine behavior in case of events in order to assure safety, quality and efficiency of the testing process. This structure is providing the set-points for the second level and can operate directly into process by directional valves.

At conceptual level the first layer is operating with raw data as pressures, the second layer is using filtered values and the third level is working with information.

Conclusions

This paper presents a structural approach of pipe testing process automation. The process is modeled as multi input multi output with the respect of the channels interactions. The target of hierarchical decomposition is to create appropriate control structures for the testing process purposes.

The core of the designed control system for pipe testing process is represented by Model Predictive Controller (MPC). This is an optimal multivariable controller, able to handle multiple interactions between process logical channels in presence of constraints.

The control strategy is detailed on three hierarchical levels as: an internal loop which controls the actuators hydraulic pressure, an external loop where the references for internal loop are generated, and a higher level that is in charge for safety, supervising and scheduling of entire process.

The control performance is benchmarked on the process simulator with several test types. The tests were designed to evidence the control structure behavior for typical situations during a testing procedure.

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Proiectarea unei structuri de reglare pentru o instalație de testare țevi

Rezumat

Această lucrare prezintă proiectare unei structuri de reglare bazată pe model pentru o instalație de testare țevi. Structura de reglare obținută este testă şi evaluată pe un simulator. Rezultatele simulărilor pot fi utilizate ca referință pentru implementarea unei structuri avansate de reglare pentru o instalație de testare țevi.