System Control logic enhancements through Fluid-Mechanical valve dynamic transfer functions

Turbomachines performances control is strictly depending from the interactions between the system control logic and devices dynamic (i.e. valves, drivers, actuators, etc…) which can act or promote modification of main fluid systems parameters over all working conditions. In order to seamlessly link the physical behavior of the system components, the functional instructions must be properly exchanged through the same language. This is possible describing the real components evolution with a system of equations that control logic can understand. Manageable input-output relations are often achieved from simplification and most of them are usually taken as they are, without any possibility of improvements. Approximations errors are inherited from previous applications and because of these, many situations arise where machine do not work as expected with the need of fine tuning in the field. In the worst scenario errors propagation in transient run may cause system response drift which cannot be recovered, with unknown consequences.

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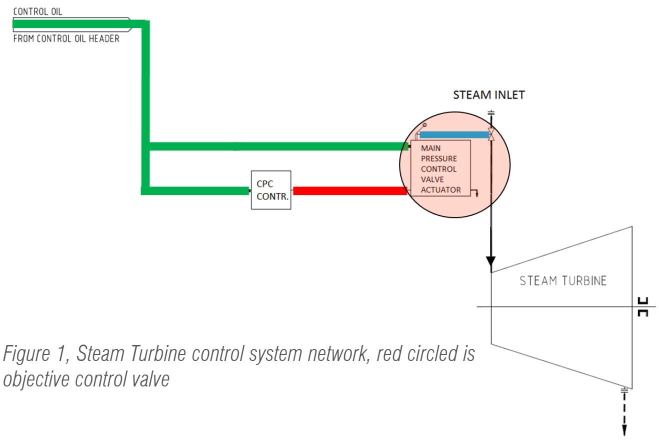

Figure 1, Steam Turbine control system network, red circled is objective control valve

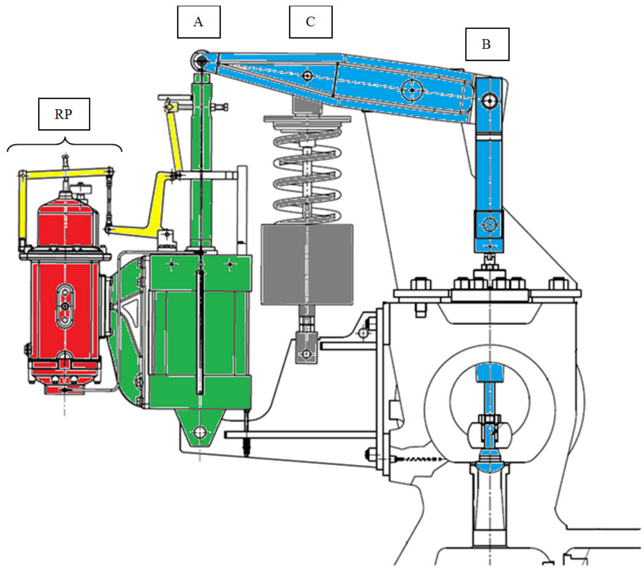

Figure 2. Steam control valve and main components

A similar issue arose in a Steam Turbine plant, where control logic became unable to manage the bulk steam control valve dynamic, resulting in output power oscillation. This article highlights how, with one-dimension CFD software such as FlowmasterTM, it is possible to improve the traditional approach on auxiliaries' characterization through analytical multi physics system study. This will lead to confirm the goodness of current approximations or rather generate an equivalent transfer function of the entire system for additional studies.

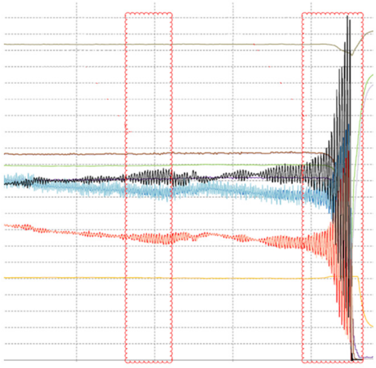

Figure 3, Output power (black), high pressure turbine (blue) and low pressure turbine (red) command fluctuations

Pressurized oil from lube console (green line) is used for two purposes. As previously said, it is the force source to move the steam valves, but it is also used to control how much these should be opened (or closed); because of this last purpose, the system needs a fine and precise regulation to be carried out. The lube oil is properly metered by a sort of PID controller named CPC (Control Pressure Converter) and transformed in lower pressure signal (red line), which is varying in a limited range.

Figure 2 shows valve main component in detail. Control functioning is below.
Starting from the left there are: the servo-cylinder in red, the actuator piston in green, the closing spring (grey), the leverism and valve stem (blue, bottom right) through which the steam passes, and the repositioning levers in yellow.
Servo-cylinder is connected to the lube oil console and to the CPC controller, from which receives the oil pressure signal in the given range. When the control oil signal is constant, the vertical servo-piston is in balanced position, under the forces of that pressure and of a movable spring inside the top cap of cylinder. In such case the lube oil can't move to actuator cylinder, because passage areas are closed by the servo-piston. In cases of CPC pressure signal change, forces balance is missed and the servo-piston starts moving up or down, depending on pressure increasing or decreasing, respectively.

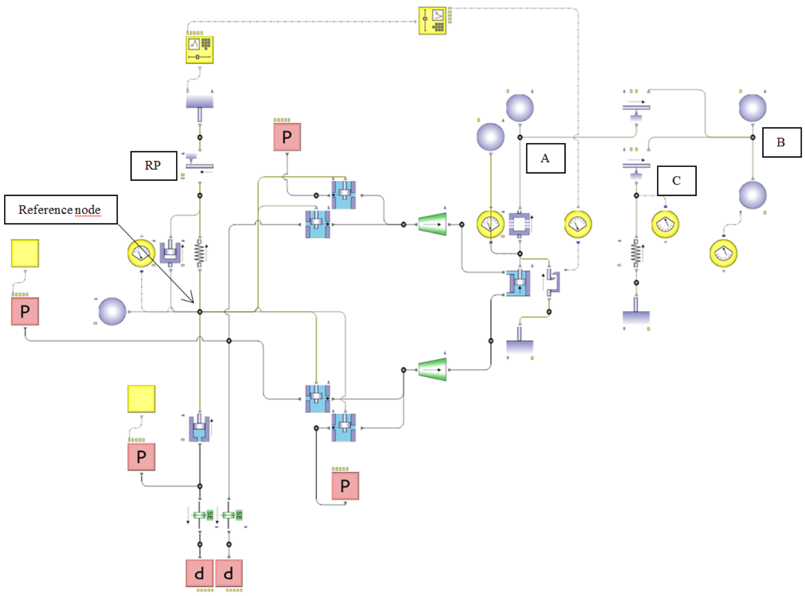

Figure 4, Steam control valve Flowmaster network

In details, the previous mentioned steam control valve is modeled within Flowmaster software to properly reproduce item dynamic. Valve working conditions are strictly connected to feeding network behavior; the simulation will take into account these influences. Once model results are validated, advantages are expected in terms of simplification and other possible situations might be explored widely. Integration of the model in the control logic environment will make easily foreseen any related communication problems.

Steam control valve

Steam Turbine power depends on quantity of steam sent inside. Control valve manages the opening of machine inlets passage, allowing the steam to entry in turbine. Opening ratio establishes the steam mass flow rate and so the produced power. Due to steam high pressure and flow rate, forces involved are high too and require bulk elements to resist. It can be imagined just considering valve total weight, which is above 500 kg. To promote motion of these heavy components it necessary to take pressure from the hydraulic circuit of lube oil console. Nominal pressure requirement is up to 10 barG, oil consumption up to 80 l/min in steady condition. In Figure 1 a schematic view of network.

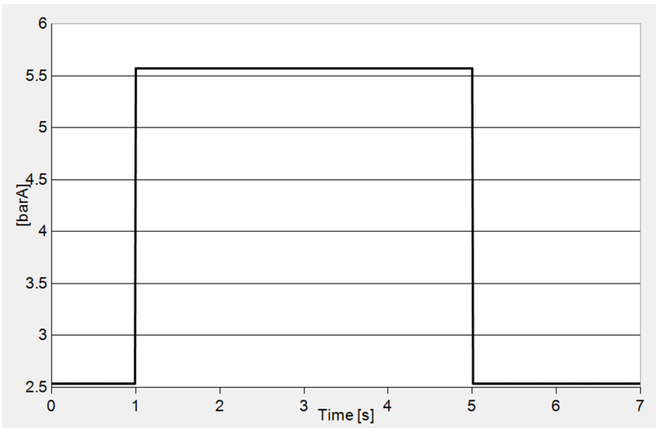

Figure 5, CPC pressure control signal for stated test

During this movement, passages area open and lube oil can reach the force cylinder. If the servo-piston moves up, oil fills the upper chamber, the lower is emptied, force piston is brought down with all the levers winning big spring force and making steam ports to open; meanwhile the repositioning levers follow the actuator piston lift and it responds in order to carry the servo-piston down and move it in the closed position. The same evolution, but in the opposite direction, takes place when the control pressure

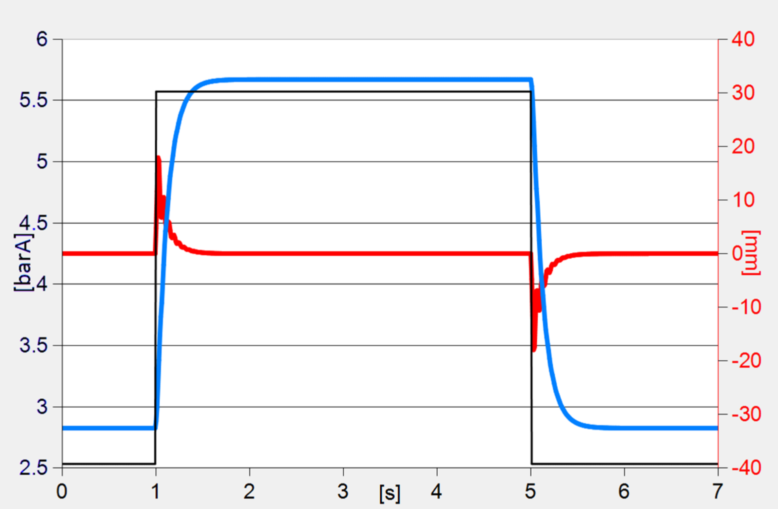

Figure 6, Servo-piston evolution (red) and valves rod position (light blue)

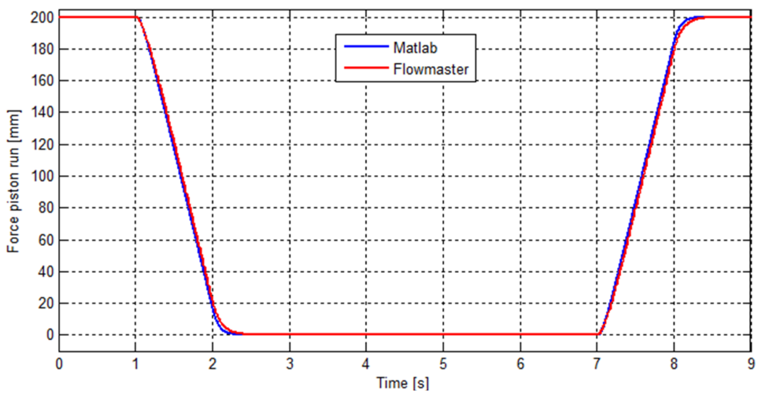

Figure 7, Flowmaster and Matlab response comparison, force piston stroke

decreases, causing the servo-piston descendent and the steam valve to close.
Steam valves opening ratio depends on control pressure signal value: for lower bound value, valves become fully closed, fully open for upper limit and an intermediate ratio for signal value within the range.

The components which are involved in control valve kinematic are bulk and much massive elements:

- Servo-piston: 4 kg
- actuator piston: 120 kg
- Levers & valves: 357 kg

These weights play a fundamental role in valve dynamic evolution, even in relation with the control logic response speed.

Control valve manufacturing is several generations of steam plants old. Tolerance gaps are not as reduced as modern solutions. Oil leakage in steady close position (up to 80 l/min) isn't negligible considering it might have effect in the lube oil console performance and it's a mandatory constraint to be evaluated in oil pump choice.

Piston motion involves big oil quantity and heavy bulk elements displacement; dynamic response depends on these parameters. The likelihood of asynchronous evolution between load and displacement could arise in case of inadequate control logic gain. Just as happened to the Steam Turbine plant, where control logic couldn't properly follow the load dynamics, bringing the turbine in an unstable power fluctuations, as in example of next Figure 3.

Flowmaster model approach

Control valve is a complex hydro-mechanical item. Flowmaster multi-physics network has to be created using, hydrodynamic, electro-mechanical and controllers libraries.
In the following Figure 4, Flowmaster steam control valve network is reported.

Single components, as they are implemented in the code, will not be able to reproduce the complexity of real behaviors. Thus, starting from those, it is required to find a particular component linking configuration which reproduces the physics as realistically as possible.
On the left side of the network is the servo-cylinder, probably the most difficult to model in order to simulate the true evolution. To schematize the servo-piston and ports interactions, two different branches are needed. One side is referred to a pressure source from lube oil console. The oil flux to the actuator cylinder chambers is alternated: when the upper channel is linked, the lower is discharging, and viceversa. For each channel, a couple of port components are used, where one port is for charging and the other for the discharging phase, acting in counter phase. Port opening command is derived from the other branch. It is in fact necessary to create a mechanical node to which referring to establishing servo-piston balance (i.e. close position). This node is the mechanical side of Single-acting Piston. That plunger replaces the servo-piston pressure area wetted by control oil from CPC. On the top, such node is linked to the over cap spring. Balance position is reached when reference node level is equal to zero. Positive deviation brings the upper charging and lower discharging ports to open. Again, opposite reaction is for negative displacement. Bottom sources refer to pressure and control oil leakage in steady balance position. Of easier modeling is force piston, with Double acting Piston, in figure right middle. The last bulk lever isn't directly available too since the libraries do not have a simple Lever item with possibility of three mechanical connections, as required instead. A possible solution is to divide the lever in two sub levers, with pivots in same position (with respect to the datum level): the longer is connected to force piston (A) and to steam valves mass component (B), the shorter to closing spring (C) and to same node of previous mass (B). Servo-piston repositioning system is in on top middle. Actuator piston stroke is read on related End Stop and sent to the Controller Template (one on the left) where compiled transfer function is to move the RP lever end. This transfer equation replaces middle L-shape yellow lever (Figure 2). Another RP lever joint is linked to the second free end of servo-cylinder cap spring. Each member has the proper mass value assigned.

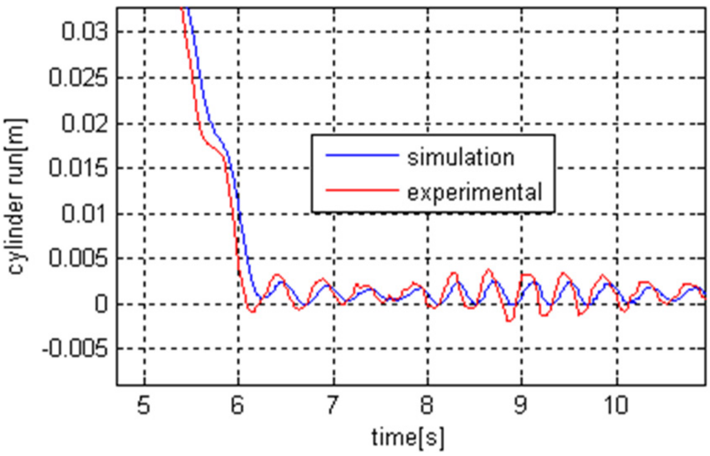

Figure 8, control system computational model vs. experimental behavior

Test transient simulation and results

Pressure control signal from PID controller is in a range from 1.5 barG to 4.5 barG. As already said, constant value of it doesn't allow valve movement, because servo-piston is balanced under oil pressure and spring force, keeping available areas closed. When control signal changes in 1.5 barG, unbalancing take place and steam valves are turned fully closed; if control pressure become 4.5 barG, those valves move to completely open position. It is important to notice that during force piston stroke, repositioning levers act on top spring: this will restore piston balance and valve stop to move.
To establish model goodness, a variable control signal is given as simulation parameter. It is expected a valve behavior as previous described. In order to highlight the right evolution of the dynamic response, a severe control signal is chosen made of impulsive steps as squared wave:

- Between 0 - 1 s constant control pressure of 2.5 barA
- At 1 s an impulsive step to about 5.5 barA occurs
- Constant pressure of about 5.5 barA till 5 s
- Sudden negative step to 2.5 barA given at 5 s
- Again 2.5 barA till the end of simulation (7 s)

In Figure 6 are shown servo-piston and steam valves rod stroke when described signal is applied.

Any CPC pressure signal changes, causes the servo-piston unbalancing and so the ports to open. With about 5.5 barA pressure the system will carry the valve lever to the upper bound position (30 mm, fully open) and 2.5 barG to the closing reference instead (-30 mm). With reference to the picture 6, the red line highlights the servo-piston while in blue the lever motion.

Parallel to the Flowmaster simulation, a Simulink/MATLAB network was built. This because all the existing control logic as implemented in the field was available in MATLAB environment, such solution will definitely fit the best the entire control network. Whenever a complete valve multi physic Flowmaster model is available, an equivalent Simulink algorithm can be tuned with the same available data in order to retrieve a comparable valve dynamic behavior. In Figure 7 the outcome of the two models with the comparison of the actuator piston as response to a CPC impulse.

The network emulates the expected dynamic of that control valve, showing an aligned response also under severe fast changing demand.
For inputs changing in assigned range, steady state simulation brings out a response surface.
Dialing with response surface means to have reproduced all the possible evolutions over the stated inputs range. Flowmaster can further extend the usage of the above network by generating a transfer function, whereby input-output correlations are turned in a program code. This would represent control valve logic block. S-function would be created in MATLAB language, matching dialogue capability of control logic system and allowing a great opportunity to properly represent the physical problem.
However, in this specific case, the generation of such transfer function isn't possible. The valve working phenomena is intrinsically transient: if steady conditions are kept, i.e. control pressure signal is constant, no valve movement will occur. Under those statements, response surface, and thus S-function, could not be created, being not able to take into account time dependences.

To bypass this missing key, contemporary Simulink simulation took place. In view of the usage of Flowmaster model to validate the Simulink one, once that comparison gives positive conclusion, with aligned responses evolution, MATLAB network can be tuned with right field gains and parameters. Then, after the integration with logic, the whole control system was tested to verify the correct modeling in reference to experimental data.

Conclusions

Steam control valve complex dynamic was reproduced through Flowmaster network. Each component could be modeled with proper elements making clever usage of scripts within controllers so to simulate the correct mechanical or fluid-dynamical behavior. Dedicated test validated the obtained valve behavior, making such model a central point for control logic integration. Since the control logics are often available in Simulink/MATLAB environment, it is desired to have the code able to generate a more complete S-function to condensate the complex valve model in a more powerful way. Simplification is clear: with a user-friendly software as Flowmaster it might be possible to define and convert any desired device into manageable and validated transfer functions, that can be connected to the rest of the control logic network. This will of course reduce internal iterations cycle and improve the time calculation speed.

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