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Nonlinear Sensitive Control of Centrifugal Compressor

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Abstract**—**In this work, we treat the problems related to chemical and petrochemical plants of a certain complex process taking the centrifugal compressor as an example, a system being very complex by its physical structure as well as its behaviour (surge phenomenon). We propose to study the application possibilities of the recent control approaches to the compressor behaviour, and consequently evaluate their contribution in the practical and theoretical fields. Facing the studied industrial process complexity, we choose to make recourse to fuzzy logic for analysis and treatment of its control problem owing to the fact that these techniques constitute the only framework in which the types of imperfect knowledge can jointly be treated (uncertainties, inaccuracies, etc..) offering suitable tools to characterise them. In the particular case of the centrifugal compressor, these imperfections are interpreted by modelling errors, the neglected dynamics, no modelisable dynamics and the parametric variations.

The purpose of this paper is to produce a total robust nonlinear controller design method to stabilize the compression process at its optimum steady state by manipulating the gas rate flow. In order to cope with both the parameter uncertainty and the structured non linearity of the plant, the proposed method consists of a linear steady state regulation that ensures robust optimal control and of a nonlinear compensation that achieves the exact input/output linearization.

Keywords**—**Compressor, Fuzzy logic, Surge control, Bilinear controller, Stability analysis, Nonlinear plant.

I. INTRODUCTION

THE control of centrifugal compressors at their optimal states is of a considerable interest as it can enable to reduce their production costs.

The control of the compression system is extremely difficult. They are characterized by:

- The lack of accurate mathematical models due to the complexity of the compression processes,
- Invariably nonlinear and time varying nature of the systems during the compression processes,
- Lack of reliable on-line controllers that makes the process state very difficult to be characterized.

Since the compression processes are inherently nonlinear the control design must be able to deal efficiently with the process nonlinearities and variations. There are in principle three different approaches to achieve it: robust control, adaptive control and nonlinear control.

The closed loop nonlinear control techniques seem to have quite good performances in comparison with other methods, but they have also some drawbacks.

The effect of parameter variations and of the compression process variables the linearizing effect of the controller and closed loop system has poor robustness properties. Therefore a total controller design method which includes both linear and nonlinear compensations is needed.

This approach is based on the following ideas: Parameters in the process model are considered as time varying quantities and the sensitivity functions are used to predict the effect of their variation on the process of compression.

The extended problem for control synthesis is formulated taking into account the requirements for low sensitivity of the obtained solution to the slowly varying parameters.

It is looked for a solution that leads to a compromise between a quality functional and these requirements. The obtained control can be called an optimal sensitive control.

- The nonlinear structure of the extended process model is directly used to derive simple nonlinear sensitive control law.
- Optimal linear sensitive control is synthesized on the basis of the linearized system to follow desired set points.

During the last decade, the **C**ontrol **T**heory and **A**pplications **L**aboratory of **A**utomatic (LAA) of Boumerdes University has been involved, in collaboration with industry, in designing new control strategies to improve the surge control of high pressure industrial compressors.

As for all practical systems, the compression system exhibit nonlinear behaviour. Hence the required system performance, when made of a standard PID controller with fixed gains is used, is reduced; especially when the controller is required to operate over a region about the point of tuning. One solution to alleviate this problem is to use a bilinear controller, which has been developed recently to improve consistency in terms of performance over a range about the point of tuning [9].

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The bilinear controller is nonlinear, involving products of system state and control. While the bilinear controller offers improvement over a linear controller, further improvement in performance is seen and it was considered that fuzzy logic techniques may be good candidates for achieving this. The aim of this paper is to describe different structures of fuzzy logic controllers, (predictive controllers) and their application on a system of compression [2, 3].

II. The Compression System Model

Over the last fifteen years, Moore and Greitzer developed a phenomenological model for rotating stall and surge [12]. This pioneering work modeled the compression system with just three components. The first component is the inlet duct that allows infinitesimally small disturbances at the duct entrance to grow until they reach an appreciable magnitude at the compressor face. The second component is the compressor itself, modeled as an actuator disk, which raises the pressure ratio by doing work on the fluid. The third component is the plenum chamber (or diffuser) downstream, which acts as a large reservoir and responds to fluctuations in mass flow with fluctuations in pressure behind the actuator disk. In this paper, we are considering a compression system consisting of a centrifugal compressor, close coupled valve, compressor duct, plenum volume and a throttle. The throttle can be regarded as a simplified model of a turbine [13]. The system is showed in Fig. 1.

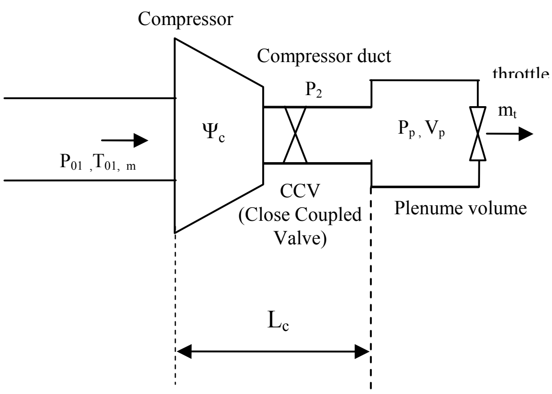

Fig. 1 Compression system with CCV

The model to be used for controller design is in the form:

$$\begin{cases} \dot{P}_p = \dfrac{k\,P_{01}}{\rho_{01}\,V_p}\left(m - k_t \sqrt{P_p - P_{01}} \right) \\[2ex] \dot{m} = \dfrac{A_1}{L_c}\left[P_{01}\left(1+\eta_i\ (m, N)\dfrac{\Delta h_{ideal}}{C_p\,T_{01}} \right)^{\frac{4(k-1)}{k}} - P_p \right] \\[2ex] \dot{N} = \dfrac{1}{2J\pi}\left(\dfrac{\eta_t\ m_{tur}\,C_{p,t}\,\Delta T_{tur}}{2\pi N} - 2\,r_{22}\,\sigma\pi N\left| m \right| \right) \end{cases} \tag{1}$$

Where m is the compressor mass flow, p_p is the pressure downstream of the compressor, a_{01} is the inlet stagnation sonic velocity, L_c is the length of compressor and duct, A_1 is the area of the impeller eye (used as reference area), N is the spool moment of inertia. The two first equations of (1) are equivalent to the model of [4].

The Moore-Greitzer model gives rise to three ordinary differential equations, the first for the non-dimensional total-to-static pressure rise Δp across the compression system, the second for the amplitude of mass flow rate fluctuations m, and the third for the non-dimensional, spool moment of inertia. In the above equations, σ and β are constants that are characteristics of the system. The quantity ϕ_T determines how much mass will be removed in a user-controlled fashion through a bleed valve. It may be written as [5]:

$$\phi_T = \gamma\sqrt{\Delta P} \tag{2}$$

Reflecting the fact that the mass flows through a bleed is proportional to the square root of the pressure drop across the bleed valve [11]. The function γ must be properly chosen as it will be discussed later.

The functional form between ϕ and ψ is simply the performance map and is often approximated by [16]:

$$\psi = a + b\phi + c\phi^2 + d\phi^3 \tag{3}$$

where a, b, c, and d are constants which must be determined by a curve fit to the experimental data. The most important approximations underlying the Moore-Greitzer model are that (i) it is valid under small perturbations m, and, (ii) the time scale of the dynamics governing m is much faster than the time scale of the dynamics governing ϕ.

The present work has analytically integrated the right hand side of equation (1). This integration does not require in priori assumptions about the analytical form of the performance map [7, 8].

Note that the Moore-Greitzer model does not attempt to explain what physical mechanism triggers these instabilities.

Rather, it attempts to determine the favourable conditions under which the disturbances will grow, and what can be done to suppress the instabilities. Its simplicity, mathematical elegance, and generality have led to a wide acceptance and the use of this model by researchers in industry, government and academia. It is also used in surge control research with the belief that rotating stall is a precursor to surge, and with the expectation that elimination of rotating stall will also eliminate the development of surge.

The instabilities within compression systems can be studied using energy considerations. As shown by Gysling and Greitzer [14] the rate of energy input by the compressor to the fluid (over and above the steady state input) may be written as:

$$\delta E = \int_{Annulus} \delta(\Delta P)\delta\phi dA \tag{4}$$

If this integral is positive, energy is added to the fluid by the compressor, and the disturbances will grow in amplitude. In the performance map shown in Fig. 2, the slope of the curve is negative to the right side of the peak. In this region, a small increase in mass rate flow $\delta\phi$ will decrease pressure, so that $\delta(\Delta p)$ is negative.

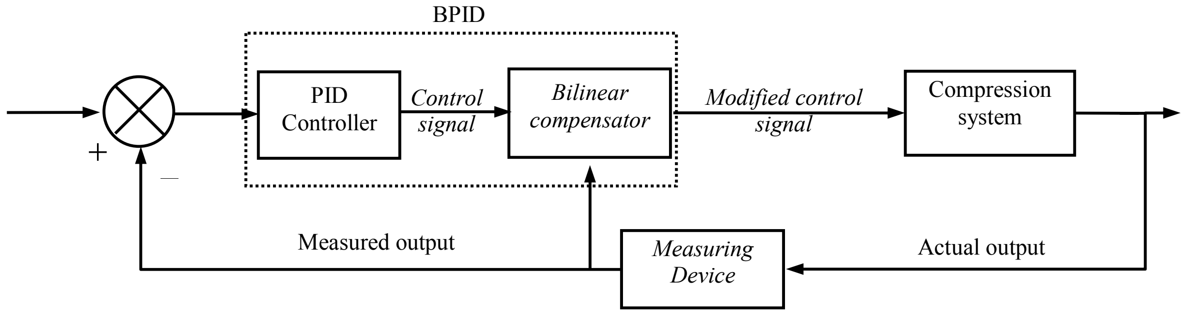

Fig. 3 Bilinear controller with PID structure for a compression system

The above integral is thus negative for the performance map that is to the right of the pressure peak. The side of the performance map to the left of the peak pressure point is, by similar arguments, unstable. Even though compression systems are designed to operate to the right of the pressure peak making them inherently stable, small disturbances such as change in the compressor RPM, rise in back pressure or inlet stall can push the operating point momentarily to the left of the pressure peak, triggering instabilities. Control systems in current generation of compressors open bleed ports in the plenum chamber downstream. This has the dual effect of increasing the mass flow rate, and/or dropping the pressure rise, thereby shifting the operating point to the right (stable) side of the performance map [6].

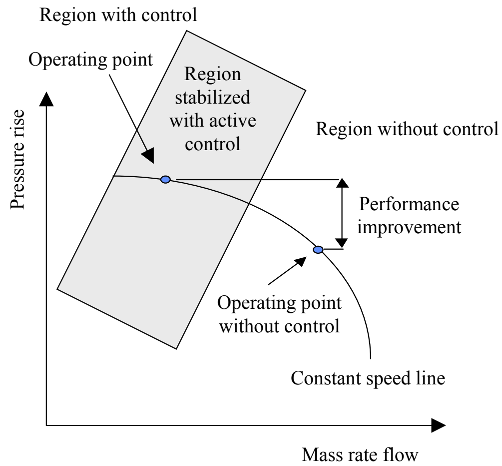

Fig. 2 Compressor performance characteristic map

The controller may be written as:

$$\gamma = C_1 + C_2 A^2 \tag{5}$$

Where C_1 and C_2 are positive constants

III. The Bilinear Controller

At present the bilinear PID controller is implemented on compression system. The bilinear controller is realised as a combination of a standard linear PID controller and a bilinear compensator. The resulting scheme is known as the BPID as illustrated in Fig. 3.

Before implementing the bilinear compensator in the compression system, a mathematical model was used to simulate the continuously operated compression system under Matlab/Simulink. The same model has been used to design the fuzzy logic controller. The simulation model corresponds to a single zone.

Two different sets of time constants are used in the PID controller [1, 11]. For a positive deviation, where the rate flow is too high, the output signal to the flow control element produces a gradual correction to allow time for the control system to react, thus avoiding over-correction and risk of surge. If there is a negative deviation from the set point, a different set of time constants is used to open the by-pass valve quickly. This allows more gas to recirculate, increasing the flow rapidly enough to avoid surge conditions. The application module offers bumpless switching between the two sets of constants [10, 15]. Fig. 4 gives a schematic representation of the compression process.

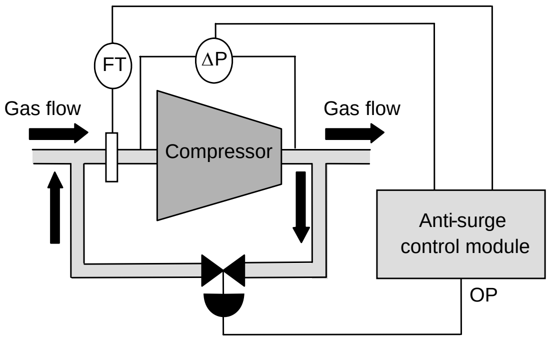

Fig. 4 Compression process

In order to avoid turbulence, the application module also monitors the rate of change of the flow through the compressor. If the rate flow begins to change rapidly, the anti-surge control module opens the valve fully [4, 9]. This allows the maximum amount of gas to recirculate and increase the flow through the compressor. In general, the control system should be tuned so that the valve is shut most of the time, since recirculating the gas consumes energy.

IV. Simulation Results

In an attempt to improve performance, different strategies to design a fuzzy logic controller were studied. The first considered approach was aimed at evaluating the complexity of a possible fuzzy logic controller, based on the existing BPID controller. In this case, the fuzzy logic controller attempts to replicate the functionality of the existing nonlinear controller using collected simulation data.

The training sets were based on sampled data taken from the simulated system including the BPID controller

A set point has been applied to the simulated system and then the sampled signals (with error, delayed system output and delayed controller output as inputs) have been recorded for subsequent use in the training of the fuzzy logic controller. The best results with the fuzzy logic controller are obtained.

The results of two simulations are presented in this section. The first is the response of the compression system (the mass flow coefficient and the response of pressure coefficient) with Greitzer parameter $B = 1.50$, and the second simulation is the response of the compression system (the mass flow coefficient and the response of pressure coefficient) with Greitzer parameter $B = 0.50$. For both simulations the value of J, the squared amplitude of rotating stall was set to zero, and the throttle gain was set so that the intersection of the throttle line and the compressor characteristic is located on the part of the characteristic that has a positive slope.

The response of the compression system with Greitzer parameter $B = 0.50$ is shown in Fig. 5 for the mass flow coefficient and the response of pressure coefficient. This figure shows the output controller with fuzzy logic and BPID controller for the mass flow coefficient and the output controller with fuzzy logic and BPID controller for the pressure coefficient.

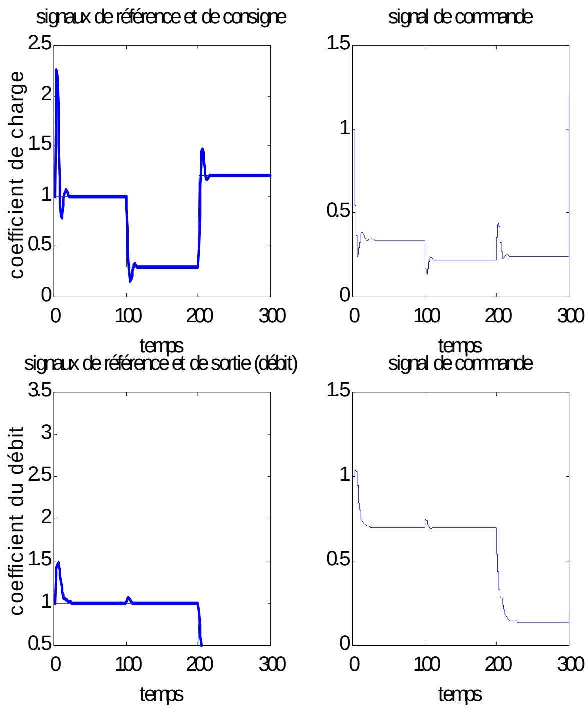

Fig. 5 .The response of the compression system with $B= 0.5$

The response of the compression system with Greitzer parameter $B = 1.50$ is shown in figure 6 for the mass flow coefficient and the response of pressure coefficient. This figure shows the output controller with fuzzy logic and BPID controller for the mass flow coefficient and the output controller with fuzzy logic and BPID controller for the pressure coefficient.

Both simulations push the design point along the compressor characteristic until it reaches a stable operating point without overshooting a stable equilibrium point. An overshoot of the equilibrium conditions would result in pressure drop across the throttle.

The development of independent fuzzy logic control strategies will be the further step in the research. Design of a adaptive control and a fuzzy logic predictive controller has led to interesting results which can be compared with the bilinear controller.

A fuzzy logic model of the plant was constructed using data from the simulation model. Then through the optimization routine, the predictive controller model provides a control action to the system depending on the predictive horizon and the control weighting factor. Fuzzy logic of different complexities were studied; the larger the computational time but also the better the results. The predictive controller model with a longer prediction horizon and a small control weighting factor provides good performance in terms of reduced error. However, the observation on the variation of the controller output provided an interesting result. Implementing such a controller on a real-time system would probably be prohibitive due to the fact that there are limitations on the incremental variation of the compression system. Different options were studied to reduce this effect (variation of the weighting factor value and variation of the control signal). The limiter block, located immediately after the controller output, corresponds to a percentage of the previous value, e.g. if the value is set to 0.04, it means that the maximum variation between the previous value and the current one is ± 4%.

So far, better performances arise when we make use of a limiter block, i.e. a reduced overshoot and a reduction in the variation of the control signal are observed.

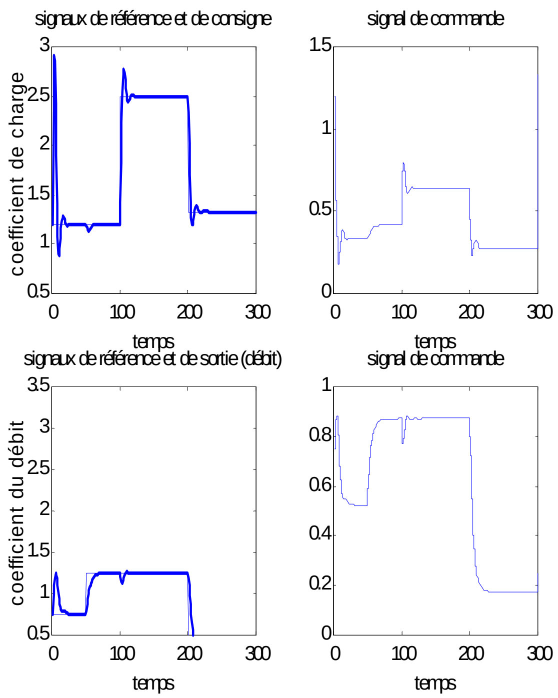

Fig. 6 The response of the compression system with $B= 1.5$

V. Conclusion

The paper has first shown how a fuzzy logic may be trained to approximate an existing nonlinear controller, namely the BPID. The development of independent fuzzy logic control, e.g. model predictive controller and fuzzy logic controller presented a further step in the research. In theory, predictive control, discussed here, would only probably provide benefits for a compression system. The Anti-surge control offers:

- Protection against compressor damage such as shafts bent, cracked or ruptured casings, damaged impeller and bearings
- Reduction in compressor downtime and productivity costs
- Savings on maintenance costs

Although all the anti-surge control techniques are based on a similar concept (Maintain a minimal flow at extreme conditions) the control module takes into account the following:

- Location of the flow measurement.
- Type of compressor (axial, reciprocating or centrifugal).
- Type of operating speed (constant or variable).
- Value of discharge and suction pressures.
- Value of inlet temperature.
- Value of the compression ratio.
- Composition of the transported gas (density, specific heat, molecular weight).
- Characteristics of all valves used in the control process.

However, the predictive controller model requires larger computational time, and also the values for the weighting factor and the prediction horizons to be determined. It is believed that it could be difficult to justify the replacement of a conventional controller (PID controller) by such controller in a real industrial environment.

Use of fuzzy logic controller, however, could provide a good compromise as the training of the fuzzy logic controller is done off-line. Performances in terms of anti- surge control system, overshoot and time to reach the set point are very similar to those of the PID controller.

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