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The Identification of the Operating Regimes of the Controllers using the Phase Trajectory of the Error

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Abstract: - The paper presents a soft computing on-line identification method of the operating regimes of the closed loop controllers. The approach is based on the qualitative analyze of the phase trajectory of the error. Four operating regimes are considered: transitory, steady, oscillating and unstable. The knowledge standing behind this analyze is provided by the linear PID controllers’ adjustment theory. The family of Fuzzy Self Adaptive Interpolative Controllers was developed on this base. The existing case studies are mentioned, proving the performance of this method that can cope with a wide domain of applicative situations in the field of adaptive control.

Key-Words: - fuzzy interpolative controllers, adaptive control, phase trajectory, heuristic adaptation rules.

1 Introduction

The control of the non-linear and time variable systems demands high quality self-adaptation. For instance the setting of an electric drive controller for ordinary speeds is not working at low speeds, because of the non-linearity of the friction load torque, which is growing when the speed is decreasing. When we dispose of valid mathematical models for the controlled plants, the adaptation strategy may be established using classic methods inspired by the linear control, like the operational calculus (transfer functions), with very good results.

Unfortunately, when we don’t have valid knowledge about the controlled plant and its mathematical model, things are changing for the worth. In fact, in most of the real applications, processes are highly non-linear, barely known from the mathematic point of view, their physical parameters are varying in time and unpredictable external perturbations may occur. In such cases, the only possible approach that can be always used is the heuristic one.

In order to achieve consistency and portability heuristic adaptation solutions need a well defined theoretical frame. In a previous paper [9] we identified the phase trajectory of the error as the basic tool able to support the on-line heuristic adaptive action. Any element of frequency analysis is skipped; no measurements of the state variables are necessary either. The adaptive laws will be defined simply on the bases of the real time evolution of the system, represented by the error’s phase trajectory. This paper is advancing new arguments in this direction.

We are interested in two basic issues related to the adaptive control applications: the on-line identification of the operating regimes of the control system and the design of appropriate adaptive laws for each particular regime and their fusion.

The judgments standing behind the proposed method will be answers to the basic question: “*how would a human operator control and adapt an unknown plant*?”

2 A Reminder on the Fuzzy Self Adapted Interpolative Controllers

In some previous works we introduced the concept of the fuzzy-interpolative controller FIC [3], [6], [7], etc. A FIC is a fuzzy controller that can be equaled with a corresponding look-up table with linear interpolations: each control rule is associated to its own interpolative node. The main advantage of FIC consists in the easiness of the implementations (software and hardware) due to their interpolative side, [5] combined with a quick and transparent development thanks to their fuzzy side [2]. The software equivalent of a FIC is the look-up-table.

The look-up tables are strictly numerical tools, their representation in the human mind being inadequate, especially when using large or multidimensional tables. That is why their association with the fuzzy systems is recommendable. The linguistic representation of the knowledge, an asset of the fuzzy theory, is revelatory for humans, catalyzing the developing stages of the control applications [2].

A specific control structure, FSAIC (*Fuzzy Self-Adapted Interpolative Controller*), able to support the phase trajectory analysis was also introduced in [6], [7], etc.

FSAIC has a variable structure. During transient regimes the main controller is a PD one (2D look-up-table). During the steady regime an integrative effect is gradually introduced, the structure becoming a PID one. This functionality is achieved with a 3D look-up table having as inputs the control error **ε**, its derivate (change) and integrative. The different PD tables corresponding to the $\int\varepsilon$ dimension differ only at the central rule, that is activated when **ε=zero** and **$\dot{\varepsilon}$=zero** [3], [6], [7]. Thus the integrative effect is gradually activated, through a linear interpolation, only when steady regimes occur. The adaptive feature is introduced by a PD FIC corrector that is acting by mean of a multiplicative correction factor *Gain*, applied over the main controller.

3 The Adaptive Rule Base

The adaptive control rules are meant to realize the adaptation of the main controller to the actual operating regime of the control system. We grouped all the possible operating regimes into four clusters: transitory (G1), steady (G2), oscillating (G3) and unstable (G4). The rules are respecting in general the next linguistic commitments:

- G1: *Gain* is **medium** and *Integrative* is **zero**
- G2: *Gain* is **great** and *Integrative* is **great**
- G3: *Gain* is **small** and *Integrative* is **zero**
- G4: *Gain* is **very small** and *Integrative* is **zero**

The justifications of these conditions are the following:

- G1: this is the basic situation, the most common regime;
- G2: when reaching the steady regime *Gain* must be increased in order to prepare the controller for the following perturbation: the higher *Gain* is, the faster the reaction of the controller will be;
- G3: in general oscillations are induced by high amplifications of the direct way of a closed loop control system; that is why *Gain* should be reduced;
- G4: this case is similar with G3, but the winding up of the system during the unstable regimes are far more dangerous than the oscillations.

The *Integrative* component is managed by the particular structure of the main controller, so the task of the adaptive corrector will be just the control of *Gain*.

The following paragraphs will show how the phase trajectory of the error can help us in the on-line identification of the operating regimes.

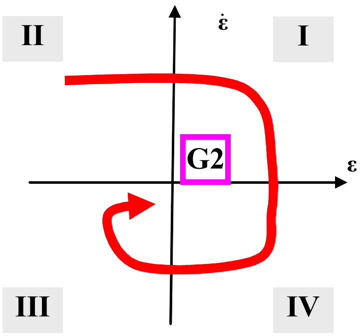


Fig. 1. A phase trajectory of the error

A phase trajectory of the error corresponding to a transitory regime and leading to a steady one is presented in fig 1.

The steady regime is the easiest to be recognized, when the trajectory is reaching the neighborhood of the origin of the axes.

The most characteristic behavior of the phase trajectory of an usual transitory regime G1, leading towards G2, is present in quadrants II and IV. In quadrants I and III this regime has medium or small values (see fig. 1).

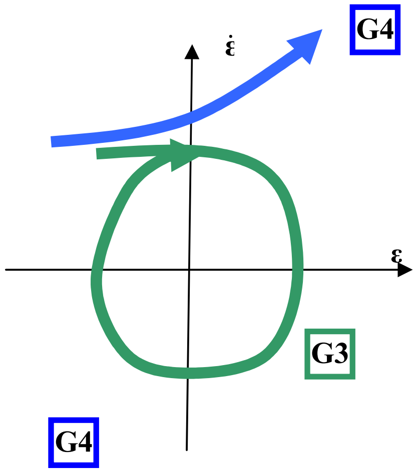
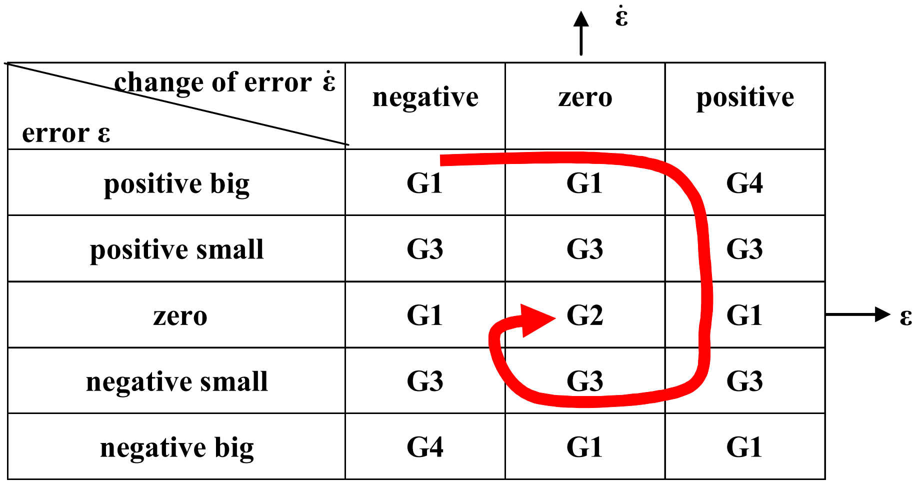


Fig. 2. The oscillatory and unstable regimes

The oscillatory regime G3 may be present in all the quadrants, with medium values for **ε** and **$\dot{\varepsilon}$**. (see fig.2).

The unstable regime G4 can be identified since the error and its derivative have both great values of the same sign (quadrants I or III) (see fig.2).

Based on these fundamental considerations, stem from the qualitative control introduced by Clocksin and Morgan [1], a complete adaptive rule base is looking as the one presented in fig. 3.



change of error $\dot{\varepsilon}$ / error ε	negative	zero	positive
positive big	G1	G1	G4
positive small	G3	G3	G3
zero	G1	G2	G1
negative small	G3	G3	G3
negative big	G4	G1	G1

Fig. 3. An adaptive rule base

The adaptive rule base is written in a heuristic manner, having in mind general knowledge about the adjustment of the linear PID controllers.

The rules G3 and G4 are applying the simplest way that can stabilize a system (in the sense of the Nyquist stability criterion), by reducing the gain of the feed-back open loop.

The nonlinear control surface resulting by the differentiation of each quadrant in several regions offers a wide range of possible adaptation strategies. One can for instance design correctors that are improving the performance of the dead time systems [3], [6]. On the other hand, this complicated operation makes very difficult a detailed description of the operation and a proper performance analyze.

The separation of the adaptive corrector from the main controller has benefic effects on the speed and on the safety of the controller because the adaptive correction is parallel to the direct control action.

The FSAIC configuration is presented in fig. 4. Further developments were made in the sense of using several adaptive contradictory correctors, each one designed for a specific and different adaptive strategy [6], [7]. Emergency refined control strategies can be introduced this way for the abnormal unexpected situations. The different correctors can be merged by the help of a fuzzy fusion mechanism, equally controlled by means of the analysis of the phase trajectory of the error. The resulting structure is called FFSAIC (*Fusion FSAIC*).

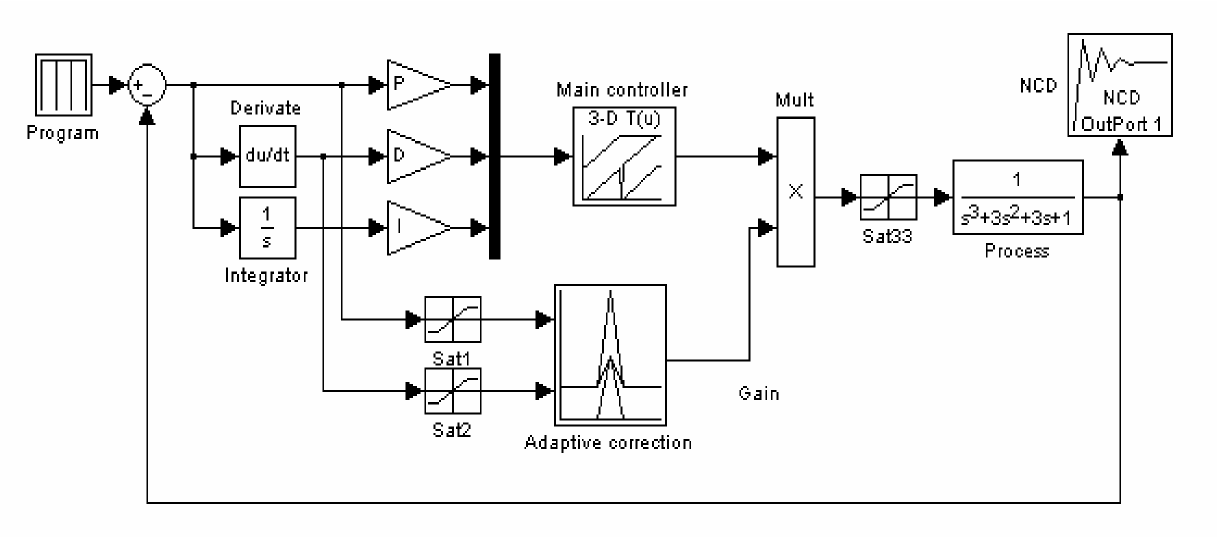


Fig. 4. The FSAIC configuration

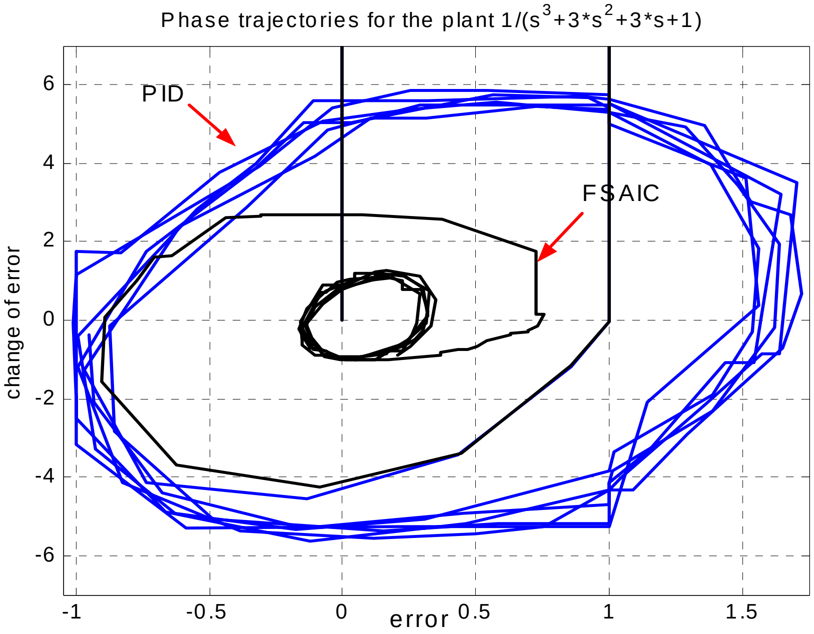


Fig. 5. The performance of FSAIC compared to linear PID

3 Experimental Results

The operational performances and the stability of such a deeply nonlinear controller can be hardly calculated. The only feasible way to study them is the empirical approach.

Two FSAIC case studies focused on the railway coaches' issues were so far communicated: the adaptive control of the air-conditioning equipment [3] and of the ABS braking [4].

The typical performance of an FSAIC, compared to a linear PID, is shown in fig. 5. The time responses are much more fast and precise, the overdrives reduced and the oscillations (limit cycles) drastically reduced.

A remarkable feature of FSAIC is the capacity to react against the instability, by reducing *Gain* (in the sense of the Nyquist stability criterion).

4 Conclusions

The identification of the operating regime of the closed loop control systems may be obtained by means of the qualitative analyze of the phase trajectory of the control error. Adaptive actions based on this approach are able to improve the control of highly nonlinear, time varying and/or important dead times processes. This analysis may be achieved with the help of fuzzy-interpolative controllers. A family of fuzzy self-adaptive interpolative controllers FSAIC is designed to implement this kind of operation. The adaptive part of FSAIC is a fuzzy-interpolative PD corrector, having as inputs the error and its derivative.

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