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DELAY DYNAMIC COMPENSATION ENHANCED PI CONTROLLERS IN AUTOMOTIVE SYSTEMS

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Abstract: Most of the systems of interest in the automotive industry have to be classified as dynamic systems with time delays. Although this is the case it happens that because of implementation and cost constraints they are almost controlled by proportional-integral (PI) type algorithms which are calibrated based on well known tuning methods. Here is presented a control algorithm the so called delay dynamic compensation that modifies the control action of PI type algorithms in order to improve the dynamic behaviour of time delay systems. The control action of the delay dynamic compensation is easy to calibrate through a set of parameters and it is only active during defined transients of the dynamic system. Benchmark and automotive applications (boost pressure control) will provide more detailed knowledge on this type of control.

Keywords: adaptive control, automotive systems, delay dynamic compensation, nonlinear systems, PI control, process control, and tuning methods.

1. INTRODUCTION

The automotive and process industries are always confronted with the need to improve their production quality. To be able to respond to such demand they rely more and more on the use and development of control strategies (Astrom and Wittenmark, 1990; Seborg, *et al.*, 1989). Most of these control strategies are based on proportional-integral (PI) type control algorithms that are enhanced by diverse mechanisms like for example gain scheduling and integrator windup prevention (Johnson and Moradi, 2005; Yu, 1999). But in general the dynamic systems found in the automotive and process industries have to be considered affected by time delays which requests for controllers particularly designed to cope with this type of phenomenon (Dugard and Verriest, 1998; Kharitonov and Niculescu, 2003; Olgac and Sipahi 2002). Although these controllers do bring better control performances their development implies a deeper understanding of the system to be controlled. Also for its implementation and maintenance phases one has to employ specialised workforce. Unfortunately it isn't always possible to justify this kind of solution in an industry where cost reduction plays an important role. One solution out of this dilemma will be presented in the next paragraphs. It is the so called delay dynamic compensation which produces a dynamic correction that counteracts the effect of the delay in the calculation of the controller's output value. First its concept will be stated and analysed which will be followed by results of case studies and an application regarding an automotive system. After that it will be provided a short conclusion highlighting the major characteristics of this control algorithm.

2. DELAY DYNAMIC COMPENSATION

As already mentioned there are several types of strategies that can be employed to control time delay systems. Nevertheless given its simplicity and widespread know-how in the engineering world PI control strategies based on tuning methods like the reaction curve or continuous cycling would be preferable. Having that as an objective and to avoid conservative control performances the output of the PI controllers must be corrected. This compensation can be achieved by dividing the system's response into two phases. One almost static where small changes on the system's output (set-point variations or disturbances) have to be taken alone by the controller and a transient phase where large changes on the system's output are observed. For this second phase the PI control strategy is then enhanced by the so called delay dynamic compensation. The delay dynamic compensation algorithm is built upon the framework provided by the switching control theory (Savkin and Evans, 2002). According with this theory it will allow for a nonlinear control action depending on the system's variables where stability and performance issues can be brought into assessment.

2.1 Concept Development.

The delay dynamic compensation control action is developed as an algorithm that uses a set of parameters to indirectly capture the dynamic characteristics of time delay systems and consequently to generate an appropriate control correction. These parameters are coupled with the time evolution of the set-point, and output and input of the time delay system. This is done in a way to produce a time limited decaying correction action that is applied to the system's input if after a change in the set-point or output of the system, as the case may be, that is followed by a defined waiting time the system's output doesn't reach an expected value around the new set-point. This will minimise the risk of under or over driving the dynamic system because of reduced or excessive control action. The delay dynamic compensation algorithm can be mathematically described by the next set of equations

$$\begin{aligned}
&\text{if } \big(\, |Out_{ref}(t_{i+1}) - Out_{ref}(t_i)| > Out_{VT} \\
&\quad \text{or } |Out(t_{i+1}) - Out(t_i)| > Out_{VT}\big) \text{ and} \\
&\quad |Out_{ref}(t_i + t_W) - Out(t_i + t_W)| > Out_{STB} \qquad (1)\\
&\text{then for } t \le t + t_W + t_{AC} \\
&\qquad u_{DDC}(t) = -f(In(t_i + t_W), t) \\
&\text{with} \\
&\quad |f(In(t_i), t_{j+1}) - f(In(t_i), t_j)| < 0
\end{aligned}$$

where $f(:)$ is a decaying function of its arguments, $Out_{ref}(t)$, $Out(t)$ and $In(t)$ are the set-point, output and input of the closed-loop system to be compensated, and $u_{DDC}(t)$ is the output of the delay dynamic compensation. The decaying function can be made linear or not and it is part of the set of parameters used to tune the delay dynamic compensation. In its simpler implementations it will have allocated two parameters that determine its magnitude and time evolution. The other parameters of the delay dynamic compensation, as seen in equation (1), are the variation threshold, Out_{VT}, the waiting time, t_W, the set-point boundary, Out_{STB}, and the action time, t_{AC}. With six parameters the delay dynamic compensation algorithm provides for enough flexibility (with some degree of redundancy) to find setting of values that improve the dynamic behaviour of the time delay system under control.

Before presenting some guidelines regarding the tuning of the parameters of the delay dynamic compensation algorithm it should be emphasized that this control algorithm has the main purpose of improving the control characteristics and not impose stability in the closed-loop system. Having this into consideration tuning procedures will be developed without going into details or mathematical proofs because in the worst case it will be always possible to find a set of values that restore the original control characteristics. The tuning procedures will depend differently on the algorithm's parameters with some of them more related with the system's time delay and predominant time constant and others with the system's static gain and damping ratio. In the first group are to be found the waiting time, the action time and the decay time of the decaying function. In general, if the dynamic system to be controlled shows low dynamics and is affected by large time delays the parameters waiting time and action time will tend to have big values whereas the decay rate of the decaying function will need to have a small value. For other weights combinations of delay time and predominant time constant it is recommended that the choice of a value for the waiting time be more connected to the system's time delay while the values for the action time and delay rate be mainly defined by the system's predominant time constant. The remaining parameters of the delay dynamic compensation are then included in the group that is most determined by the system's static gain and damping ratio. In this case it is more difficult to attribute specific parameters to compensate for influences of the system's static gain or damping ratio. Nevertheless, it can be stated that the parameter set-point boundary is to be defined depending on the damping factor shown by the closed-loop system while the amplification factor for the decaying function is to be tuned depending on the closed-loop's static gain. This is to be realised so that for systems with low static gain and low damping factor the set-point boundary will tend to have a large value but a small one for the amplification factor. The last parameter to be mentioned is the variation threshold which can be employed, after valued in an initial setting, as a fine tuning parameter that ensures a good compromise concerning the weighing of the closed-loop system's damping factor and static gain in the control action produced by the delay dynamic compensation algorithm.

Before proceeding it should be noticed that the above described guidelines don't take into consideration situations where the input of the delay dynamic compensation is disturbed by noise. In such cases it is better to do some additional testing when applying

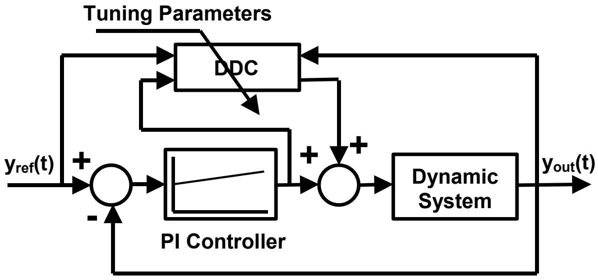

Fig. 1. Dynamic system with time delay controlled by a delay dynamic compensation enhanced PI controller.

these tuning procedures. The integration of the delay dynamic compensation algorithm in the closed-loop control is illustrated in Fig. 1 where it can be seen that its inputs are made of the system's reference and output signals, and controller's output. By its turn the control compensation is achieved by adding its output to the controller's output.

2.2 Case Study.

Although here isn't given a deep theoretical analysis of the delay dynamic compensation algorithm, for an easy understanding of its characteristics some application examples are presented which are representative of the spectrum of closed-loop dynamic systems that can profit from its use. These are systems that can be well defined by low order differential equations, i.e., first and second order, affected by single time delays. The dynamic systems of first order were given by differential equations of the form

$$\frac{dy(t)}{dt} + b_0 y(t) = a_0 u(t-\theta) \quad \text{with} \quad \theta > 0 \qquad (1)$$

with θ the system's time delay, $\frac{1}{b_0}$ the system's time constant and $\frac{a_0}{b_0}$ the system's static gain. Regarding the dynamic systems of second order they were defined by differential equations of following structure

$$\frac{d^2 y(t)}{dt^2} + b_1 \frac{dy(t)}{dt} + b_0 y(t) = a_0 u(t-\theta) \qquad (2)$$
$$\text{with} \quad \theta > 0$$

where θ is the system's time delay, $\sqrt{b_0}$ the system's undamped natural frequency, $\frac{b_1}{2\sqrt{b_0}}$ the system's damping and $\frac{a_0}{b_0}$ the system's static gain. From the several simulation tests performed on this type of systems some of them were chosen and will be next analysed in detail.

The analyse will begin by looking into the control of a first order system controlled by a PI controller tuned using the Ziegler-Nichols step response method. Given that the dynamic system was affected by a time delay this tuning method produced a closed-loop that is fast but shows low damping as can be seen in Fig. 2a. In this case the delay dynamic compensation is employed to increase the damping without slowing the closed-loop system. The required behaviour is provided by a nonlinear control signal as it is presented in Fig. 2b. This signal is achieved by setting the parameter values of the delay dynamic compensation to generate a big and fast decaying correction action.

The following case will focus on a second order dynamic system with a PI controller that was tuned using the Cohen-Coon step response method. Also here the resulting closed-loop system gives too oscillatory transients although possessing slower dynamics, please see Fig. 3a. The delay dynamic compensation is again employed with the objective of preventing such type of transients while not degra-

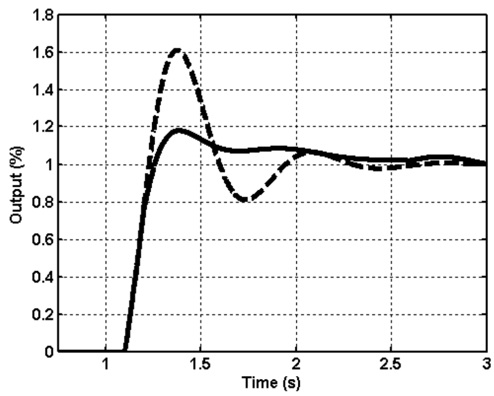

Fig. 2a. Step response of a first order system with time delay: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

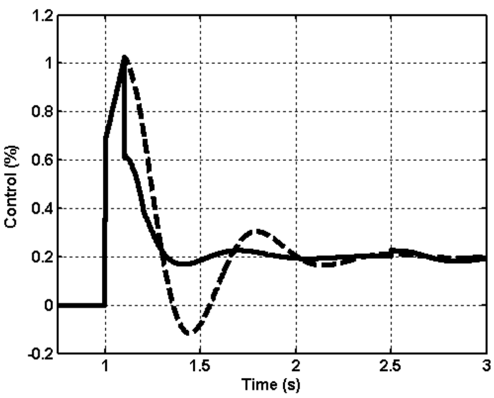

Fig. 2b. Control signal for a first order system with time delay: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

ding the closed-loop response. For this purpose its parameter values were defined to provide for a big and slow decaying correction action that together with the output of the PI controller determines a control signal as illustrated in Fig. 3b.

Finally, it will be regarded the use of the delay dynamic compensation algorithm when the PI controller to be enhanced is applied to a dynamic system subjected to noise. As already mentioned the tuning procedure has to be performed in such a way as to possess robustness against this type of disturbances. This is mainly achieved by readjusting the values of the parameters set-point boundary, variation threshold and action time obtained during the tuning with comparatively small influence of noise. It should be also emphasize that this readjustment while done by try and error didn't required large amounts of time.

The compensation will be demonstrated by showing the results of retuning the delay dynamic compensation algorithm for the case where noise was added to the output signal of the dynamic system first considered in this case study, please refer to Fig. 2. With this modification the closed-loop system re-

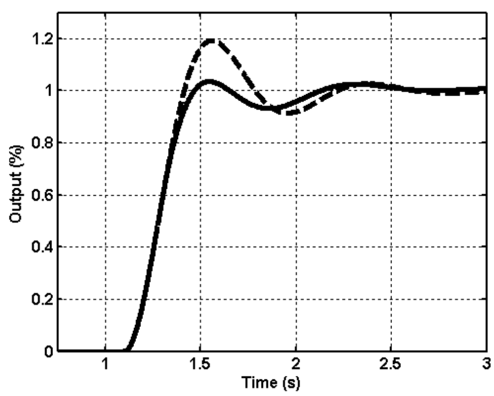

Fig. 3a. Step response of a second order system with time delay: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

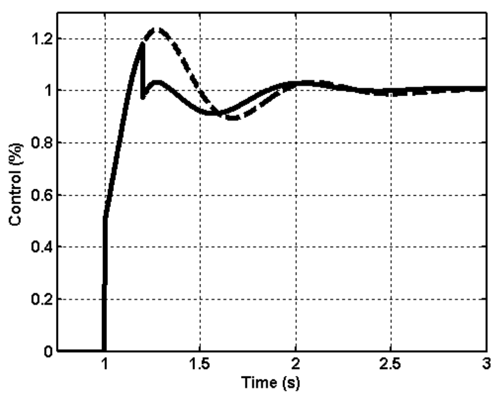

Fig. 3b. Control signal for a second order system with time delay: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

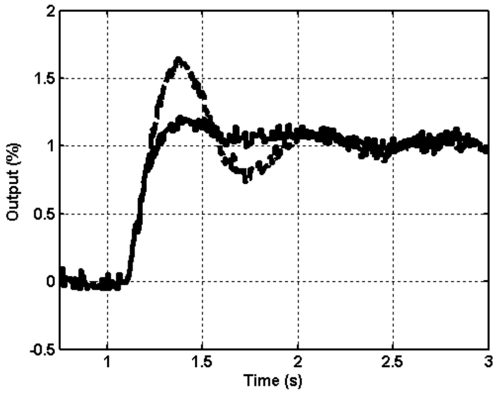

Fig. 4a. Step response of a first order system with time delay and affected by noise: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

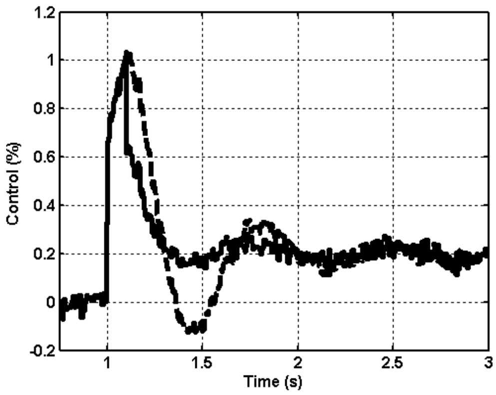

Fig. 4b. Control signal for a first order system with time delay and affected by noise: PI controlled (dash line) and delay dynamic compensation enhanced PI controlled (solid line).

tains most of the previous control characteristics although the noise level observed at its output was relatively high. But this behaviour was expected because the delay dynamic compensation algorithm isn't designed to counteract such phenomenon. A comparative control quality overview can be taken from Fig. 4.

3. DELAY DYNAMIC COMPENSATION ENHANCED PI CONTROLLERS IN BOOST PRESSURE SYSTEMS

Some of the improvements to be made in diesel engines (increase of power, decrease of emissions and downsizing) are very dependent on the further advancement of the characteristics of its intake air system. The function of the intake air system is to provide for the amount of air to the engine that allows for an optimal combustion. Basically, this is achieved by regulating the flow and pressure of the air entering the cylinders by means of an EGR actuator and a turbo charger (Bosch, 2003; Glover and Merten, 2006; Schwarte, *et al.*, 2006). In general the control of the turbo charger is done using PI type control strategies although it is to be operated in a closed-loop system were time delays are typical (Gu-

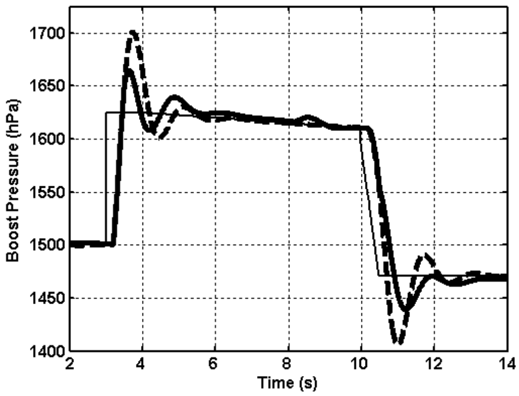

Fig. 5. Boost pressure control within the boost pressure (BP) system: boost pressure set-point (thin solid line), PI controlled (dash line), and delay dynamic compensation enhanced PI controlled (solid line).

zzella and Amstutz, 1998). Next it will be shown the advantages of enhancing this type of strategies with the delay dynamic compensation algorithm. For this purpose a simplified model of a four cylinder diesel engine was employed and driven in the part load engine characteristic (830-2200rpm/5-30mg/stroke).

The original PI control strategy implemented in the vehicle's ECU (Engine Control Unit) is extended by having a gain scheduling mechanism dependent among others on the actual engine speed and desired fuel quantity. In Fig. 5 is to be seen the action of this controller in the regulation of boost pressure during a change in the engine operating point. It produces a good steady state control quality but this isn't the case for the transients where big overshoots and undershoots are observed which are a direct consequence of the existence of delays in the vehicle intake air system. In the same figure it is also presented the boost pressure build up after the introduction of the delay dynamic compensation into the control strategy. Now it is obtained a boost pressure build up equally fast but with smaller overshoots and undershoots. It remains to be said that the tuning of the delay dynamic compensation parameters didn't require much time nor did involve extensive try and error testing.

4. CONCLUSION

The delay dynamic compensation algorithm is able to improve the performance of closed-loop systems that rely on PI type control structures to fulfil their designated tasks. It is also easy to bring the algorithm into these structures and its parameters are tuned following understandable rules that do not imply a lot of try and error testing. The tuning procedure can be made related to the use of other well known tuning methods, i.e., Ziegler-Nichols or Cohen-Coon step response, which opens new possibilities concerning the control of many industrial processes.

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