Dead Time Compensation of Main Irrigation Canal using a Filtred Smith Predictor

MERABTI Nardjes
Department of Electronics Engineering
Badji-Mokhtar University
Laboratory of automation and signals
Annaba, Algeria
merabti.nardjes@yahoo.fr

ARBAOUI Faycel
Department of Electronics Engineering
Badji-Mokhtar University
Laboratory of Automation and Signals
Annaba, Algeria
arbaoui@univ-annaba.org

SAIDI Mohamed Larbi
Department of Electronics Engineering
Badji-Mokhtar University
Laboratory of Automation and Signals
Annaba, Algeria
saidi-m@univ-annaba.org

***Abstract*—The dead time problem in control systems is an everlasting problem which is a primary importance in process control as well. This paper presents a work in progress concerning the use of a delay compensation technique based on Smith predictor for the control of real systems with large variant time delay and load disturbances. The main objective is to control the level water of an irrigation main canal that presents a large time delay. The Smith predictor is a well-known control structure for industrial dead time systems, where the basic idea is to estimate the non-delayed process output by use of a process model, and to use this estimate in an inner feedback control loop combined with an outer feedback control loop based on the delayed estimation error.**

Keywords—irrigation canal; water distribution control; dead time compensation; filtred Smith predictor;

I. Introduction

Irrigation systems are the largest water users in the world, using up to 80% of the fresh water available. Irrigated agriculture therefore has a significant impact on water resources [1].

Canals have been used since irrigation first began to convey water from one place to another. An irrigation canal can be represented as a series of pools where each pool represents a portion of canal between two hydraulic structures (gates or weirs). The gates need to be operated in order to deliver water to the user in navigation waterways, water levels must be controlled accurately ensure given water depths along the reaches and overflow maybe prevented to opening or closing gates. The dynamic parameters of the canal pools vary with the change of hydraulic conditions.

Nowadays, a lot of water in irrigation canals is wasted because of the shortage of an effective control. Automatic control may be considered as a powerful tool for improving efficiency of water distribution in irrigation systems, consequently it has been increasingly introduced in main irrigation canals are complex systems distributed over long distances, with significant time delays and dynamics that change with the operating conditions [2][3].

The problem of effective control of main irrigation canals has been the subject of numerous scientific publications [4][5]. However, only few of the proposed controllers have been effectively implemented in real main irrigation canals. The PI controllers are more used than PID because of their tuning easiness [6]; Moreover, the controller derivative action establishes sensitivity to sensor noises to time delay systems but don't improve the control system performance.

The approach classically used to tune PI controller for a canal pool is by trial and error or by optimization [8], these methods are usually based on a nominal model, while dynamic parameters of the canal pools vary with the change of hydraulic conditions [9][10].

The main objective of this work is to develop a control structure based on a filtered Smith predictor (FSP), which is a Smith predictor compensator including a reference filter [9] to improve the control characteristics of the Aragon Imperial Main Canal AIMC [11].

The paper is organized as follow. In Section 2 a description of the DTC, SP and FSP method, a brief presentation of the Aragon's Imperial Main Canal (AIMC) is offered and a description of the main canal pool (Bocal) is revealed in Section 3. The application of the SP, FSP is exposed in Section 4. The last section resumes the main conclusions obtained during the development of this work.

II. Preliminaries

Time delay occurs frequently in irrigation canals, it is a typical phenomenon in real processes that is caused by the distance between the water resources and the water users.

Compared to processes without delay, the presence of delay in processes greatly complicates the analytical aspects of control system design and makes satisfactory control more difficult to achieve [12].

Smith [13] proposed a delay compensation technique which utilizes a mathematical model of the process in the minor feedback loop around the conventional controller. This technique became known as the Smith predictor method; the main advantage of this method is that time delay is eliminated from the characteristic equation of the closed loop system; Thus, the design problem for the process with delay can be converted to the one without delay.

It is difficult to tune the parameters and get satisfied control characteristics by using normal conventional PID controller. The Smith predictor controller has the ability to satisfy control characteristics and is easy to compute, therefore has better performance than a PID controller.

A. *Dead time compensation*

A time delay may be defined as the time interval between the start of an event at one point in a system and its resulting action at another point in the system.

The first common dead time compensation (DTC) structure and the most compensating controller is the Smith predictor; it was presented to improve the performance of classical controllers (PI or PID controllers) for plants with dead time. It is one of the most popular dead time compensating methods and most widely used algorithm for dead time compensation in industry [14].

It is a control structure for industrial time delay systems, where the basic idea is to estimate the non-delayed process output by use of a process model, and to use this estimate in an inner feedback control loop combined with an outer feedback loop based on the delayed estimation error.

B. *Smith predictor control*

The smith predictor is a simple and effective controller for dead time processes; it is theoretically a good solution to the problem of controlling, the time delay systems. It is widely used for the control of systems with time delays. Fig. 1 presents a block diagram of the conventional Smith predictor configuration, in which L_n is the dead time of the process, *C(s)* denotes the controller, and *P(s)* is the plant, which is assumed to be open-loop stable. The transfer function from the reference input y_{sp} to the output y of the system has the from

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{C(s)P(s)e^{-L_n s}}{1+C(s)P(s)} \qquad (1)$$

As shown in (1), the main advantage of the Smith predictor is that delay component can be eliminated from the characteristic equation for the closed-loop system.

The transfer function from the disturbance *l* to the output y of the system is given by:

$$\frac{Y(s)}{L(s)} = \frac{P(s)e^{-L_n s}}{1+C(s)P(s)} + \frac{C(s)P(s)e^{-L_n s}}{1+C(s)P(s)}\left[P(s) - G(s)e^{-L_n s}\right] \qquad (2)$$

The transient response for the disturbance depends on the plant, and whether the poles of the plant are close to the imaginary axis, in which case the effect of the disturbance could exist for a long time. The poor disturbance rejection capability of the Smith predictor control is obvious in (2). It cannot be used to control processes having an integral mode since a constant load disturbance will result in a steady-state error [16].

The structure of the SP, shown in Fig. 1, can be divided into two parts: the primary controller *C(s)* and the predictor structure. The predictor is composed of a model of the plant without dead time $G_n(s)$, also known in literature as the fast model, and a model of the dead time e^{-LnS} . Thus, the complete process model $P_n(s) = G_n(s)\ e^{-LnS}$. The fast model $G_n(s)$ is used to compute an open-loop prediction.

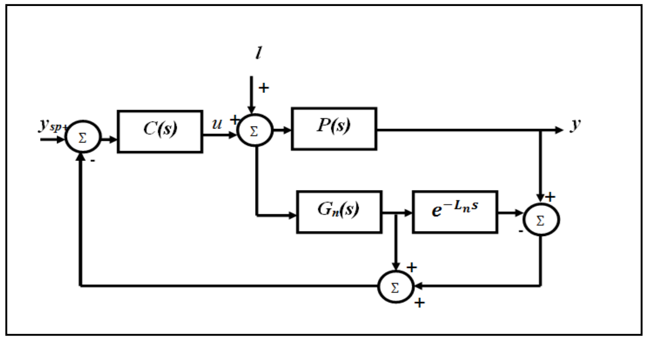

Fig. 1. Smith predictor controller

C. *Filtered Smith predictor*

Dead-time errors can drive the SP to instability. A simple solution to this problem is to use a filter *F(s)* with unity static gain *(F(0) = 1)*, as shown in Fig. 2 [11]. The filter inserted to attenuate the oscillations in the plant output especially at the frequency where the uncertainty errors are important. In this case, the filter *F(s)* can be defined as a first-order filter with only one parameter (the time constant T_f) related to L_n [11]:

$$F(s) = \frac{1}{1+T_f s} \text{ where } T_f = \varepsilon L_n \text{ and } \varepsilon > 0 \qquad (3)$$

To consider the modeling errors, the difference between the output of the process and the model including dead time is added to the open-loop prediction, as can be seen in the scheme of Fig. 2. If there are no modeling errors or disturbances, the error between the current process output and the model output will be null and the predictor output signal $Y_p(t)$ will be the dead-time-free output of the plant. Under these conditions, *C(s)* can be tuned, at least in the nominal characteristics of the SP must be analyzed when considering perfect modeling [17], that is when $P(s); G(s) = G_n(s)$ and $L = L_n$.

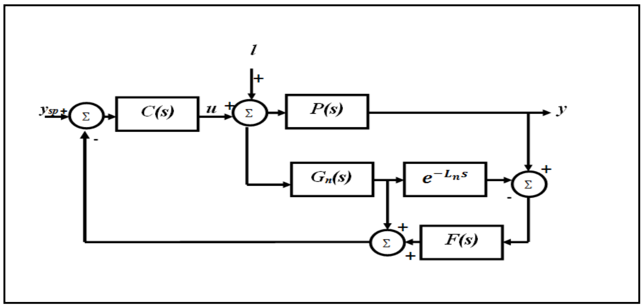

Fig. 2. Filtred Smith predictor

III. APPLICATION: IRRIGATION MAIN CANAL POOLS

A typical main irrigation canal consists of several pools separated by gates that are used for regulating the water distribution from one pool to the next on (see Fig. 3); the gate opening is modified adequately to maintain a given profile of water along the canal pool. In particular, in automatically regulated canals, the controlled variables are the water levels $y_i(t)$ measured near the end of the canal pool (it is called downstream end control), the manipulated variables are the gate positions $u_i(t)$ and the fundamental perturbation variables are the unknown offtake discharges $q_i(t)$, where $i= 1, 2,\ldots, n$; n: the canal pools total number.

The irrigation main canal considered in this paper is the Aragon Imperial Main Canal 'AIMC= (Fig. 2), which obtains its water from the Ebro river [2]. The AIMC is a 108 km long cross-structure canal with a design head discharge of 30 m^3/s. It has a trapezoidal cross-section and ten pools of different lengths which are separated by undershoot flow gates.

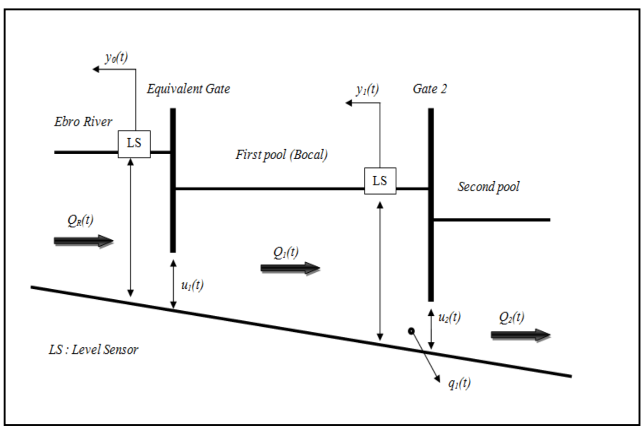

Fig. 3. Equivalent schematic representation of the irrigation main canal pool

For effective control of water distribution in a main irrigation canal pool, it is not necessary to know the water level variations along the whole pool. It is enough to measure it in some specific points that depend on the regulation method to be used. Considering this, a linear model with concentrated parameters and a time delay can adequately characterize the dynamical behavior of a main irrigation canal pool in a measurement point [8][9]. The canal pool dynamic behavior can be represented by a second order system with a time delay, that is to say:

$$G(s) = \frac{\Delta y_1(s)}{\Delta u_1(s)} = \frac{K}{(1+T_1 s)(1+T_2 s)} e^{-\tau s} \qquad (4)$$

Where $\Delta y_1(s)$: downstream end water level variation; $\Delta u_1(s)$: upstream gate position variation; K: static gain; T_1, T_2: time constants; τ: time delay. We consider that T_1 is the dominant time constant (the larger one associated to the dynamics of the canal pool), while T_2 is the smaller time constant that represents the motors + gates dynamics, which is much faster than the canal pool dynamics. The canal pool nominal model is given equation (5):

$$G(s) = \frac{\Delta y_1(s)}{\Delta u_1(s)} = \frac{0{,}0401}{(1+880{,}79s)(1+81{,}27s)} e^{-360s} \qquad (5)$$

But large variations in model parameters are obtained when the discharge regimes change in the operation range (Q_{min}, Q_{max}) in the following ranges [2]:

$$0.01 \le K(t) \le 0.1$$

$$500 \le T_1(t) \le 15000$$

$$10 \le T_2(t) \le 300$$

$$300 \le \tau\,(t) \le 360$$

IV. RESULTS AND DISCUSSION

The control system of the irrigation main canal pool given is considered where four controllers will be designed in this section. These are: a PI, a PID, a Smith Predictor structure denoted as SP, and a modification of a SP denoted as FSP for Filtered Smith Predictor.

Furthermore, the nominal time response provided by the controller must fulfill a trade-off between good time domain performance (settling time in the $\pm 5\%$ band, t_s, overshoot, M_p , steady state error, e_{ss}) and a good signal control, i.e. the maximum control signal amplitude must be limited. Their behavior will be compared, and it will be shown that the Smith predictor and its filtered version – if properly designed – achieve a more robust performance than the PI and the PID. A full attention will be given to robustness to model mismatch and improving disturbance rejection.

A. Design of the PI and PID controllers for the Bocal

Our aim objective is to design controllers that ensure the reduction the settling time in the corresponding closed loop system as much as possible bearing in mind that the open loop settling time of the nominal plant is $t_{so} \approx 3000s$. The constraint of having a phase margin $\phi_m \ge 60°$ with the nominal plant must be considered (in order to guarantee a strong damping or, equivalently, an overshoot of less than 10%). With respect to the previous constraint, a PI is designed that minimizes the settling time. The resulting controller is:

$$C_{PI} = 19{,}1493 + 0{,}02451\,\frac{1}{s} \qquad (6)$$

Which exhibits a settling time $ts \approx 1890s$, an overshoot $Mp \approx 3.38\ \%$, a crossover frequency $\omega_c \approx 0.000937 [rad/s]$, and a phase margin $\phi_m = 63°$ for the nominal plant. Moreover, the phase crossover frequency is $\omega_g \approx 0.00349\ [rad/s]$, and the gain margin $M_g = 12.3$. Moreover, the maximum control stress is only 31.2 (Fig.4). With its three parameters, a parallel PID controller must be tuned to accomplish a good performance subject to the same constraint of phase margin and minimizing the settling time. The obtained controller is:

$$C_{PID} = 16,1009 + 0,0172\,\frac{1}{s} - 5694,9453\,\frac{0,00283}{1+0,00283\frac{1}{s}} \quad (7)$$

This controller guarantees a settling time $ts \approx 2220s$, an overshoot $M_p \approx 1.92\ \%$, a crossover frequency $\omega c \approx 0.000775\ [rad/s]$, and a phase margin $\phi_m = 65,7°$ for the nominal plant. Moreover, the phase crossover frequency is $\omega_g \approx 0.00231\ [rad/s]$, and the gain margin $M_g = 10$. Moreover, the maximum control stress is only 30.8 (Fig.5).

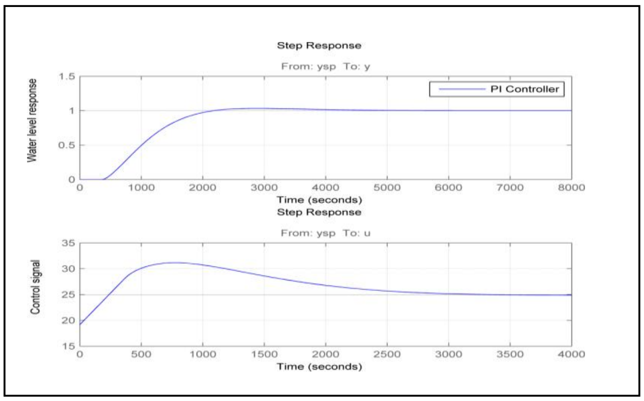

Fig. 4. Closed loop response of plant to a unity step command and control signal.

B. *Design of the SP and FSP controllers for the Bocal*

By following the design procedure shown in Section IV, a Smith predictor controller is used (perfect tuning case). Assuming the following:

Settling time $t_s \approx 1500s$, an overshoot $M_p \approx 3.62\ \%$, a crossover frequency $\omega c \approx 2.05e^{-11}\ [rad/s]$, and a phase margin $\phi_m = 180°$ for the nominal plant. Moreover, the phase crossover frequency is $\omega g \approx 0.00359\ [rad/s]$, and the gain margin $Mg = 7.19$, but the maximum value of the control signal is 36.9 (Fig.6). The following PI controller is obtained:

$$C_{SP} = 32,2569 + 0,05544\,\frac{1}{s} \quad (8)$$

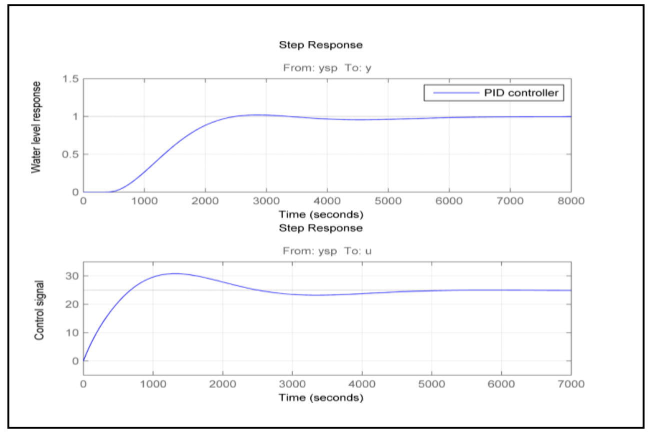

Fig. 5. Closed loop response of the plant to a unity step command and controls signal.

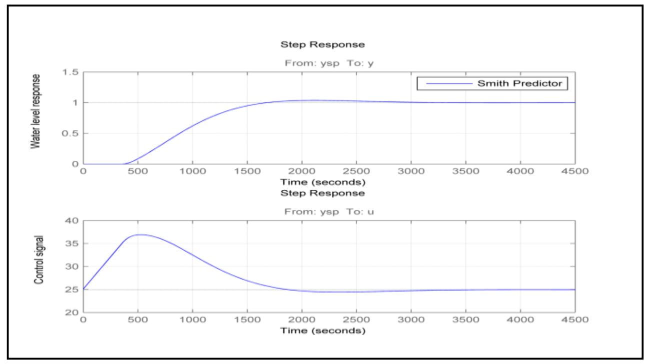

Fig. 6. Water level response of the plant to a unity step command and control signal.

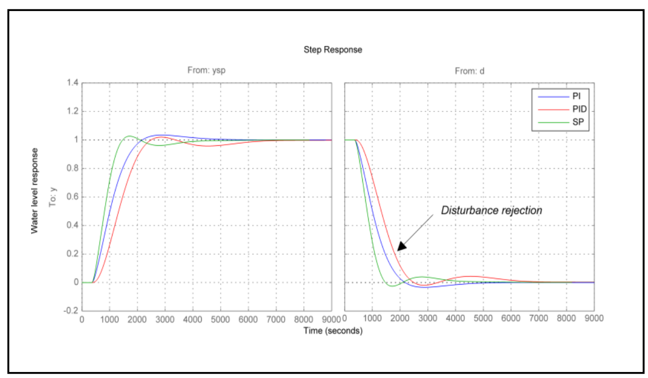

Fig. 7. Disturbance rejection comparison

The Smith Predictor provides much faster response with bigger value of the maximum control signal. Also, we can see (fig. 7) that the disturbance rejection of the SP is superior.
Model uncertainties always exist. In practice the modeling errors have to be taken into account. For instance, dead-time errors can drive the SP to instability. Let us choose the filtered version of the SP to deal with this problem. T_f can be chosen

as $T_f = 0.5\ L_n$ $(\varepsilon = 0.5)$ this choice gives a good solution for dead-time errors of up to *30%* [11]. The performance of the filtered Smith predictor is illustrated in figure 8.

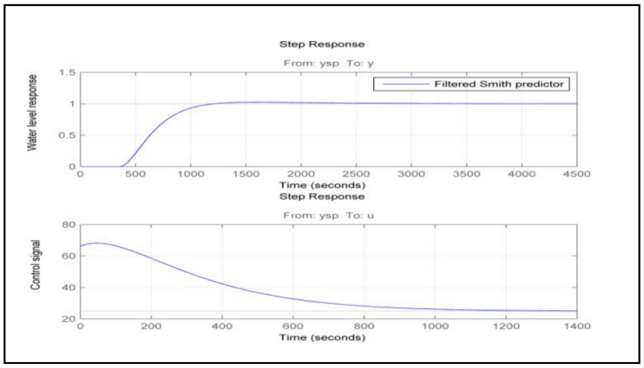

Fig. 8. Water level response of the plant and control action.

This controller guarantees a settling time $ts \approx 1040s$, an overshoot $M_p \approx 2.35\ \%$, a crossover frequency $\omega c \approx 0.00116\ [rad/s]$, *and* a phase margin $\phi_m = 136°$ for the nominal plant. Moreover, the phase crossover frequency is $\omega g \approx 0.0048$[rad/s], and the gain margin $M_g = 4.11$, but exhibits a control signal with a maximum value at 68.1.

Another advantage of this controller is its faster disturbance rejection (figure 9). We can appreciate the higher bandwidth of the filtered Smith predictor (fig. 10).

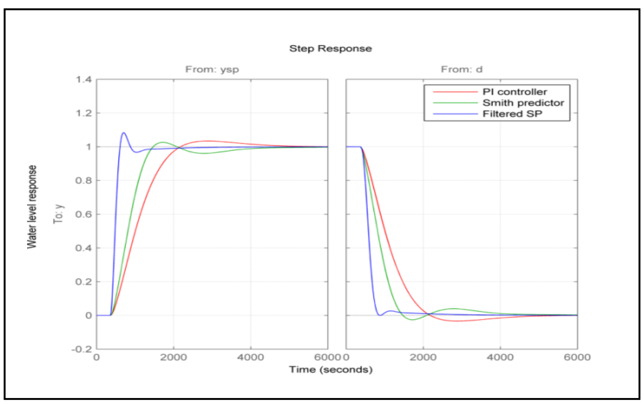

Fig. 9. Superiority of the FSP in term of disturbance rejection

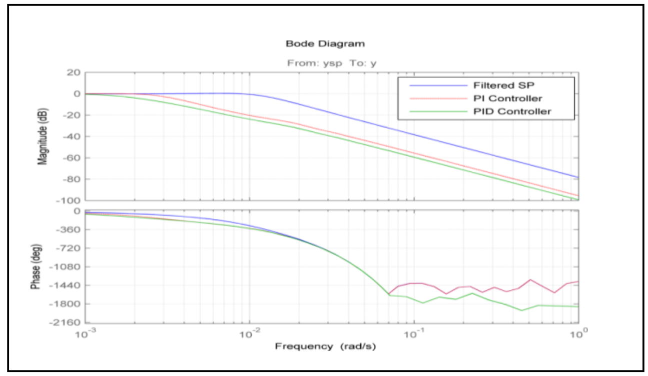

Fig. 10. Bode diagram showing the higher bandwidth of the FSP.

In practical situations, the internal model $G_n e^{-L_n s}$ is only an approximation of the true process dynamics, so it is important to understand how robust the FSP is to uncertainty on the process dynamics and dead time.

In practical situations, the internal model is only an approximation of the true process dynamics. So, let us consider two perturbed plant models representative of the range of uncertainty on the process parameters:

$$\begin{cases} G_1(s) = \frac{0{,}03}{(1+870s)(1+75s)} e^{-370s} \\ G_2(s) = \frac{0{,}05}{(1+890s)(1+85s)} e^{-370s} \end{cases} \tag{9}$$

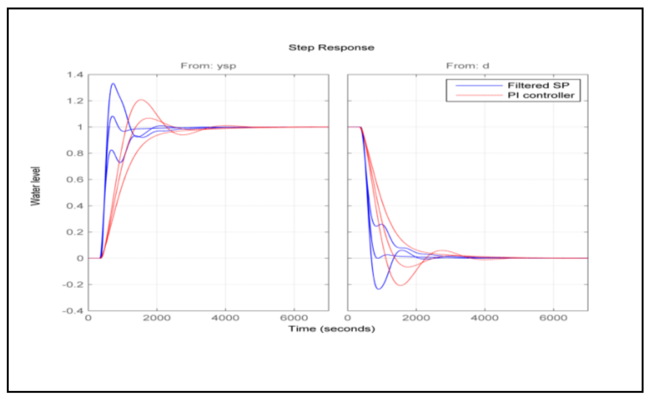

Fig. 11. Closed loop response of the nominal and perturbed plants

It is obvious that the PI controller is much better than the PID one, so if we compare between the PI and FSP designs one can perceive that they are not very sensitive to model mismatch, as confirmed by the closed-loop Bode plots with an obvious advantage to the latter (figures 11 & 12). It proves that if the primary controller of the FSP is properly tuned because it is known that this DTC may be unstable when a small mismatch in the dead-time is considered, in spite of having good values of gain margin and phase margin.

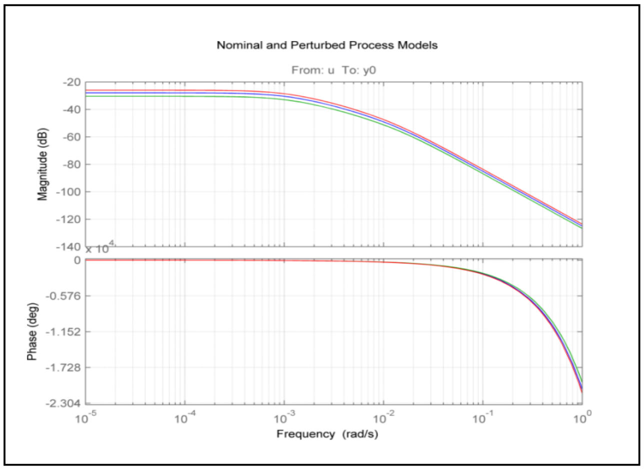

Fig. 12. Bode diagram of the nominal and perturbed plants

V. COMMENTS AND CONCLUSION

This paper described the model predictive for control procedure of the first pool (Bocal) of the Aragon's Imperial Irrigation Main Canal, two different controller structures have been compared. The first presenting a PI and a PID controller, the other including the Smith Predictor, SP, and a Filtered Smith Predictor, FSP. We can conclude that both the controllers of the latter structure are superior in performance. Simulated results show the robustness improvements achieved with FSP controller compared with a other controllers. They have shown, with an advantage to the FSP:

- A faster and more damped dynamic behavior than the PI and the PID.
- A better overall dynamic behavior for the nominal plant parameters than the PI and the PID when considering settling time, overshoot but at cost of an important maximum control signal amplitude.
- An enhanced robustness to model mismatch, especially when the controller is well tuned.
- A better disturbance rejection which can be improved in the case of optimal choice of the filter ($F(s) = e^{\tau s}$) by using the phase lead approximation: $e^{\tau s} = \frac{1+B(s)}{1+B(s)e^{-\tau s}}$ where B is a low-pass filter [18].

REFERENCES

[1] R. Perez et al. "Control-oriented model of a complex irrigation main canal pool. » IFAC World Cong. 18th ed, Italy, August 2011.

[2] V. Feliu-Batlle et al. "Robust Fractional Order PI Controller for a Main Irrigation Canal Pool." IFAC Proceedings of the 17th World Cong. Korea, July2008.

[3] V. Feliu-Batlle et al. « Robust fractional order controller for irrigation main canal pools with time-varying dynamical parameters." Computers and Electronics in Agriculture 76, pp. 205–217, 2011.

[4] Mareels et al."Systems engineering for irrigation systems: successes and challenges." *Annual reviews in Control*, 29, pp 191-204, 2007.

[5] M. Cantoni, et al. "Control of large-scale irrigation networks." *Proceedings of the IEEE*, 95(1),pp 75-91, 2007.

[6] C. Burt et al. "Improved proportional integral (PI) logic for canal automation". J. Irrig. Drainage Eng. ASCE 124 (1), 53–57 , 1998.

[7] Aström, K.J., Hägglund, T. "PID Controllers: Theory, Design and Tuning.", Second edition. Instrument Society of America, USA, Research Triangle Park, NC. , 1995.

[8] Clemmens, A. J. and Schuurmans J. "Simple optimal downstream feedback canal controllers: theory. *Journal of Irrigation and Drainage Engineering.*" 130(1),pp 26-34, 2004.

[9] X. Litrico, and V. Fromion "Tuning of robust distant downstream PI controllers for an irrigation canal pool." Journal of irrigation and drainage Engineering, vol. 132, No.4, pp. 359-368 August 2007.

[10] Feliu et al. "Fractional robust control of main irrigation canals with variable dynamic parameters." Control Engineering Practice 15 pp. 673–686 ;2007.

[11] J-E Normey-Rico &E.F Camacho; "Control of Dead-time Processes" Springer 2007.

[12] K. Watanabe. "A Process-Model Control for Linear Systems with Delay." IEEE Trans. Auto. Cont, vol.AC-26, December 1981.

[13] Smith. "Closed control of loops with dead time. " *Chem. Eng. Progress*, 53:217–219, 1957.

[14] S.Shokri et al. "Improved PI Controllers Tuning in Time-delay Smith Predictor with Model Mismatch." International Journal of Chemical Engineering and Applications, Vol. 1, No. 4, ISSN: 2010-0221, December 2010.

[15] Yi-De Chen et al. "Modified Smith predictor scheme for periodic disturbance reduction in linear delay systems.. Journal of Process Control" 17 pp. 799–804, 2007.

[16] E. Julio et al. "Dead-time compensators: A survey." Science direct Control Engineering Practice, pp.407–428, 2008.

[17] N.F. Jerome and W.H. Ray. "High performance multivariable control strategies for systems having time delays." *AIChE Journal*, 32(6): 914–931, 1986.

[18] H.P.Hung et al. « a Smith predictor with ann approximate inverse of dead time." AiChE Journal, 36 pp. 1025-1031, 1990.