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Study on the influence of Lambda parameter on several performance indexes in Dynamic Matrix Control

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Abstract **– Dynamic Matrix Control (DMC) is a concrete Model Predictive Control (MPC) algorithm. DMC controllers are characterized by means of a set of three parameters, i.e., prediction horizon *p*, control horizon *m* and implementation parameter lambda. In this paper authors provide further insight into the performance of DMC controllers when dealing with unstable systems carrying out a sensibility analysis with the lambda parameter, analyzing the value of four performance indexes devoted to measure the accuracy and the time issues of the response of the controlled unstable systems. To accomplish this study a total of 2,400 different experiments have been carried out.**

Keywords-Model Predictive Control; Dynamic Matrix Control; Accuracy; Sensitivity; Lambda

I. INTRODUCTION

There are complex systems that classic control techniques [1] [2] [3] [4] cannot deal with due to their instability, so, in that case engineers or practitioners use a number of advanced techniques as Model Predictive Control (MPC) [5] [6] [7] [8] [9] [10] [11].

There a number of advanced control techniques, namely MPC, which are used to control systems which are difficult to operate with classic control techniques. MPC controllers are similar to biological brains because they do not use the past errors between the obtained output of the systems and the reference values, but they try to deal with the systems making a prediction of the value of the output of the systems in a short time. MPC is a variety of techniques which share main three common characteristics. The first one is that there is a system model which is used to make predictions about the system output after p time samples. The second one is that there is an objective function which the controller tries to minimize, while the last one is that there is a control law in order to minimize the previous objective function. The working cycle of MPC controllers is composed of the following steps:

- For all sampling times, the controller obtains the output of the system from now until the next p sampling times using the model of the system.
- Later, m control signals are calculated in order to minimize the objective function during m sampling times.
- Finally, each time that these steps are executed only the first of those m control signals is used.

As stated before, we conclude that MPC is composed of a number of techniques that have common characteristics, and the designer can determine which option is the best suited for each of them. In this way there is a number of types of predictive controllers, one of them named Dynamic Matrix Control (DMC).

MPC and DMC have been extensively used in the literature for a number of applications of different domains: in [12] there is reported a Robotics related application, [13] uses this kind of control for a solar plant related application, [14] for modeling problems, while [15] [16] [17] [18] [19] describe Chemistry related works. References [20] [21] [22] show applications of other domains.

Several previous analyses have been published by our research group in order to provide deeper insight into the influence of relevant parameters of the DMC controller on the response when dealing with unstable systems. In [23] we reported a study on the influence of the implementation parameter λ on the accuracy indexes *mse* (Medium Squared Error) and M_p. Several studies have been published [24] [25] [26] [27] [28] showing the influence of the control horizon m on several accuracy indexes (*mse*, M_p, J) and time sensitivity indexes (t_p, t_s, t_{a2}). Finally, the influence of the prediction horizon p has been also studied [29] [30] through the indexes the t_{r100}, t_{a5} and t_p.

The objective of this paper is to analyze the sensitivity of four performance indexes devoted to measure the accuracy (through the value of J and J' taken as indexes), the stability and the immediacy of the response (through t_{r100} and t_{a5} indexes) of a unstable system under a number of DMC controllers designed with different controller implementation parameter λ values. We think that it is a relevant analysis because we have neither studied nor found in the literature any study about the influence of the λ parameter on these four indexes.

The paper is structured as follows. The second section is devoted to the description of the four performance indexes that are going to be analyzed. In the third we introduce the system to control, the determination of the working point and we describe the experimental design that we have carried out. The fourth section discusses the obtained results on the different performance indexes, while the last section provides our conclusions.

II. Performance Indexes Description

This second section introduces the performance indexes that have been analyzed along all the experimentation phase with different DMC structures, paying special attention to the variation of the λ parameter.

A. Optimization Function

This class of indexes is focused on the accuracy of the value of the response of the controllers following the reference signal, so they do not pay attention to time issues.

These indexes are based on the fact that MPC controllers and DMC as an instance of MPC are objective function driven methods. As can be seen clearly in the basic literature, to use this kind on control always is mandatory to define an objective function that the controller tries to minimize by means of a control law. Typically the objective function is defined through (1):

$$J = \sum_{j=1}^{p} \left[\hat{y}(t+j \mid t) - w(t+j) \right]^2 + \sum_{j=1}^{m} \lambda \left[\Delta u(t+j-1) \right]^2 \quad (1)$$

where:

p is the prediction horizon

m is the control horizon

$\hat{y}$ is the prediction of the output

t is the time instant

w is the reference signal

m is the control horizon

λ is the parameter of the DMC controller related to its embodiment.

Δu is the variation of the whole input of the controlled system at time t

The second performance index to which we have paid attention is the variation of the objective function defined in (1). In this paper we have represented this index as J', and it has been included in the study because we consider that it is interesting to analyze its variation in junction with J.

B. Time Indexes

This class of indexes is focused on the immediacy (time response) and the sensitivity of the response of the controllers following the reference signal, so they do pay attention to time issues.

The first one is the t_{a5} index, which is monitored and used to measure the stability of the system focusing on the time needed to the stabilization of the output of the system in the neighborhood of 5% of the reference value $w(t)$. Obviously, the smaller the t_{a5} index, the more stable will be the controlled response of the system.

The second one of these indexes is the t_{r100} index, and it indicates the immediacy of the response of the system measuring the first time that the output of the system reaches the 100% of the reference value $w(t)$. The smaller the t_{r100} index, the more immediate will be the controlled response of the system.

We have described these two time related indexes by means a graphical representation in Fig. 1, while a summary of all indexes of this section can be found in Table I.

III. Experimental Design

This third section aim is to describe the experimental configuration that has been used to give further insight on the effect of the controller implementation parameter λ in the four performance indexes described in the previous section.

In order to evaluate the different DMC controller structures, we have used the system whose dynamics is described by (2):

Figure 1. Graphical representation of the time related indexes

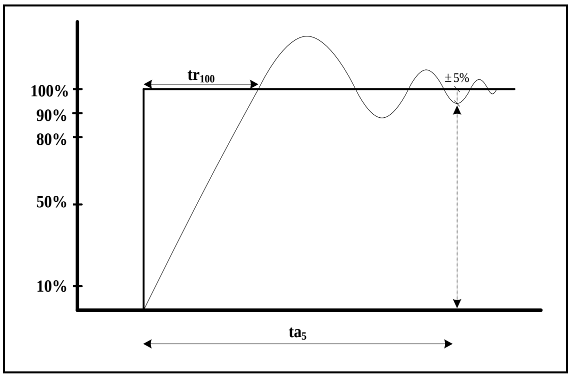


TABLE I. Description of Indexes

Index	Description
J	Objective function of the DMC controller
J'	Variation of J
t_{a5}	Time elapsed between the rising edge of the reference step $w(t)$ and the stabilization of the output of the system in the neighborhood of 5% of the reference value $w(t)$
t_{r100}	Time elapsed between the rising edge of the reference step $w(t)$ and the output of the system when it reaches the first time the reference value $w(t)$

$$H(z) = \frac{1}{z - 0.5} \qquad (2)$$

We were worried about the dynamics of this system, so, in order to know its behavior, first of all we have tried to control it by means of a discrete PID controller tuned using the Ziegler-Nichols method, but we found that its response is clearly unstable when the system is excited by a unitary step [23], as shown in Fig. 2. So, it is an interesting system to test different advanced control structures.

In order to define the working point of the closed loop system, namely, the frequency of the reference signal at its input the Bode diagram of Fig. 3 has been used. Taking this diagram into account, a frequency of 30 sample times has been chosen. This decision has been taken because the gain at that frequency is quite similar of the gain of many other frequencies of the system represented by (2). Since it is not the main idea of this paper, the detailed argumentation on its utilization has been intentionally omitted due to space issues, but the detailed description and the determination of the working point can be found in [23].

A wide range of different values of the parameters λ, *p* and *m* have been chosen. The values that have been used for the controller implementation λ (the parameter for which the analysis is being carried out) are $\{\lambda \in \{10^{-3}, 10^{-2}, 10^{-1}, 1, 10^{1}, 10^{2}\}\}$. The value for the prediction horizon *p* is contained in the set $\{p \in N + \wedge\ p \in [1, 20]\}$.

Figure 2. Response of the closed loop system while controllerd by a discrete PID controller when excited by a unitary step

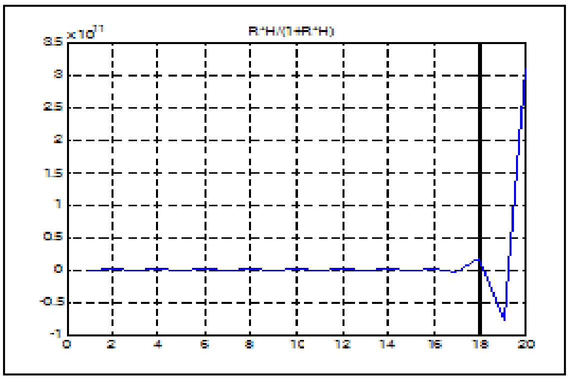
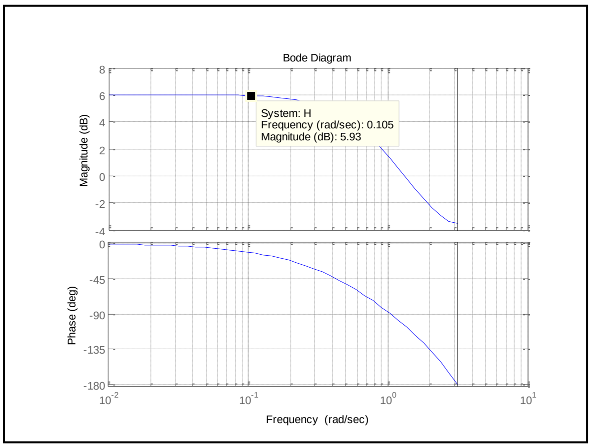


Figure 3. Determination of the working point of the system



Finally, the value for the control horizon *m* is also contained in the set $\{m \in N + \wedge\ m \in [1, 20]\}$. Carrying out the Cartesian product of these sets, the result is composed of 2,400 simulations.

IV. Experimental Results

This fourth section is devoted to the discussion the results that have been reached after carrying out the 2,400 experiments resulting of the experimental design described in the previous section.

A. *Influence on Objective Function J'*

In this subsection, we describe the results that we have reached on the *J'* objective function (taken as a performance index) under the controlling action of DMC controllers with different controller implementation λ values. A number of figures have been obtained varying the λ parameter, as can be seen through Fig. 4-9. After analyzing those figures, we can conclude that in general, the shape of the objective function *J'* is roughly maintained for the different values of the λ parameter; however, the offset of the curve varies clearly. The range of values goes from less than 10^{-7} (with $\lambda=10^{-3}$) to more than 10^{1} (with $\lambda=10^{2}$).

For a given values of the *p* and *m* parameters, the value of the objective function *J'* increases and becomes worst as the controller implementation parameter λ increases.

This is a clearly expected effect because this parameter models the ability of the controller to implement quickly the derived control law. It is also

Figure 4. Effect on *J'* with λ=0.001

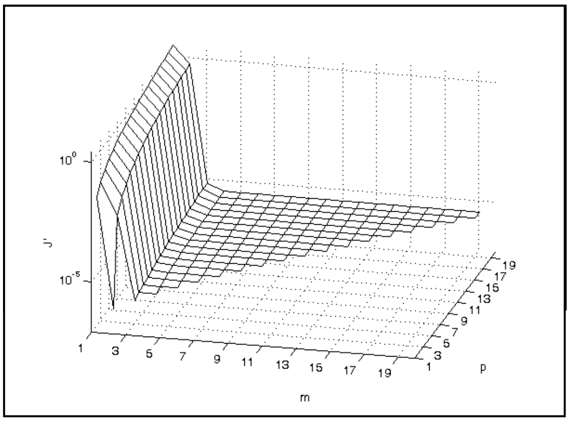


Figure 5. Effect on *J'* with λ=0.01

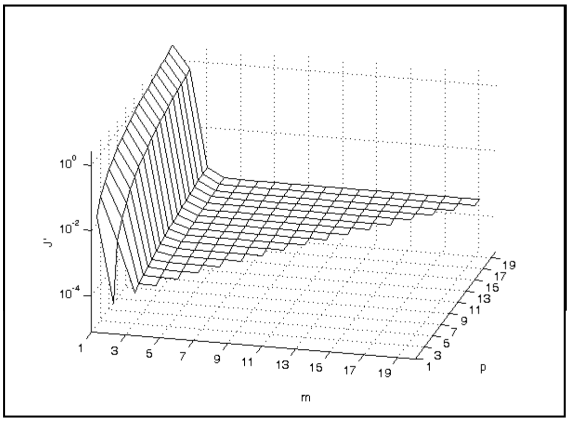


Figure 6. Effect on *J'* with λ=0.1

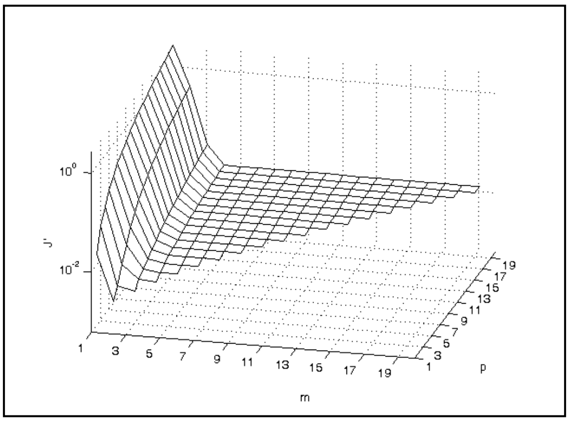


Figure 7. Effect on *J'* with λ=1

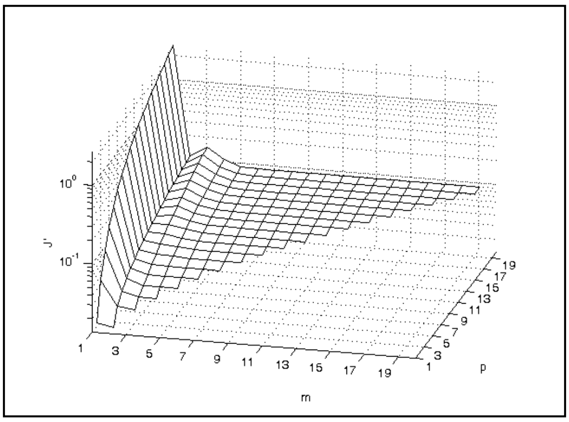


Figure 8. Effect on *J'* with λ=10

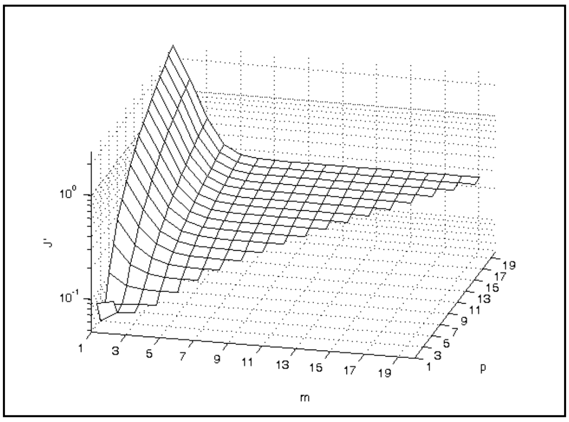
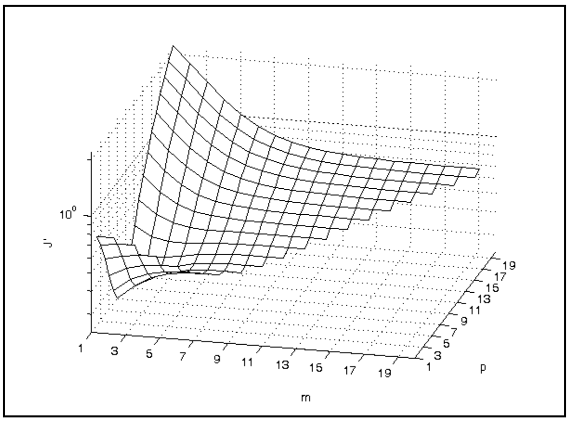


Figure 9. Effect on *J'* with λ=100



clearly shown that because the predictions of the future output of the controlled system are less accurate when they are more distant in time, the controller results is worst when *p* increases. We can also see that the control horizon parameter *m* is an important one, because even with very small values of *p*, in all figures that use values of the control horizon $m \leq 2$, the minimization of the objective function *J'* is better than for the remaining values, even for high values of the λ parameter.

B. Influence on Objective Function J

In this subsection we describe the results that we have reached on the sensibility of the objective function *J* under the controlling action of DMC controllers with different controller implementation λ values. A number of figures have been obtained varying the λ parameter, as can be seen through Fig. 10-15.

There is a first obvious and expected result, i.e., the shape of the curves is similar to the curves of the *J'* objective function (previous subsection), but modified in the value by an offset due to the control effort. It reflects the effort (and probably the energy) that the DMC controller has to use to exert its controlling action. It is also related to the variations of the controlling signal, and usually it is desired that the control action is smooth.

C. Influence on t_{r100} index

In this subsection we describe the results that have

Figure 10. Effect on *J* with λ=0.001

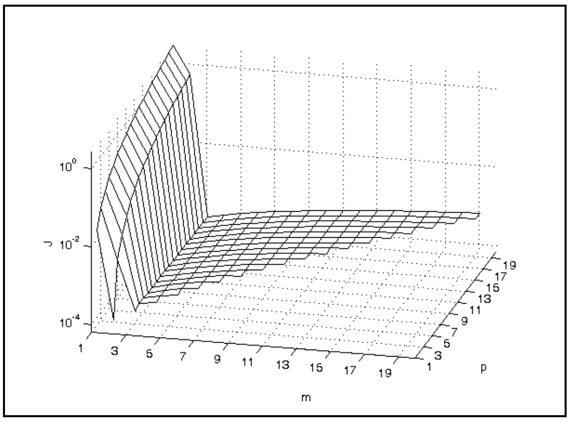


Figure 11. Effect on *J* with λ=0.01

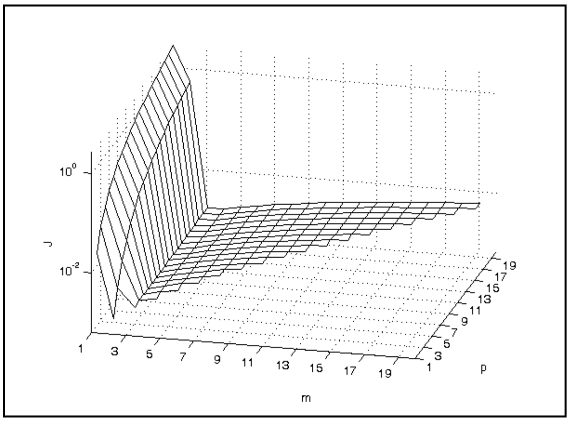


Figure 12. Effect on J with λ=0.1

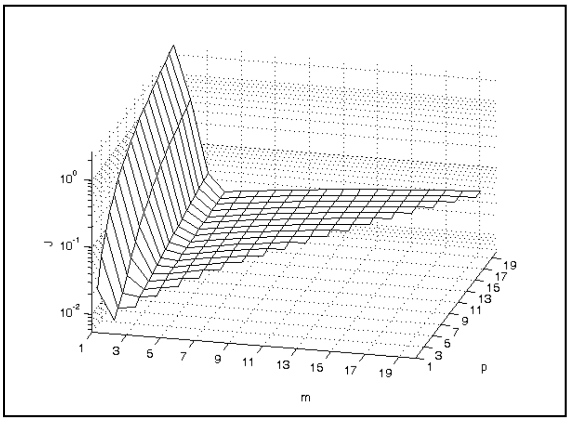


Figure 13. Effect on J with λ=1

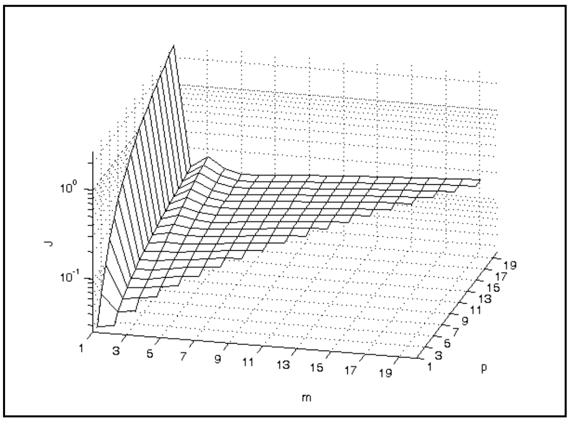


Figure 14. Effect on J with λ=10

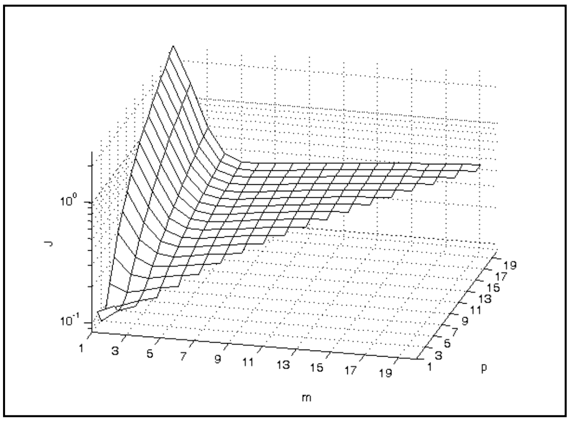
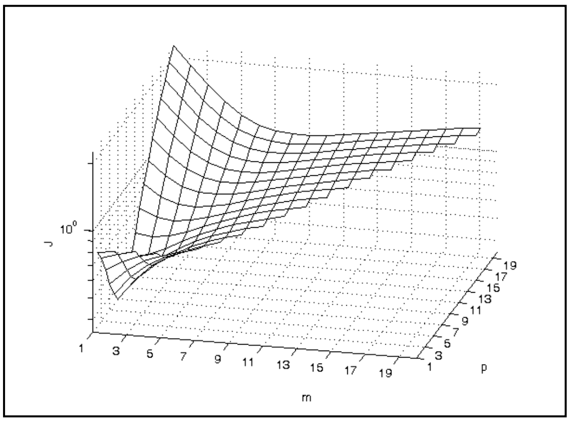


Figure 15. Effect on J with λ=100



been reached on the sensibility of the t_{r100} immediacy index under the controlling action of DMC controllers with different controller implementation parameter λ values. A number of figures have been obtained varying the λ parameter, as can be seen through Fig. 16-21.

After analyzing those figures, we conclude that in general, the shape of the immediacy index t_{r100} is maintained for a concrete combination of values of the p and m parameters, being not dependent of the λ parameter. I.e., its shape is mainly determined by both the prediction and the control horizons.

However, its value is clearly dependent on the λ parameter due to the offset that can be observed in the

Figure 16. Effect on t_{r100} with λ=0.001

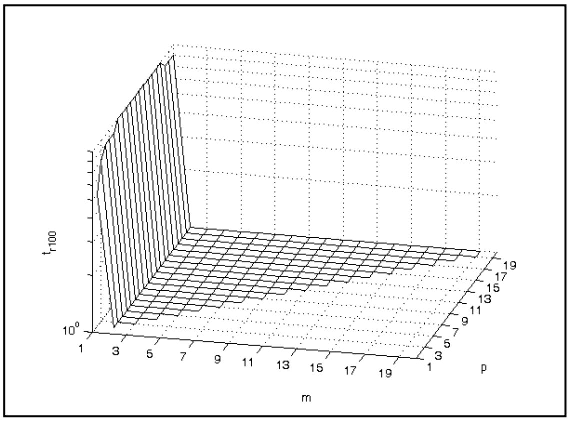


Figure 17. Effect on t_{r100} with λ=0.01

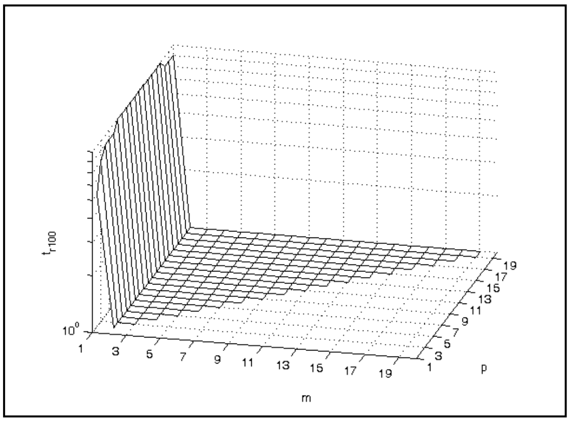


Figure 18. Effect on t_{r100} with λ=0.1

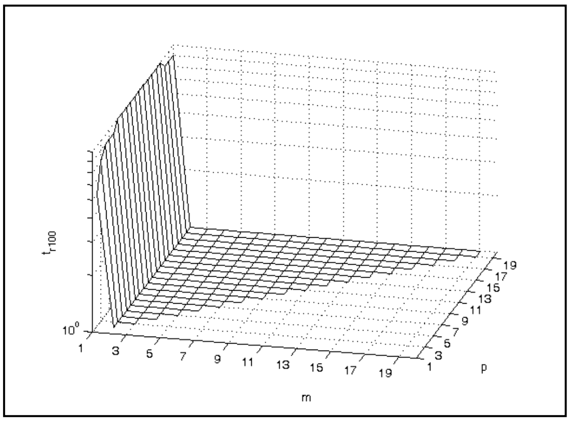


Figure 19. Effect on t_{r100} with λ=1

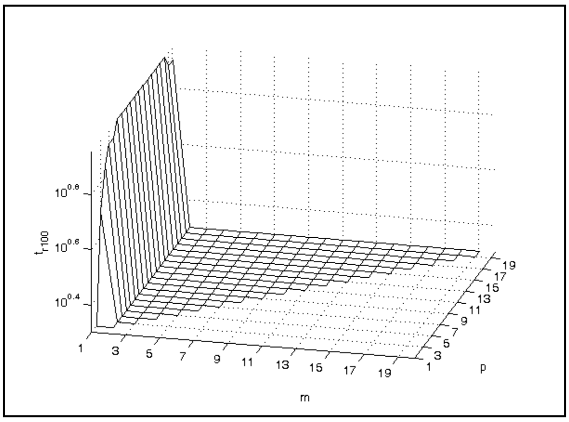


Figure 20. Effect on t_{r100} with λ=10

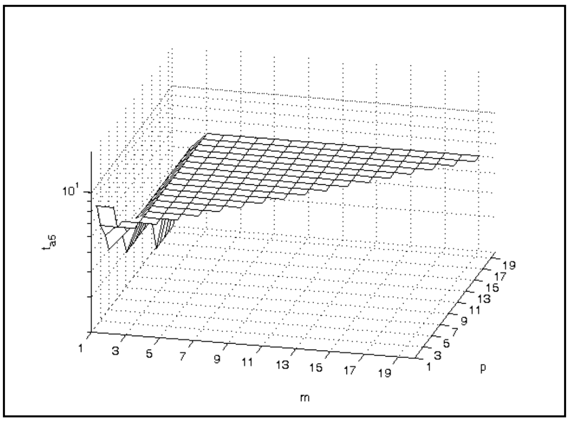
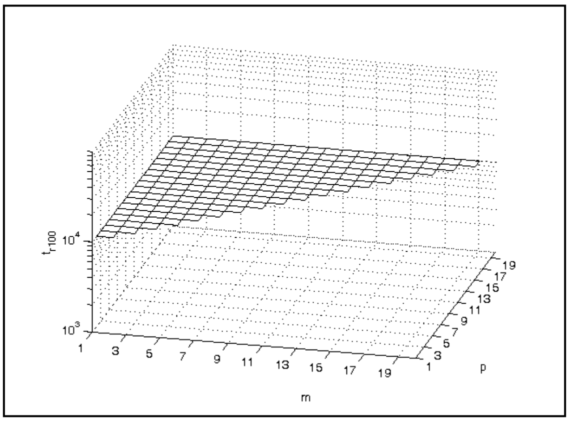


Figure 21. Effect on t_{r100} with λ=100



figures: the range of values starts from 10^0 s with $\lambda=10^{-3}$, to a value of 10^4 s (the reference signal $w(t)$ is never reached) with $\lambda=1$. The unique difference between the shapes of all figures arises when we are dealing with very small values of both the p and m parameters. The small values of the t_{r100} index indicate that the system controlled by means these DMC configurations does not need a lot of time to reach the reference value $w(t)$, i.e., the response is quite immediate.

D. Influence on t_{a5} index

In this subsection we describe the results that have been found on the sensibility of the t_{a5} stability index under the controlling action of DMC controllers with different controller implementation parameter λ values. A number of figures have been obtained varying the p parameter, as can be seen through Fig. 22-27.

In this case the shape of the figures is again quite similar, but there are clear differences when low values of the control horizon m (m=1) and high values of prediction horizon p (p=13 to p=20) are involved. There is also a clear difference on the absolute values of the t_{a5} index, that go from $10^{0.31}$ s when $\lambda=10^{-3}$ to 10^4 s when $\lambda=10^2$ as expected, since the controller can follow faster the changes on the $\Delta u(t)$ signal. The main difference arises when m=1 as stated before.

V. CONCLUSIONS

The first section of the paper reviews the scope and the application field of Model Predictive Control (MPC) and Dynamic Matrix Control (DMC) techniques. It also gives a short background and references some previous related works, where authors have also described mathematically the objective function that is usually used in DMC control. The second section describes the four performance indexes that have been analyzed along this paper, paying attention both to accuracy itself and to the time issues needed to reach so accurate results by the response of the controlled system.

The third section describes the experimental design carried out, which involves a total of 2,400 experiments with different DMC controller configurations with the aim of analyzing the effect of

Figure 22. Effect on t_{a5} with λ=0.001

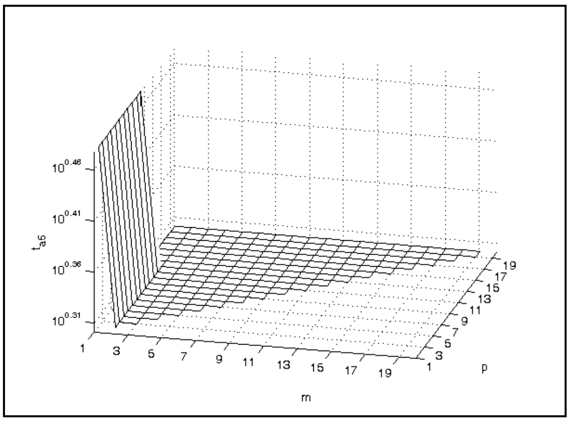


Figure 23. Effect on t_{a5} with λ=0.01

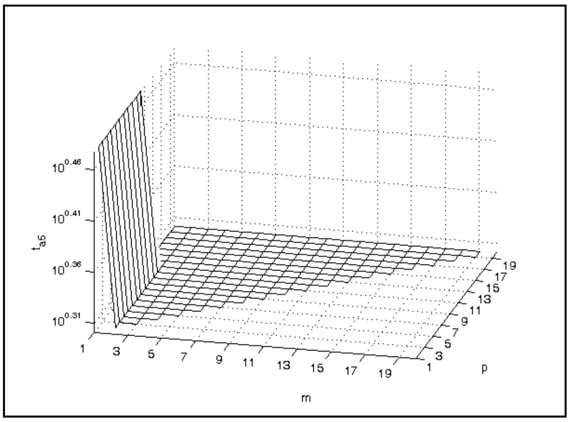


Figure 24. Effect on t_{a5} with λ=0.1

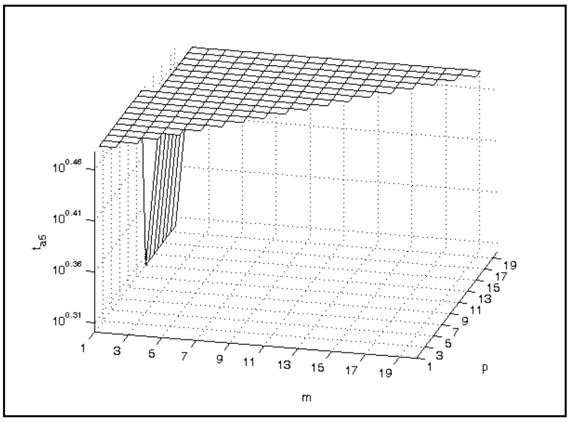


Figure 25. Effect on t_{a5} with λ=1

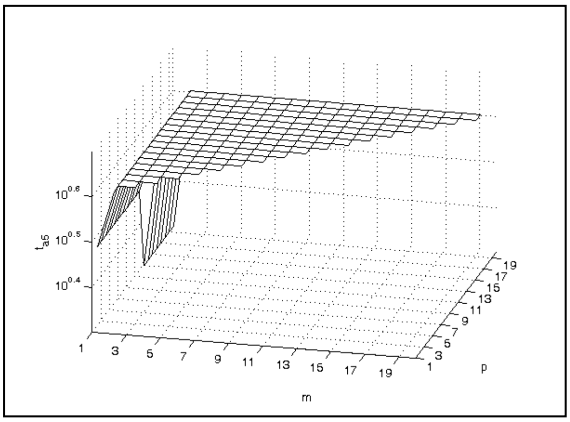


Figure 26. Effect on t_{a5} with λ=10

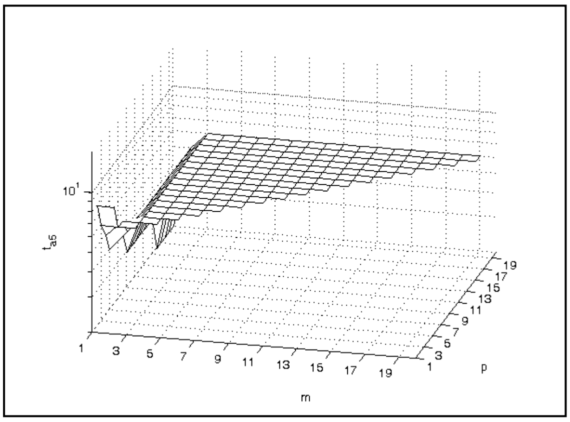
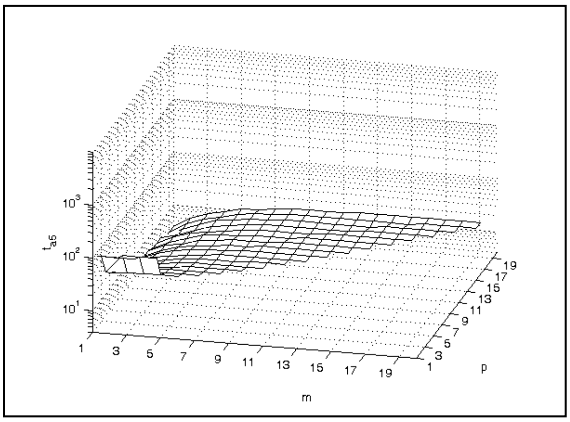


Figure 27. Effect on t_{a5} with λ=100



the controller implementation parameter λ. The obtained results were discussed in the fourth section showing that the controller implementation parameter λ for the studied values has a relative importance for J', J, t_{r100} and t_{a5} indexes. In general, the shape of all indexes are quite similar for the main part of prediction and control horizon values combinations, but the absolute values are different, showing a faster response with low values of the λ parameter, and showing a better performance with low values of *m*.

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