Demonstration of the Internal Model Principle by Digital Repetitive Control of an Educational Laboratory Plant

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***Abstract*—A key topic in classical control theory is the Internal Model Principle (IMP). A particular case of the IMP for tracking periodic references or attenuating periodic disturbances in closed-loop control systems is a technique called repetitive control. This paper proposes and describes an educational laboratory plant to show the students the advantages of repetitive controllers in systems with periodic references or disturbances. The plant has been designed to be low cost, easy to build, and subject to periodic disturbances with a clear physical explanation. More specifically, it consists of a pulsewidth modulation (PWM) electronic amplifier, a small dc motor, and a magnetic setup that generates a periodic load torque under constant mechanical speed operation. The control objective for the closed-loop control system is to regulate the mechanical speed to a constant value in spite of the periodic load torque disturbance. In order to accomplish this performance specification, a detailed design of a digital repetitive controller is presented, and some basic experimental results are provided to prove its good behavior. The paper also includes some repetitive control concepts and facts that teaching experience shows as essential to understand the design process.**

***Index Terms*—Digital control, Internal Model Principle (IMP), repetitive control, tracking and disturbance attenuation.**

I. Introduction

A KEY topic in classical control theory is the Internal Model Principle (IMP) [1]. This principle states that if a certain signal must be tracked or rejected without steady-state error, the generator must be inside the control loop, in the controller, or in the plant itself. Standard classical control subjects include this concept implicitly when they introduce the system-type concept [2]. This concept relates the structure of the open-loop system with closed-loop tracking/rejection capabilities in steady state. However, this type concept can only be applied to polynomial signals (step, ramp, and parabola) whose generator has the form $(1)/(s^n)$ in the Laplace domain.

In practice, many real systems have to handle tracking and rejecting periodic signals. For these cases, the tracking or rejection of these signals cannot be solved through this type concept; these must include in the open-loop transfer function of the system the corresponding generator of the signal to track or to reject. A well-known technique that uses the IMP concept to address this problem is repetitive control [3]. This technique has been extensively used in different engineering areas, such as CD and hard-disk arm actuators [4], robotics [5], machining [6], electrohydraulics [7], electronic rectifiers [8], pulsewidth modulation (PWM) inverters [9], and current harmonics active filters [10]. For these reasons, the authors think that this subject must be part of the control engineering students curricula at senior undergraduate level or junior graduate level.

The main idea of this paper is to show an educational laboratory plant with its corresponding theoretical support to introduce the IMP and repetitive control in advanced digital control courses through laboratory experimentation. Therefore, the plant has been designed to be low cost, to be easy to build, and to illustrate periodic disturbances with a clear and an intuitive physical explanation. The authors know of no commercial educational laboratory plant with this kind of disturbance load.

The paper is organized as follows. Section II describes the proposed plant. Sections III and IV introduce the basic repetitive control theory as it will be taught to the students. Section V shows the application of the described techniques to the proposed plant providing design criteria and showing some experimental results. Finally, some conclusions are drawn.

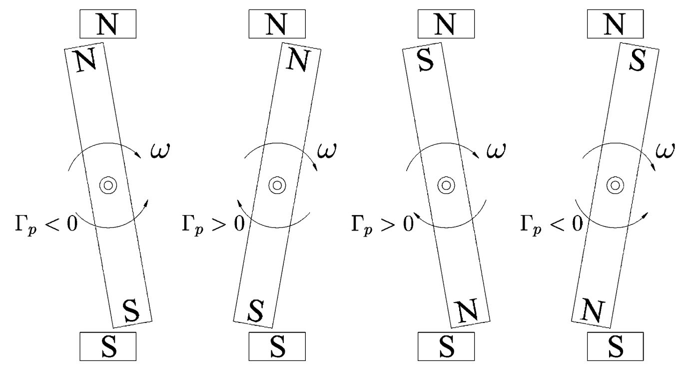

Fig. 1. Mechanical load: fixed and moving permanent magnets sketch (ω and Γ_p stand for the angular speed and the disturbance torque, respectively).

II. Plant Description

A. Basic Idea

Systems with rotary elements are usually affected by periodic disturbances because of the movement of these parts (e.g., electrical machines or CD players). This kind of system is supposed to be moving, in some cases, at fixed angular speed, and under these working conditions any friction, unbalance, or asymmetry

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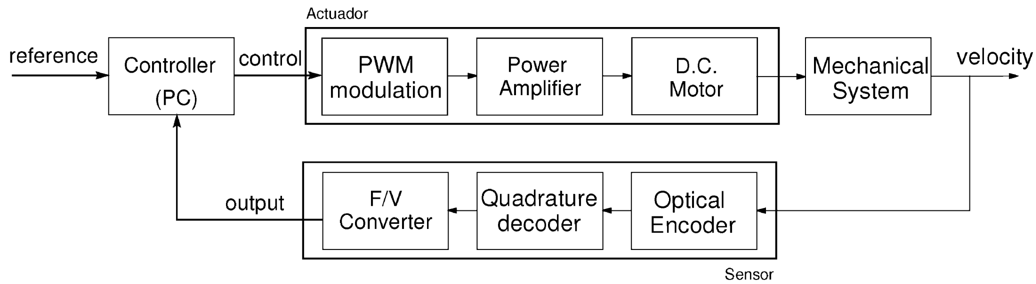

Fig. 2. Block diagram of the closed-loop control system.

appearing on the system generates a periodic disturbance that affects its dynamic behavior.

From this main fact, the basic idea of the plant is to attach a mechanism to a dc motor to generate a pulsating load torque (Γ_p). In case of fixed angular speed (ω), the selected medium to generate the periodic load torque is the magnetic system that can be seen in Fig. 1. As the figure shows, a bar holding a permanent magnet in each end (each magnet magnetically oriented in the opposite way[1]) rotates inside the magnetic field generated by two permanent magnets of different polarity placed on the same plane of the bar.

In this experimental setup, the rotation of the dc motor causes, as a result of the interaction between fixed and moving magnets, a pulsating load torque that depends on the mechanical angle (θ) of the motor axis. When the motor axis angular speed is constant $(\ddot{\theta} = \dot{\omega} = 0)$, the pulsating torque is a periodic signal with a fundamental period directly related to the axis speed. The control goal for this plant will be to keep the motor axis angular speed constant, i.e., to regulate the angular speed to the desired value. Thus, the periodic load torque will be the disturbance signal of the closed-loop system. Then, the control problem arises as a periodic disturbance attenuation problem with a clear physical explanation. Since the other components of the load torque, e.g., viscous friction, are small, all the torque can be considered of periodic nature, and this fact stresses the different closed-loop behavior between loops with classical controllers (lead-lag or PID) and loops with controllers based on the application of the IMP, like repetitive controllers.

B. Prototype Construction

The block diagram in Fig. 2 shows the general structure of the closed-loop control system. Apart from the magnetic and mechanical parts commented upon in the previous section, the closed loop includes the actuator, the feedback sensor, and the digital controller.

The actuator consists of the dc motor, the full-bridge inverter, and the hardware PWM. The dc motor used in this plant is a Johnson Electric HC615L (20 W, 5 A) that supplies enough motor torque to counteract the pulsating load torque. The pulse-amplitude-modulated (PAM) control signal of the digital controller is converted to a PWM signal using the National Semiconductor PWM modulator LM3524D that drives the 3-A full-bridge inverter LMD18200.

The speed sensor consists of an optical encoder, a quadrature decoder, and a frequency to voltage converter. The main reason for using the last element is to obtain an analog signal proportional to the motor axis speed. Then, a low cost analog-to-digital/digital-to-analog (A/D–D/A) conversion PC card (e.g., Advantech PCL812-PG) is used to convert the continuous time signals to discrete time, and vice versa. The optical quadrature encoder used in the plant is the two-channel 500-pulse-per-revolution Hewlett-Packard H9730A. Its output signal is then converted to pulse and sign format using an LSI LS7804 device that feeds the frequency to voltage converter (Burr-Brown VFC32C). The picture in Fig. 3 shows the magnetic and mechanic parts, the dc motor, and the encoder arranged in their final form.

[1]With this arrangement, the complete bar is seen as a large permanent magnet.

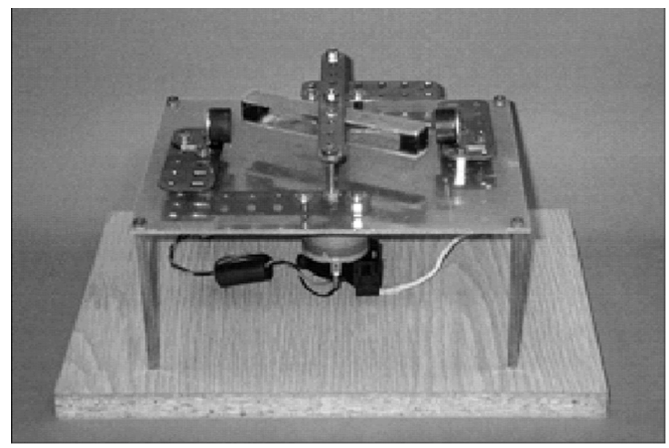

Fig. 3. Picture of the main part of the plant: dc motor, optical encoder, magnetic system (load), and supporting structure.

C. Plant Behavior Without Disturbances

This section shows the results of the modeling and identification process of the plant without the pulsating load torque, that is, the behavior of the actuator-dc motor-speed sensor cascade (open-loop transfer function) under no-load conditions.

The static input–output calibration curve is almost linear $(y = 5.47 \cdot x)$ over the full operation range with only a nonlinear distortion around 0 V because of the nonlinear behavior of the dc motor near stall condition and the dry friction phenomenon.

In order to obtain an accurate dynamic model of the open-loop system (including power electronics, sensor chain, and A/D–D/A conversion process), a discrete-time transfer function was identified from experiments on the real plant using standard methods of identification theory for ARMAX models. The final order was selected according to the Akaike Information Criterion [11]. The input signal used in the experiments was a pseudorandom binary signal (PRBS) with an

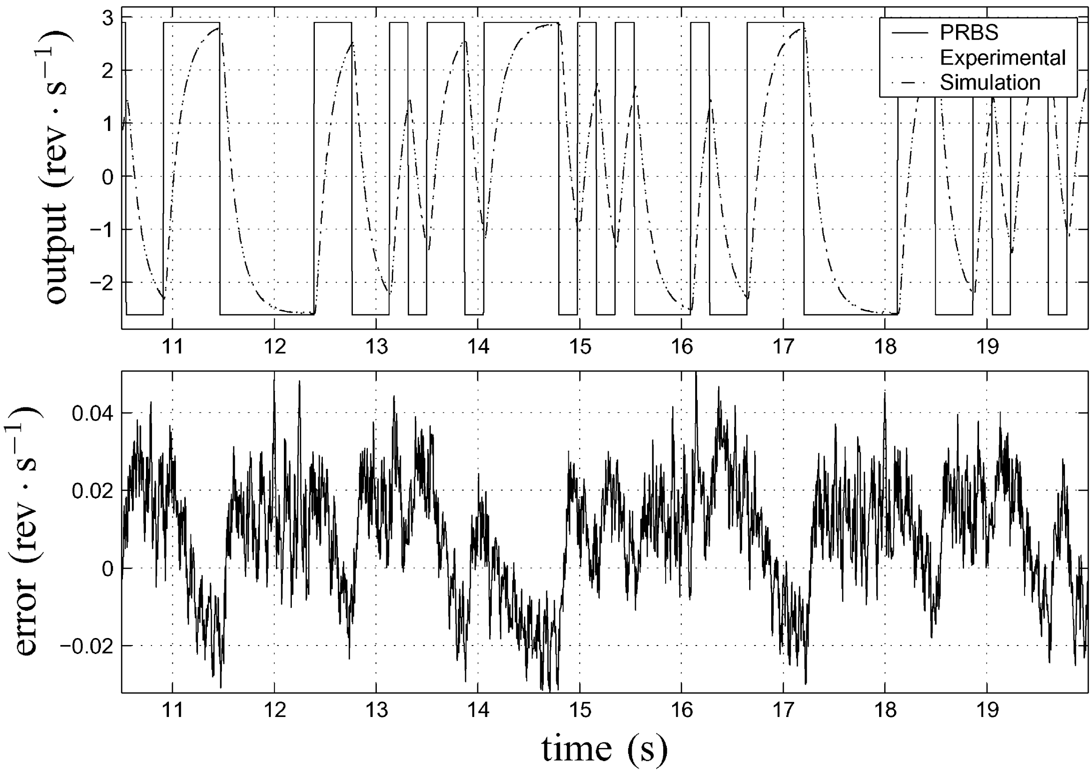

Fig. 4. Dynamic model validation (no-load conditions). (Top) Scaled PRBS input signal to the experimental plant and the model, experimental output, and simulated model output. (Bottom) Error between the experimental plant output and the simulated model output.

adequate bandwidth for the system under study. The sampling period[2] was fixed to $T_s = 0.005$ s. The resulting transfer function model without incorporating the dc gain is

$$G_p(z) = \frac{0.004\,225z^{-2} + 0.008\,491z^{-3} + 0.005\,81z^{-4}}{1 - 0.9749z^{-1} - 0.4759z^{-2} + 0.4694z^{-3}}. \quad (1)$$

Fig. 4 shows some validation results of this model: the upper plot shows the real and simulated output with a PRBS input,[3] and the bottom plot shows the corresponding error between them. Although the error is correlated, its magnitude is very small compared with the output values (less than 2% in the worst case). The model captures the complete linear relation between the input and the output (the complete open-loop chain, including sensor dynamics). However, between the input and the output, there are several nonlinear phenomena (A/D–D/A quantization, friction, etc.) that cannot be assumed by a linear model, and for this reason, the error in Fig. 4 appears correlated. In addition, since the sampling period is small, all the dynamic modes are relevant, giving a high-order model.

D. Plant Behavior With Disturbances

If no disturbances are introduced in the system when a voltage is applied to the motor, it rotates at a certain constant velocity in steady state. When the fixed magnets are introduced in the system, the interaction among them and the moving ones introduces a periodic disturbance in the system so that it cannot keep the velocity constant. Instead, its velocity describes a periodic function that can be observed in the power spectrum of Fig. 5, showing the typical shape of a periodic signal. The period of this function depends on the input voltage (angular speed).

E. Programming Environment

In order to implement the controllers, one must use a platform that allows closure of the loop at high frequency. This kind of performance could be obtained through the use of a digital signal processing (DSP) system or by using a real-time operating system (RTOS). The second option has been selected because special programming skills are not required. In this paper, RTLinux has been selected; this RTOS is programmed using standard POSIX (portable operating system interface) system calls [12] and a standard PC platform working under the Linux operating system.

To simplify the development and test, the real time controls laboratory (RTIC-lab) environment [13] has been used. Within this environment, the user is only in charge of defining the controller in standard C language, while RTIC takes care of handling the real-time implementation and the information exchange between Linux and RTLinux. In addition, once the experiments have been placed, RTIC allows one to obtain an ASCII file with experimental data. These data can be analyzed through any standard numerical package, such as MATLAB, Octave, or Scilab.

[2]The selected value of the sampling period will be justified hereafter.

[3]The PRBS signals used in the validation process are different from the ones used in the identification process.

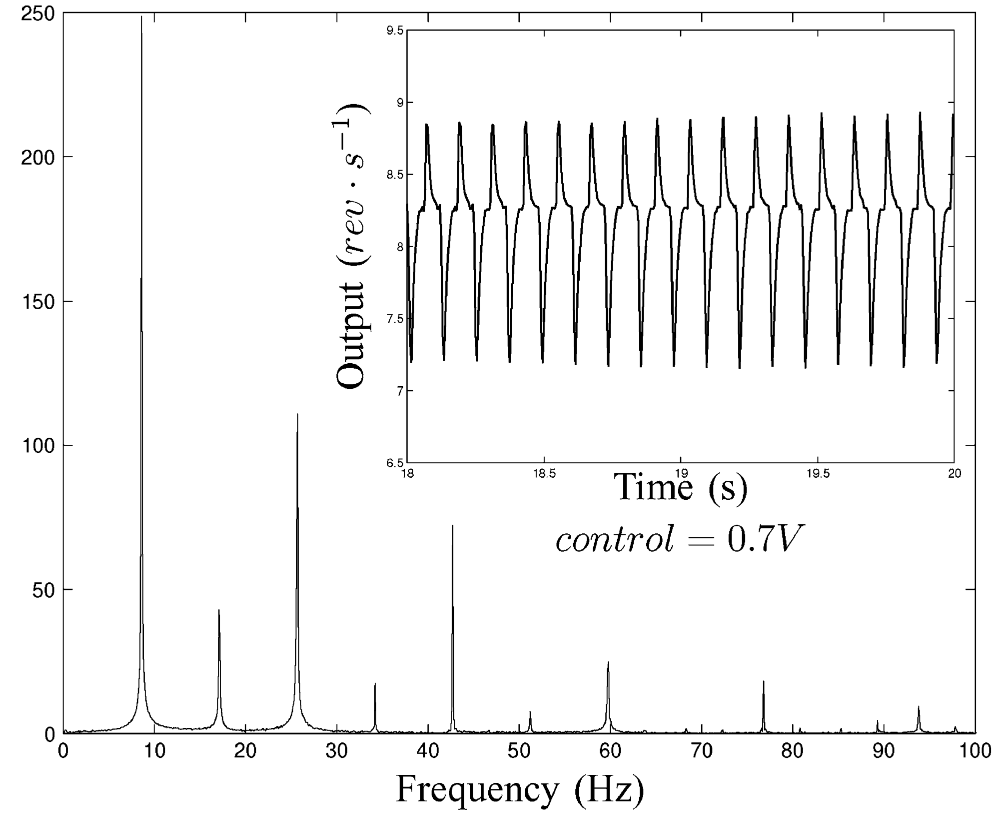

Fig. 5. System output with magnetic load (constant input control = 0.7 V): angular speed versus time and corresponding power spectrum.

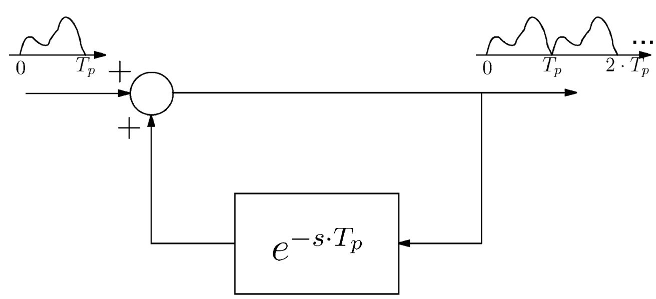

Fig. 6. Basic structure for a continuous-time repetitive loop.

III. Repetitive Control Basics

A periodic signal (with period T_p) can be developed in Fourier series as

$$r(t) = \sum_{n=-\infty}^{\infty} a_n e^{j\frac{2 \cdot n \cdot \pi \cdot t}{T_p}}. \tag{2}$$

Then, by the IMP, the following transfer function should be included in the control loop:

$$R(s) = \frac{1}{s} \prod_{n=1}^{\infty} \frac{\left(\frac{2n\pi}{T_p}\right)^2}{s^2 + \left(\left(\frac{2n\pi}{T_p}\right)^2\right)} \tag{3}$$

which can be stated in closed form [14] as

$$R(s) = \frac{T_p \cdot e^{\frac{-T_p \cdot s}{2}}}{1 - e^{-T_p \cdot s}}. \tag{4}$$

Because $T_p \cdot e^{(-T_p \cdot s/2)}$ is a delay term with a gain T_p, it will be enough to include $(1)/(1 - e^{-T_p \cdot s})$ inside the control loop. This transfer function can be implemented as a positive feedback loop with $e^{-T_p \cdot s}$ in the feedback path (Fig. 6).

From a frequency point of view, the transfer function in (4) has the property of infinity gain at frequencies $(n/T_p), \forall n \in \mathbb{Z}$. This property assures zero-error tracking at these frequencies in closed loop. Some works relate repetitive techniques with control-learning techniques [14]. Therefore, the basic repetitive structure learns a signal of length T_p and repeats it as a periodical signal of period T_p if the input to the system is set to zero (Fig. 6).

The implementation of a time delay in continuous time is a complicated matter. Fortunately, this implementation in discrete time is an easier task. Thus, the transfer function that should be included in the loop is

$$G_r(z) = \frac{z^{-N}}{1 - z^{-N}} = \frac{1}{z^N - 1} \tag{5}$$

where $N = (T_p)/(T_s) \in \mathbb{N}$, and T_s is the sampling time. In addition to the constraint in the relation between the signal period and the sampling period, the discrete-time implementations can only cancel those harmonics that are below the Nyquist frequency $((\omega_s/2) = (\pi/T_s))$.

IV. Controller Structure and Stability Analysis

Repetitive controllers are usually implemented in a "plug-in" fashion; that is to say, the repetitive compensator is used to augment an existing nominal controller $G_c(z)$ (Fig. 7). This nominal compensator is designed so that it stabilizes the plant

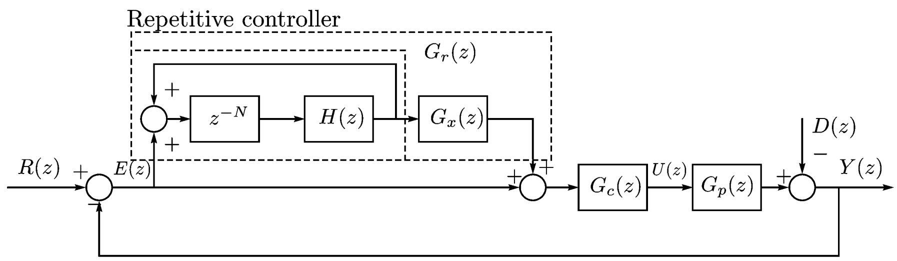

Fig. 7. Closed-loop control system block diagram with the "plug-in" repetitive controller.

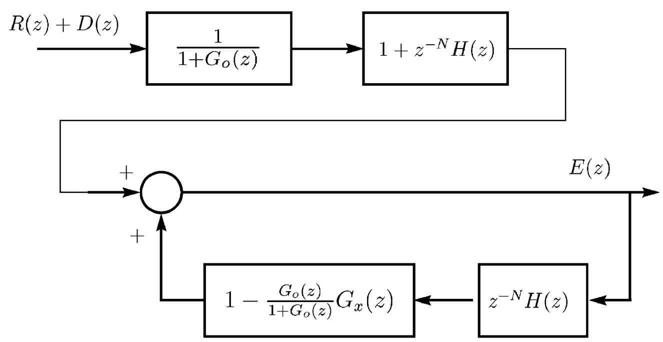

Fig. 8. Alternative block diagram for the closed-loop control system in Fig. 7.

$G_p(z)$ and provides disturbance $D(z)$ rejection across a broad frequency spectrum. This scheme also introduces a filter $H(z)$ in charge of improving robustness and a filter $G_x(z)$ in charge of assuring closed-loop stability. The closed-loop stability of this system could be studied by analyzing the closed-loop poles or the Nyquist plot of the corresponding open-loop transfer function. Although the closed-loop poles could be characterized [15], the authors preferred to follow the original stability proof in [16]. By algebraic manipulation, the block diagram in Fig. 7 can be redrawn as shown in Fig. 8. This new system consists of the cascade connection of three systems whose stability can be studied in a decoupled way. To prove the equivalence of the systems of Figs. 7 and 8, the second system will be obtained from the first one. The relation between the error signal $E(z)$ and the reference and disturbance $(W(z) = R(z) + D(z))$ can be obtained from the analysis of Fig. 7.

$$\frac{E(z)}{W(z)} = \frac{1}{1+\left(1+\frac{z^{-N}H(z)}{1-z^{-N}H(z)}G_x(z)\right)G_c(z)G_p(z)}. \quad (6)$$

By multiplying numerator and denominator by $1 - z^{-N}H(z)$, this equation can be rewritten as[4]

$$\frac{E}{W} = \frac{1-z^{-N}H}{1-z^{-N}H+(1+z^{-N}H(G_x-1))G_cG_p}. \quad (7)$$

Defining $G_o \triangleq G_cG_p$, multiplying numerator and denominator by $(1)/(1+G_o)$, and simplifying, the previous equation can be rewritten as

$$\frac{E(z)}{W(z)} = \frac{(1-z^{-N}H(z))\frac{1}{1+G_o(z)}}{1-\left(1-\frac{G_o(z)G_x(z)}{1+G_o(z)}\right)z^{-N}H(z)}. \quad (8)$$

[4]The dependency on z has been eliminated in order to improve compactness.

As previously stated, and shown in Fig. 8, the system can be written as three systems connected in cascade.

Once the equivalence has been shown, one must establish under which conditions each block in Fig. 8 is stable. The first block $(1 - z^{-N}H(z))$ is nothing more than a filter and a time delay. $H(z)$ is usually a finite-impulse response (FIR) filter; under this assumption, the first system is always stable. The second one has as denominator $1 + G_o(z)$ which has the same roots as the closed-loop system without repetitive controller; thus, it should be stable by construction (*first stability condition*). Finally, the third one can be described as a positive-feedback closed-loop system with the term $(1 - (G_o(z)G_x(z))/(1+G_o(z)))z^{-N}H(z)$ in the feedback path. A sufficient condition for the stability of this loop is

$$\left|\left(1-\frac{G_o(z)G_x(z)}{1+G_o(z)}\right)H(z)\right|_{z=e^{j\omega T_s}} < 1, \quad \forall\omega \in \left[0, \frac{\pi}{T_s}\right]. \quad (9)$$

This condition can be interpreted in the context of the Small Gain Theorem, and it can be split into two additional conditions.

- *Second stability condition*:

$$\|H(z)\|_{z=e^{j\omega T_s}} < 1, \quad \forall\omega \in \left[0, \frac{\pi}{T_s}\right]. \quad (10)$$

  Since $H(z)$ is a designed filter, this condition introduces some constraints over this filter.
- *Third stability condition*:

$$\left|1-\frac{G_o(z)G_x(z)}{1+G_o(z)}\right|_{z=e^{j\omega T_s}} < 1, \quad \forall\omega \in \left[0, \frac{\pi}{T_s}\right] \quad (11)$$

  where G_x should be designed to fulfill this condition.

These three stability conditions are an easy way of designing repetitive control systems. Therefore, this relatively simple stability study can be easily introduced to students.

V. Controller Design

In this section, the design procedure of a repetitive controller from the plant presented in Section II will be described. An important step is to select the sampling period. This selection is carried out according to several criteria. The first one is to have enough samples in transient response. From experimental results, the plant time constant has been established as $\tau \approx 0.135$ s. One condition that is usually used is the selection of a sampling time that is ten times lower than the lowest time constant $(10 \cdot T_s < \tau)$; therefore, T_s should be less than 0.01 s.

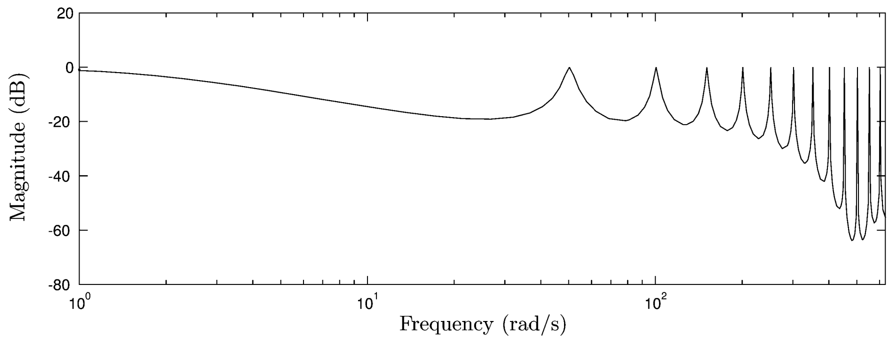

Fig. 9. Closed-loop frequency response ($k_r = 0.2$): gain (decibels) versus frequency.

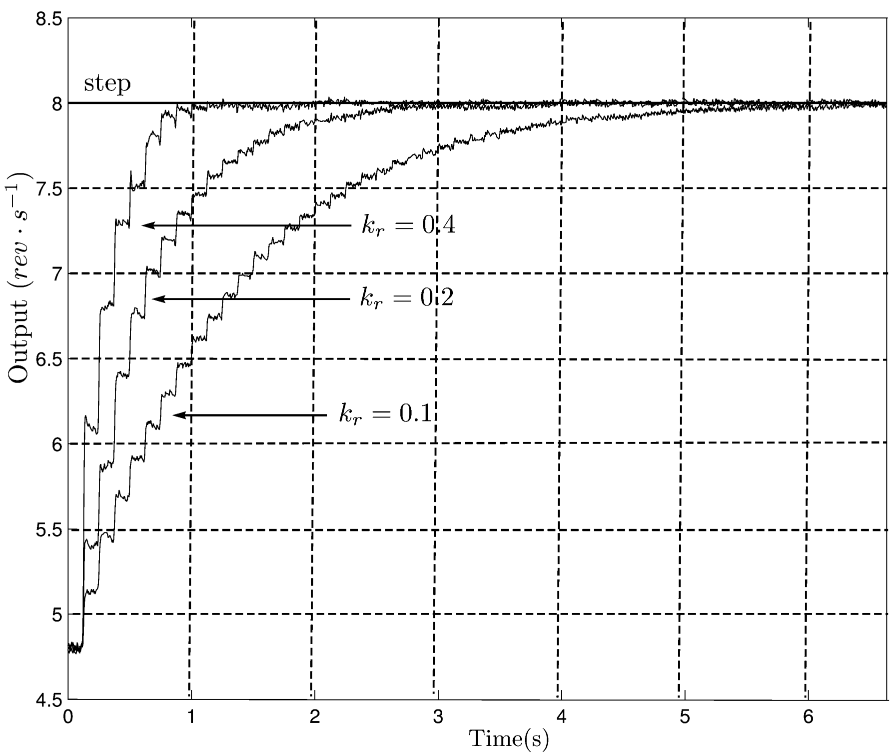

Fig. 10. Experimental closed-loop step response (with the repetitive "plug-in" controller) for the system under no-load condition.

As introduced in previous sections, the sampling period should be a submultiple of the disturbance fundamental period ($T_p = N \cdot T_s, N \in \mathbb{Z}_+ \backslash \{0\}$). In this paper, the authors are interested in developing a controller that allows the system to turn at a constant speed of 8 rad $\cdot$ s^{-1}. This constancy will generate periodic disturbances with the fundamental period $T_p =$ 0.125 s. The selection of N must be large enough so that the sampled-data disturbance can approximate the continuous-time one. In this paper, the authors have determined that $N = 25$ would be adequate for this system. Taking into account this condition and the previous one, a sampling period of $T_s =$ 0.005 s has been selected.

To conclude the design, one must establish $G_c(z), G_x(z)$, and $H(z)$ to fulfill the three stability conditions. G_c should be designed in order to fulfill the first stability condition and to assure closed-loop stability without the repetitive controller. The plant is open-loop stable and is in closed loop. According to simplicity criteria, $G_c = 1$ has been selected.

$H(z)$ should fulfill the second stability condition; in this paper, two different approaches will be used. In the first one, $H(z) = 1$ is selected; thus, no filtering is introduced. In the second one, a low-pass null-phase FIR filter is used ($H(z) = q_1 \cdot z + q_0 + q_1 \cdot z^{-1}$).[5] No causality problems exist because the filter is in cascade with an N periods delay. This filter allows for the reduction of gain at those frequencies at which uncertainty exists, but unfortunately it slightly moves the closed-loop pole positions in z plane.

A common approach to design G_x is using $G_x = k_r((G_o)/(1+G_o))^{-1}$. Unfortunately, this approach cannot be applied to nonminimum-phase plants like this one because forbidden cancellations would appear in the open-loop transfer function construction, and then the system would no longer be internally stable. Another approach is to cancel minimum-phase

[5]To assure unitary gain at dc frequency the parameters must fulfill the constraint $q_0 + 2 \cdot q_1 = 1$.

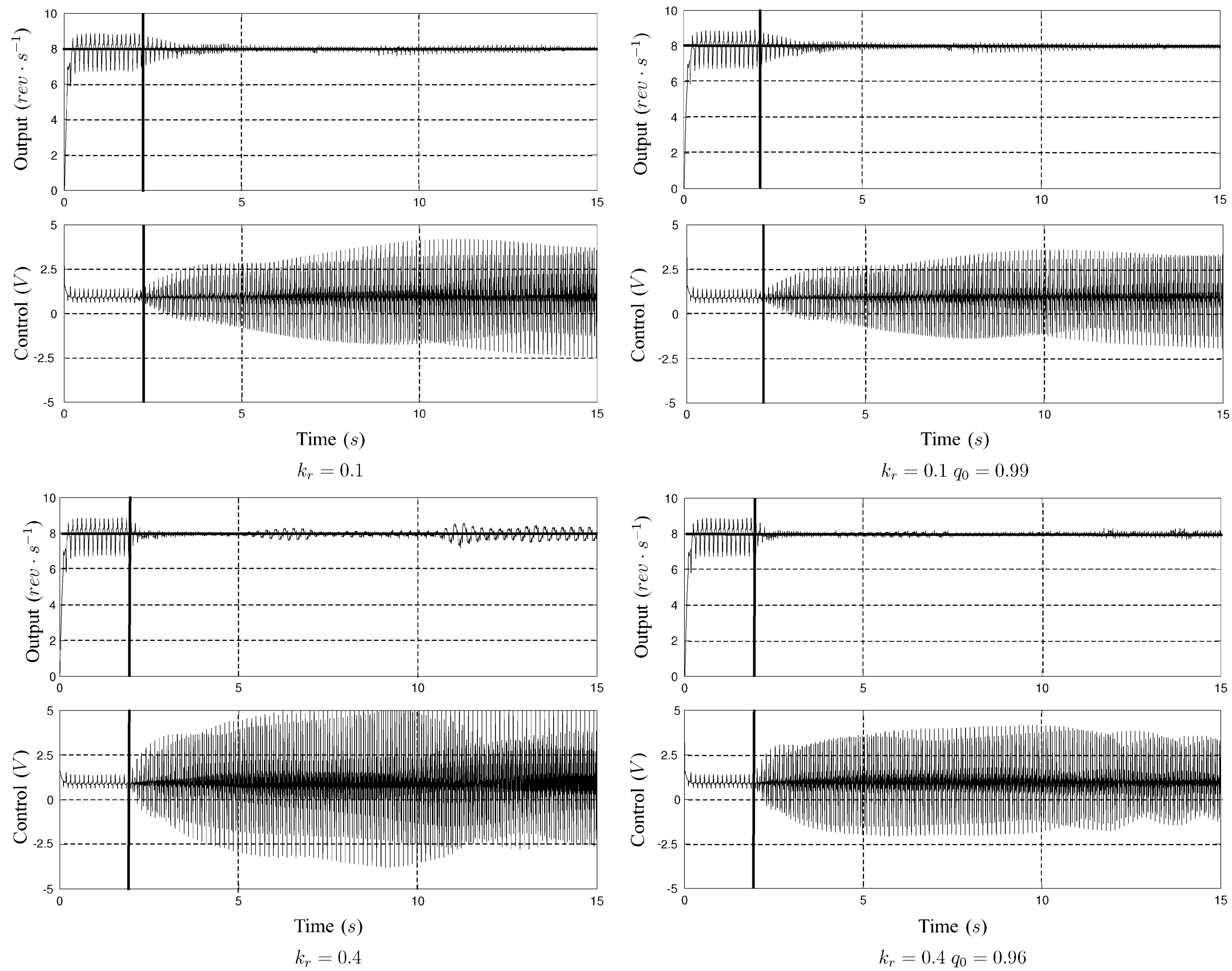

Fig. 11. Experimental closed-loop step response for the system with the magnetic load: without (left) and with (right) $H(z)$ filter, and $k_r = 0.1$ (top) and $k_r = 0.4$ (bottom). For each case, the top figure shows the reference and output signals, and the bottom figure shows the corresponding control effort. The vertical bar indicates the introduction of the "plug-in" repetitive controller.

zeros and compensate the phase for the non-minimum-phase ones [17]. In this approach, G_x has the shape

$$G_x(z) = k_r \frac{D(z)N^-(z^{-1})}{N^+(z)b_{\max}} \tag{12}$$

where $(N(z))/(D(z)) \triangleq (G_o(z)/1 + G_o(z)), N(z) \triangleq N^-(z)N^+(z)$. The roots of $N^-(z) = 0$ are non-minimum-phase zeros, the roots of $N^+(z) = 0$ are minimum-phase zeros, and $b_{\max} = \max_\omega \mid N^-(z)N^-(z^{-1}) \mid_{z=e^{j\omega T_s}}$. Again, the controller causality has no problem because it is in cascade with several delays.

With this controller, the third stability condition can be rewritten as

$$\left| 1 - k_r \frac{N^-(z^{-1})N^-(z)}{b_{\max}} \right|_{z=e^{j\omega T_s}} < 1.$$

Since $N^-(z^{-1})N^-(z)$ has null phase, k_r should belong to $(0, 1)$ in order to fulfill the condition. The final value of k_r should be fixed, noting the tradeoff between robustness and transient response [18].

Fig. 9 shows the closed-loop frequency response of the system. For a value of $k_r = 0.2$ (with $H(z) = 1$), one can see that the closed-loop system has unitary gain at the disturbance fundamental frequency, and all of its harmonics are within the closed-loop system bandwidth. This fact assures that the system will be able to reject the disturbance.

The complete controller has been experimentally validated in the plant. In Fig. 10, the closed-loop system step response can be seen when permanent magnets are not present; therefore, there is no periodic disturbance (the experiment has been completed for $H(z) = 1$ and several values of k_r). One can observe that the system time response is slower than the original one, and the system has complex dynamics behavior because of the high-order controller. One can also see that high values of k_r increase system time response. For all values of k_r, the system has no steady-state error because of the open-loop pole placed in $z = 1$ by the repetitive controller.

Fig. 11 shows the experimental closed-loop step response for the system under periodic disturbance for several values of k_r and $H(z)$. The system output and control action are shown for each experiment. One can see that in all cases, the system converges to the desired value without steady-state error after entering the repetitive "plug-in" controller at time 2 s (see vertical bar in Fig. 11). However, for $k_r = 0.4$ and without $H(z)$, some oscillations appear. These oscillations are related to the control action saturation and the high gain introduced at high frequencies where model uncertainties are relevant. These problems can be minimized through the use of a $H(z)$ filter which reduces gain at the high-frequency band.

VI. Conclusion

This paper has presented the description of a low-cost educational laboratory plant designed to show the application of the IMP and, in particular, the digital repetitive control technique that is based on it. The plant is easy to build with inexpensive elements, and the magnetic setup generates, under speed regulation, a periodic disturbance which shows clearly the advantages of the repetitive controllers over the usual undergraduate-level, classical-control course controllers.

In addition, the basic aspects of repetitive control are presented and applied to the designed plant to show a practical way to teach them. The repetitive controller is designed in the usual plug-in manner with detail of all the design steps involved. This approach shows a systematic way of designing this class of controllers and facilitates its use for the students. Besides, experience shows that, by comparing these results with the ones obtained while using classical controllers, the students acquire a deep understanding of the IMP meaning.

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