

## AN EDUCATIONAL APPROACH TO THE INTERNAL MODEL PRINCIPLE FOR PERIODIC SIGNALS

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**ABSTRACT.** *This article presents an educational approach to resonant control and repetitive control, which are Internal Model Principle-based control techniques specifically designed for the tracking/rejection of periodic signals. The analytical formulation is completed by a set of simulations and physical experiments on a mechatronic educational plant integrated in a virtual/remote laboratory. The laboratory features are oriented to realize the limited performance of classic PID control to reject non-constant disturbances and, at the same time, to show the effectiveness of the Internal Model Principle for the rejection of periodic disturbances by means of resonators and repetitive control. Assessment based on students' perception reveals it as a useful distance learning tool. The laboratory is integrated in Automatl@bs, a Spanish interuniversity network of web-based laboratories devoted to distance learning of control engineering.*

**Keywords:** Control education, Internal model principle, Resonant control, Repetitive control, Distance learning, Virtual/remote laboratory

**1. Introduction.** A key topic in classical control theory is the Internal Model Principle (IMP) [1], which states that if a certain signal is wanted to be tracked or rejected without steady state error, it is necessary to include its generator inside the control loop.

Although the IMP is generic, it has special interest for signals that could be termed as marginally stables, i.e., with generators such that their Laplace transforms exhibit simple poles on the imaginary axis. The case of signals with simple poles on the origin, i.e., steps, can be easily studied through the system type concept [2]. Instead, this article focuses on the tracking/rejection of signals with purely imaginary simple poles, i.e., periodic signals. This problem can be addressed with resonant control [3-5] and repetitive control [6-9], which are well-known techniques that rely on the IMP.

It is worth remarking that, in practice, many real applications are related to tracking and rejecting periodic signals. We may find important examples in the mechanical systems field: on the one hand, robotic systems doing repetitive tasks receive periodic references [16-18]; on the other hand, most turning devices are subject to periodic disturbances

whose frequency depends directly on the turning speed, CD players being a challenging scenario [15]; also, periodic components are present in vibration suppression tasks [19-21]. Another essential area is power electronics, where IMP applications may be found in PWM Inverters [5,22], UPS systems [23] and harmonic active filters [24]. In fact, green energies and other new energy sources use power converters to adapt or transform electrical power. In order to reduce losses and to improve performances, sophisticated control methods, such as the ones arising from the IMP, are needed. The increasing importance of this area has caused the inclusion of this techniques in most graduate studies.

The article sketches the basics of resonant control and repetitive control starting with a simple and homogeneous educational description of the IMP, which also allows the comparison of their main features. Hence, these control techniques, which show an independent evolution from each other, are here introduced within a unified frame. The novelty of the approach lies, precisely, on this unified presentation which, to the authors' knowledge, is so far absent in the control education literature. Then, the concepts included in the theoretical part are illustrated by a set of simulations and physical experiments integrated in a virtual/remote laboratory.

Virtual/remote laboratories are experiencing an increasing importance as teaching/learning tools in higher education contexts. This is because their excellent performance in continuous learning processes is enhanced by the fact that the consumption of human, spatial and temporal resources associated to its use is much less than those inherent to traditional laboratories. Indeed, virtual laboratories constitute an efficient instrument for simulating the behavior of specific systems [25]. They provide an interactive framework which includes the dynamical model and a set of basic tools that allow the study of its performance features with a important savings of simulation development time. On the other hand, remote laboratories aim at providing the possibility of experimenting with real devices, physically located far from the user, through local networks or internet access.

The virtual/remote laboratory developed in this work is based on a mechatronic educational plant and has been built using EJS software and LABVIEW. Its features are oriented to realize the limited performance of classic PID control towards the rejection of non-constant disturbances and, at the same time, to show the effectiveness of the IMP for the rejection of periodic disturbances by means of resonators and repetitive control. The laboratory has been integrated in the Automat@b network, a Spanish interuniversity network of web-based laboratories devoted to distance learning of control engineering [10].

Finally, the article includes an assessment of the virtual/remote laboratory capabilities based on students' perception. The results reveal, among other conclusions, that the laboratory is indeed seen as a useful distance learning tool with a strong added value with respect to traditional methods.

The paper is organized as follows. Section 2 is devoted to the educational context in which the proposal is integrated. Section 3 contains a brief introduction to resonant control and repetitive control, as well as specific details regarding their implementation in the virtual/remote laboratory. Sections 4 and 5 describe, respectively, the plant used in the virtual/remote laboratory and the laboratory itself, the latter including a practical example. Assessment results are reported in Section 6, while conclusions are presented in Section 7.

## 2. Educational Context.

**2.1. The Automatl@bs network.** The Automatl@bs project [10,11] is a Spanish interuniversity experience that aims at the design, development and exploitation of a network of virtual and remote laboratories for the distance learning of automatic control. Its origin can be traced back to 2004 when, having in mind the challenging educational changes derived from the European Higher Education Space (EHES), the Education in Automatic Control group of the Spanish Automatic Control Committee boosted the research on improvement and adaptation of the teaching-learning quality in Automatic Control to the EHES requirements.

The laboratories that constitute the Automatl@bs network have been developed by the groups that are involved in the project, which belong to the Universities of Alicante, Almería, León, Miguel Hernández (Elche), UNED, Technical University of Catalonia and Politechnical University of Valencia [11-13]. The labs offer an integrated environment where to carry out practical activities at different levels. As it provides a common working setting and a time booking system to perform the remote experiments, Automatl@bs can be regarded as a single laboratory despite the fact that the plants are physically located in different places.

**2.2. Curricular aspects.** The servomechanism problem lies at the foundations of Control Theory. Essentially, it aims at designing a feedback controller capable of rendering asymptotic tracking of a class of inputs and/or rejection of a class of disturbances in the face of model uncertainties.

The IMP constitutes the key tool for the solution of the servomechanism problem in linear systems. Hence, such an advanced control concept is usually introduced in graduate courses on Control Theory. This is the reason why the virtual/remote laboratory presented in this article has been used by graduate students following engineering M.Sc. programmes in the universities that are in the Automatl@bs project.

However, as suggested in Section 1, one has to bear in mind that standard classical control subjects include implicitly the IMP concept when they introduce the system type [2], which can be applied to signals with generator of the form  $1/s^n$  in the Laplace domain. This encompasses most of the main signals in classical Control Theory, namely, steps, ramps and parabolas [14]. Hence, the IMP could be introduced via the type concept to undergraduate students in elementary control courses, which would allow them to use the here proposed virtual/remote laboratory.

**3. Tracking/Rejection of Periodic Signals by the IMP.** This section describes the essential mathematical formulation of the IMP-based tools for the tracking/rejection of periodic signals.

The Fourier series expansion of a continuous-time  $T_p$ -periodic signal  $s(t)$  can be written as

$$s(t) = \sum_{k=-\infty}^{\infty} a_k e^{j\omega_k t},$$

with  $\omega_k = 2k\pi/T_p$ . Denoting by  $S(s)$  the Laplace transform of  $s(t)$ , it is immediate that

$$S(s) = \frac{a_0}{s} + \sum_{k=1}^{\infty} R_k(s), \quad (1)$$

where

$$R_k(s) = \frac{Re(a_k)s - Im(a_k)\omega_k}{s^2 + \omega_k^2}. \quad (2)$$

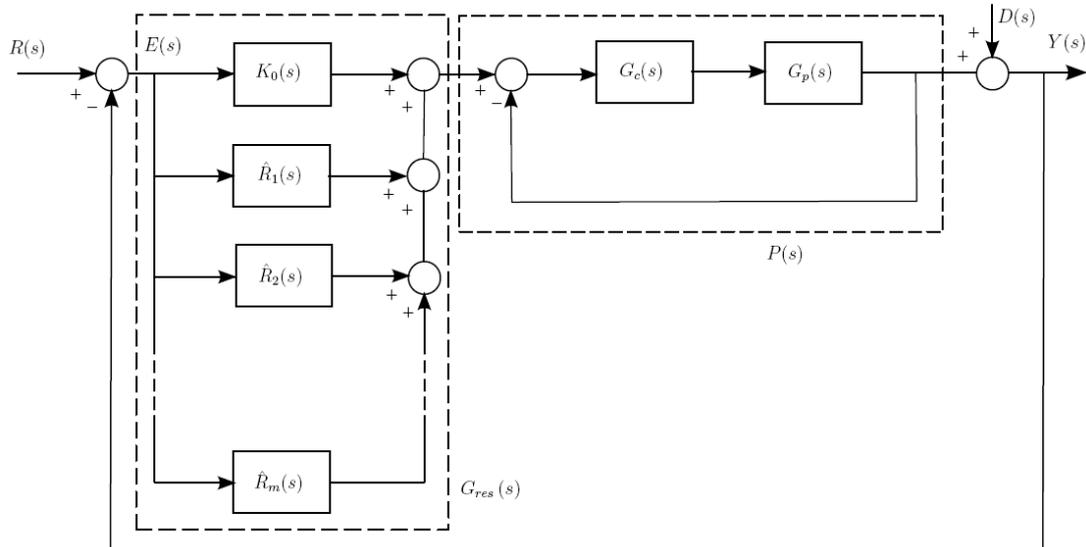


FIGURE 1. AFC-resonant control loop architecture

According to the IMP, if a periodic reference/disturbance wants to be tracked/rejected in the steady-state, then the corresponding generating polynomial, i.e., the denominator of (1) and (2), should be included in the controller [26]. Resonant control and repetitive control are two different approaches to carry out this task, and are available in the virtual/remote laboratory.

**3.1. Resonant control.** Resonant control bases its strategy on introducing a truncated version of the generator of (1), including only the first  $m$  harmonics, in the open-loop transfer function. This allows the tracking/rejection of all the harmonics of  $s(t)$  up to order  $m$  in case that the closed-loop system is stable. Unfortunately, due to the phase lag introduced by  $R_k(s)$ , assuring closed-loop stability is not a simple task. However, the use of suitable zeros may simplify the procedure. A common approach is to use the zeros obtained in the Adaptive Feedforward Cancellation (AFC) technique [5,27]:

$$\hat{R}_k(s) = g_k \frac{s \cos(\phi_k) + \omega_k \cos(\omega_k)}{s^2 + \omega_k^2}, \quad (3)$$

where  $g_k$  is a positive real gain and  $\phi_k$  is the mean phase shift of  $\hat{R}_k(s)$  at  $\omega_k$ .

Figure 1 shows the block diagram of the AFC closed-loop architecture, which is composed by two hierarchical control loops. Given a plant,  $G_p(s)$ , a controller,  $G_c(s)$ , is introduced in the inner loop to provide good stability margins and robustness. The inner loop transfer function is

$$P(s) = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)}.$$

In addition,  $G_c(s)$  is assumed to place  $\angle P(j\omega)$  in the range  $[-90^\circ, 90^\circ]$  within the desired bandwidth.

The outer loop, in charge of assuring steady-state tracking/rejecting performance, includes: (i)  $K_0(s)$ , usually a PI controller, which guarantees steady-state performance at dc-frequency, and (ii) a finite number of resonators  $\hat{R}_k(s)$  (see (3)),  $k = 1, \dots, m$ , with

$$\phi_k = -\angle P(j\omega_k). \quad (4)$$

Note that (4) has solution if  $\angle P(j\omega) \in [-90^\circ, 90^\circ]$ . If  $\angle P(j\omega) < 0$ , which is a usual case,  $\hat{R}_k(s)$  is as non-minimum-phase element [3,5].

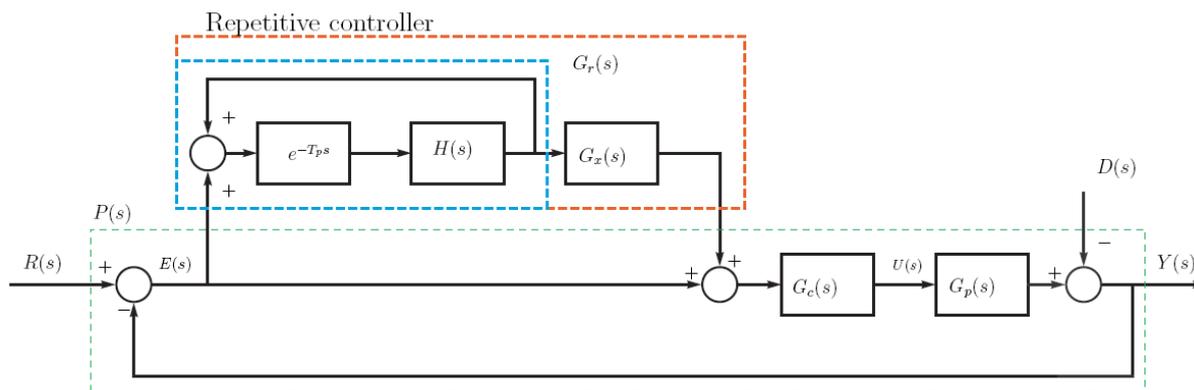


FIGURE 2. Closed-loop control system block diagram with the “plug-in” repetitive controller

This last choice ensures zero phase at  $\omega_k$  in the open loop of the outer loop transfer function  $G_{res}(s)P(s)$  [3,5], where

$$G_{res}(s) = K_0(s) + \sum_{k=1}^m \hat{R}_k(s).$$

Finally, the gains  $g_k$  are tuned to guarantee closed-loop stability. They are usually selected to describe a hyperbolic profile, giving more gain to low frequencies and less gain to high frequencies, although other profiles may be of interest in specific cases.

**3.2. Repetitive control.** In contrast to resonant control, repetitive control includes (1) completely in the control loop. Following [28], (1) may be written as

$$G_r(s) = \frac{T_p e^{-\frac{T_p s}{2}}}{1 - e^{-T_p s}},$$

which can be implemented as a positive feedback loop with  $e^{-T_p s}$  in the feedback path (see Figure 2). A low-pass filter  $H(s)$  is commonly included in the feedback path as well, aimed at reducing the open-loop high gain outside its bandwidth and also to improve the system robustness, this yielding:

$$\hat{G}_r(s) = \frac{T_p e^{-\frac{T_p s}{2}} H(s)}{1 - e^{-T_p s} H(s)}.$$

Notice that  $T_p$  in the numerator is just a simple gain and, therefore, it is usually omitted.

Repetitive controllers are commonly implemented in a “plug-in” fashion, as depicted in Figure 2. Thus, the repetitive compensator is used to augment an existing nominal controller: given a plant  $G_p(s)$ , the nominal controller  $G_c(s)$  is designed to stabilize  $G_p(s)$  and to reject disturbances across a broad frequency spectrum, this yielding the internal transfer function

$$P(s) = \frac{G_c(s)G_c(p)}{1 + G_c(s)G_p(s)}.$$

Finally, a stabilizing controller,  $G_x(s)$ , is introduced to assure closed-loop stability.

Indeed, closed-loop stability is met if the following conditions are fulfilled [6]:

1. The closed-loop system without repetitive control, i.e.,  $P(s)$ , is stable.
2.  $\|H(s)[1 - P(s)G_x(s)]\|_\infty < 1$ .

TABLE 1. Resonant and repetitive controllers: continuous-time and discrete-time equivalence

|                   | Continuous-time  | Discrete-time  |
|-------------------|--|--|
| Period            | $T_p$  | $N$  |
| Pulsation         | $\omega_k = 2k\pi/T_p$   | $\omega_k = 2k\pi/N$   |
| Series            | $s(t) = \sum_{k=-\infty}^{\infty} a_k e^{j\omega_k t}$   | $s(n) = \sum_{k=0}^{N-1} b_k e^{j\omega_k n}$  |
| Series transform  | $S(s) = \frac{a_0}{s} + \sum_{k=1}^{\infty} R_k(s)$<br>$R_k(s) = \frac{s \operatorname{Re}(a_k) - \operatorname{Im}(a_k)\omega_k}{s^2 + \omega_k^2}$ | $S(z) = \frac{b_0 z}{z-1} + \sum_{k=1}^{N-1} R_k(z)$<br>$R_k(z) = \frac{2 b_k z[z \cos(\angle b_k) - \cos(\omega_k - \angle b_k)]}{z^2 - 2z \cos(\omega_k) + 1}$ |
| AFC resonator     | $\hat{R}_k(s) = g_k \frac{s \cos(\phi_k) + \omega_k \cos(\omega_k)}{s^2 + \omega_k^2}$   | $\hat{R}_k(z) = g_k \frac{z^2 \cos(\phi_k) + z \cos(\omega_k + \phi_k)}{z^2 - 2z \cos(\omega_k) + 1}$  |
| Period delay      | $e^{-T_p s}$   | $z^{-N}$   |
| RC internal model | $G_r(s) = \frac{e^{-T_p s}}{1 - e^{-T_p s}}$   | $G_r(z) = \frac{z^{-N}}{1 - z^{-N}}$   |

In practice, condition 2 is ensured designing the low pass filter  $H(s)$  so as to verify  $\|H(s)\|_{\infty} < 1$ , while  $G_x(s)$  is designed to fulfill  $\|1 - P(s)G_x(s)\|_{\infty} < 1$ . This last requirement is usually obtained through a phase cancellation approach [29]. For minimum phase plants, this may be achieved with

$$G_x(s) = \frac{k_r}{P(s)}. \quad (5)$$

The proof of this stability condition is carried out decomposing the system in three parts and applying the *small gain theorem* to the most involved one [7]. This analysis can be easily introduced to graduate students.

**3.3. Comparison and implementation comments.** Resonant and repetitive control techniques are based on introducing very high (or infinite) gain at the frequencies  $\omega_k$ . This is done parametrically except for digital repetitive controllers, where the embedding is structural.

In both approaches the plant phase is cancelled to obtain high gain combined with null-phase, which guarantees robustness and simplifies the stability analysis. In resonant control this cancellation is carried out only at each harmonic frequency through the zeros of  $\hat{R}_k(s)$  (recall (3) and (4)), while in repetitive control it is applied to all frequencies via  $G_x(s)$  (recall (5) in case of a minimum phase plant).

From the implementation viewpoint, repetitive control is simpler and needs less computational resources but memory. Alternatively, resonant control allows a specific control of each harmonic and also the tracking/rejection of non-harmonic components, but it may exhibit implementation issues when using fixed-point arithmetics.

Finally, it is worth remarking that, while in practice most plants are continuous time, the controllers are implemented in discrete time. In these cases it is usual to work out the problem in discrete-time by obtaining the  $z$ -transfer function of the plant,

$$G_p(z) = \mathcal{Z} \{G_p(s)\}_{T_s},$$

$T_s$  being the sampling period; hence, the period of the discrete-time signal is  $N = T_p/T_s$ . The correspondence between continuous-time and discrete-time formulations is shown in Table 1. Notice that discrete-time implementations can only cancel those harmonics which are below the Nyquist frequency ( $\omega_s/2 = \pi/T_s$ ).

**4. Plant Description.** Systems with rotatory elements are usually affected by periodic disturbances due to the relative movement of these components (e.g., electrical machines

and CD players). These kinds of systems are supposed to be moving at a fixed angular speed but, under such operating conditions, any friction, unbalance or asymmetry generates a periodic disturbance that affects its dynamic behavior. The virtual/remote laboratory is based on a rotatory mechatronic plant subject to periodic disturbances which has been specifically designed to reproduce these working conditions [7]. The device is composed of a bar holding a permanent magnet in each end, with each magnet magnetically oriented in the opposite way, and attached to a DC motor and to two fixed permanent magnets. The rotation of the DC motor causes a pulsating load torque that depends on the mechanical angle  $\theta$  of the motor axis. When the motor axis angular speed  $\omega = \dot{\theta}$  is constant, the pulsating torque is a periodic signal with fundamental period directly related to the axis speed:  $T_p = \omega^{-1}$ , with  $\omega$  expressed in rev/s. Figure 5 shows the schemes viewed in the virtual laboratory and Figure 8 shows the remote view of the plant.

In a disturbance-free environment, when a certain voltage is applied to the motor it rotates at a certain constant angular speed in the steady-state. When the fixed magnets are introduced in the system, the interaction between them and the moving ones creates a periodic disturbance in the system so that a constant angular speed cannot be maintained any longer. Instead, its velocity describes a periodic function whose period depends on the input voltage, i.e., on the angular speed (see Figure 5). The control goal is to attenuate this periodic disturbance in order to keep constant the motor speed.

The controllers have been constructed for a nominal speed of  $\omega = 8$  rev/s, which entails a disturbance period of  $T_p = 1/\omega = 125$  ms. Moreover, both controllers work with 25 samples per period, i.e.,  $N = 25$ , this yielding a sampling period of  $T_s = T_p/N = 5$  ms.

## 5. Virtual/Remote Laboratory.

**5.1. Application structure.** The application has been built using Easy JAVA Simulations (EJS), which is a JAVA-based software tool for the simulation of physical systems [30]. EJS allows the development of a powerful Graphic User Interface (GUI) (see Figure 5), thus yielding an interactive illustration of the time and frequency characteristics of a system. The virtual setting is completely developed in EJS using an existing mathematical model of the plant [31] and a GUI designed with EJS. The remote setting has been created using EJS and Laboratory Virtual Instrumentation Engineering Workbench (LABVIEW), which is an application from National Instruments (NI). Both settings have been designed in a homogeneous manner, so few differences exist between the two interfaces.

**5.2. EJS-LABVIEW connection.** LABVIEW allows a local interaction with the plant and the development of controllers in a simple and straightforward way (see Figure 3).

LABVIEW includes the feature of Remote Panels, by which the front panel of the application is published on the Internet. This allows the remote control of the LABVIEW application over the web. The drawback of this method is that the remote user needs to install an additional software in the client machine, the so-called *run-time engine*, provided by NI.

Aiming at providing a solution, the Department of Computer Science and Automatic Control of the UNED has produced a set of software applications that allows the development of virtual and remote laboratories using EJS and LABVIEW [32,33]. Figure 4 depicts the communication structure used in this approach. It is based on a JAVA-Internet-LABVIEW (JIL) software module called *JIL server*. This server provides of a plain way to communicate JAVA applets or applications with LABVIEW applications running in remote computers. With this, an EJS application can be integrated with the

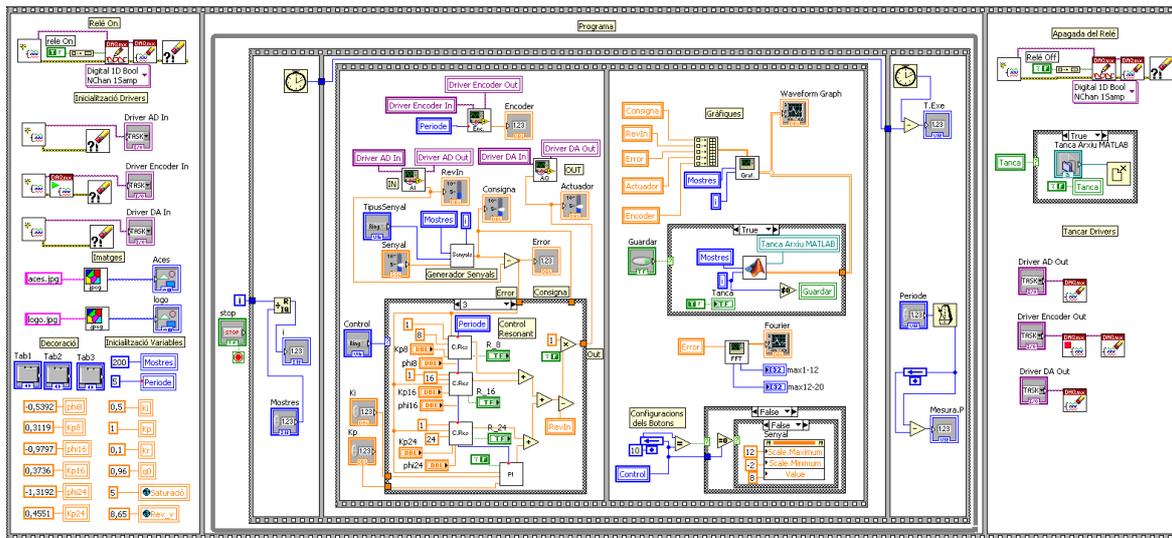


FIGURE 3. Main local control program in LABVIEW

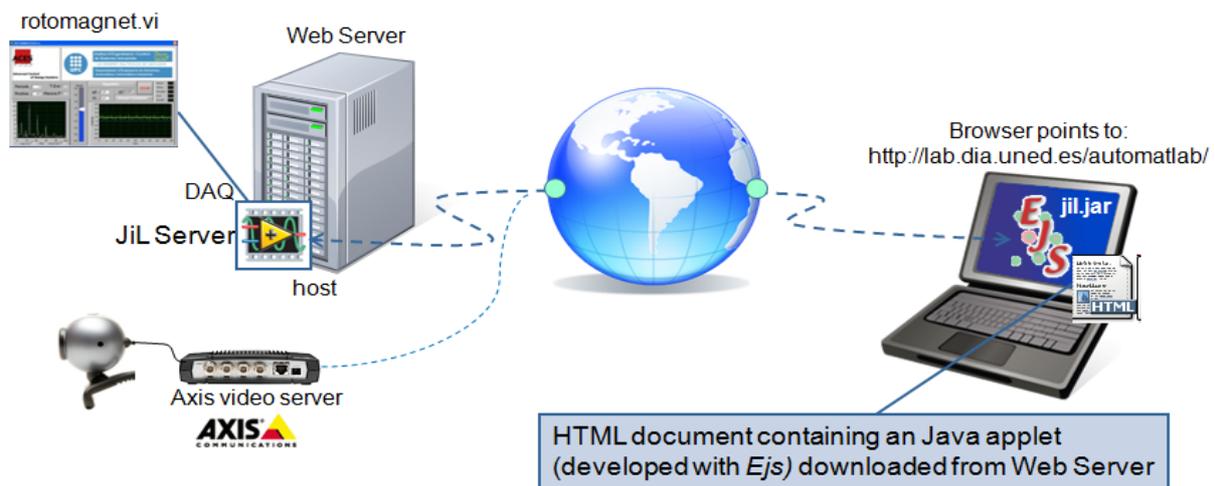


FIGURE 4. Laboratory architecture with JIL server

ability of monitoring, changing and manipulating variables and parameters of a remote LABVIEW application. This setup is combined with a camera and Axis video server (Axis-2400) integrated in the EJS application which provides of visual feedback for the experiments.

**5.3. Virtual and remote environments.** The laboratory application consists of two homogeneous settings:

- The virtual laboratory: in this framework, the plant model is used to compute the time evolution of the system. As shown in Figure 5, the plant is represented by a geometric scheme. Through the virtual setting the students are introduced for the first time to the system features and serves as a validation tool for analytical calculations. This setting does not consume network resources, operates locally and with no access restrictions.
- The remote laboratory: in this framework it is possible to work with the real plant located in a remote laboratory. In order to ease the use of this setting the GUI is

the same used in the virtual laboratory, but the graphic schematic representation of the physical system is here combined with the video streaming of the real plant. The setting also includes an augmented reality [34] display option, in which the simulation model is superimposed to the camera view of the plant (see Figure 8). This aims at compensating for possible video transmission delays.

The access to the remote lab is restricted to students who have previously passed the activities performed with the virtual lab, which results in a substantial decrease of the experimentation time required in this setting.

The settings may operate in two ways:

- Manual mode: this mode allows one to carry out open-loop experiments with two main educational purposes. Firstly, to get acquainted with the time and frequency characteristics of the plant and disturbances and, secondly, to understand the need for closed-loop control.
- Automatic mode: this mode allows closed-loop experimentation with different controllers. The experiments are oriented to show the limited performance of PID control for the rejection of non-constant disturbances and to illustrate the IMP benefits for such purpose by means of resonators and repetitive control. Also, the limitations of both control techniques can be tested in this mode.

**5.4. Practical example.** In this subsection, the theoretical concepts introduced in Section 3 are illustrated by means of a practical example which, in turn, aims at revealing the virtual/remote laboratory capabilities.

The GUI of the virtual/remote laboratory is divided in two main parts (see Figure 5). The left hand side hosts the representation window, where the system scheme is portrayed. The right hand side, where the evolution of the main system variables are shown both graphically and numerically, contains the system evolution window.

When the plant described in Section 4 receives a constant voltage input, its steady-state speed describes a periodic signal (recall Figure 5). Its specific shape depends on the features of the magnets and on its geometrical distribution, while the frequency depends on the input voltage. In the **Device** tab, four sliders are shown and four actions can be taken through them in order to modify the geometry and distribution of the fixed and mobile magnets of the plant, thus generating different disturbance shapes. Therefore, the possible actions are:

- Close/move away the fixed magnets to/from the axis system
- Rotate the left hand side fixed magnet a certain angle ( $\beta$ )
- Reduce the magnetic pole intensity of one mobile magnet ( $rq$ )

All these changes are reflected in the plant scheme.

The limited performance of classic PI control towards the rejection of periodic disturbances can be shown by means of the virtual laboratory. Indeed, Figure 6 depicts the steady-state speed error Fourier transform of the PI controlled plant when the reference speed is set at 8 rev/s. Notice that the error frequency components are distributed around 8 Hz and its harmonics. The tab **PI** allows to tune the proportional and integral gains.

The use of a resonant controller composed of two resonators, placed at frequencies of 8 Hz and 16 Hz, allows to overcome the problem. This may be realized from Figure 7, where the steady-state error Fourier transform shows no components at these frequencies. Furthermore, with the inclusion of additional resonant elements the error could be almost zeroed. The virtual/remote laboratory contains a **Resonator** tab which allows to apply and modify each resonator implemented for frequencies of 8, 16 and 24 Hz and, thus, to

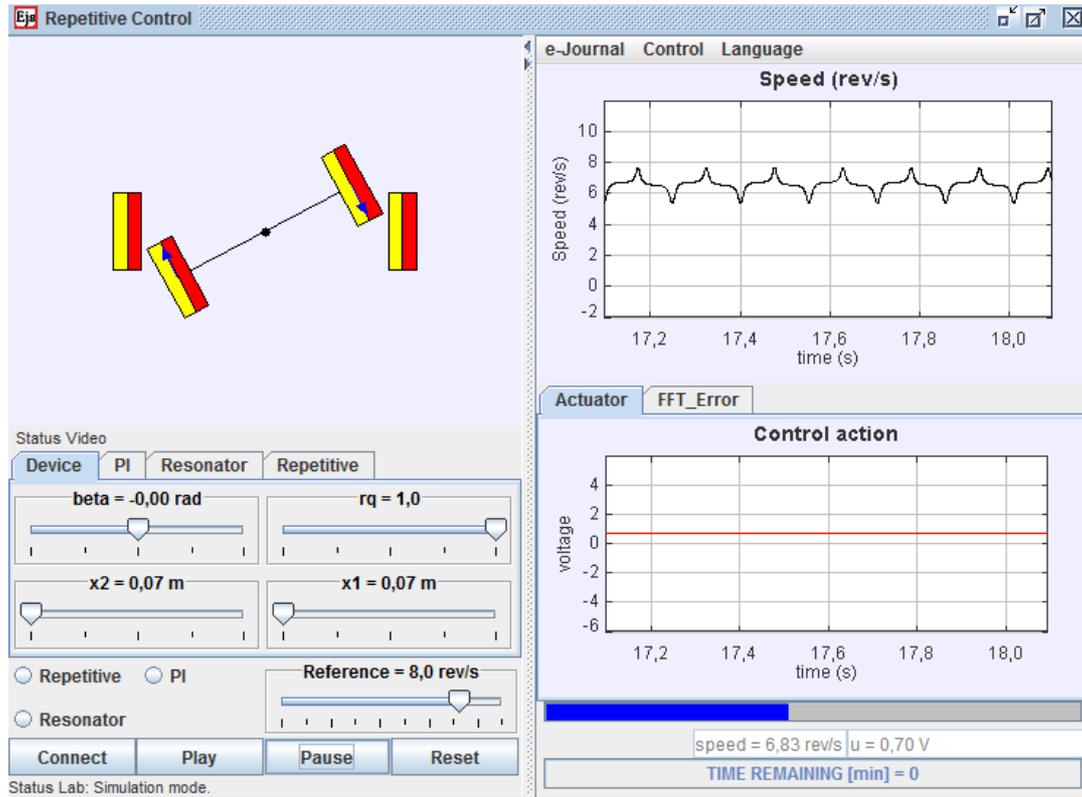


FIGURE 5. Rotomagnet virtual laboratory view (open-loop experiments)

observe separately its effect on the system dynamics. The shift phase and gain parameters can be set independently for each resonator.

Alternatively, Figure 8 shows the speed steady-state behaviour in remote setting when applying a repetitive controller. As it can be seen, disturbances are completely rejected, while the control action contains the harmonic components. The **Repetitive** tab allows to tune the repetitive controller, namely, the gain  $k_r$ , which can take values in the interval  $[0, 1]$ , and the parameter  $q_0$  of the filter  $H(z) = \frac{1-q_0}{2z} + q_0 + \frac{(1-q_0)z}{2}$ , which can be adjusted to obtain different frequency responses.

Also, with the **Device** tab it is possible to change the disturbance shape. In this case it is important to emphasize that performance is maintained, because it depends on the frequency of the disturbance and not in its specific shape.

However, the most important weak point of resonant and repetitive controllers is the need to know the reference/disturbance frequency. As an example, Figure 9 shows the steady-state speed when the reference frequency is 7.5 Hz, while the design frequency of the repetitive controller is 8 Hz. Notice that the control action cannot reject the disturbance effect, and the steady-state error becomes a periodical signal. In fact, the results remind those obtained with a regular PI controller (see Figure 6). Resonant-based controllers show a similar performance if the frequency of the reference/disturbance does not match any of the frequencies of the resonators. This problem can be addressed by means of adaptive schemes [35,36].

**6. Assessment.** The assessment is based on the capture of the students' perception of their learning experience, which is a primary tool for the evaluation of the quality of educational proposals.

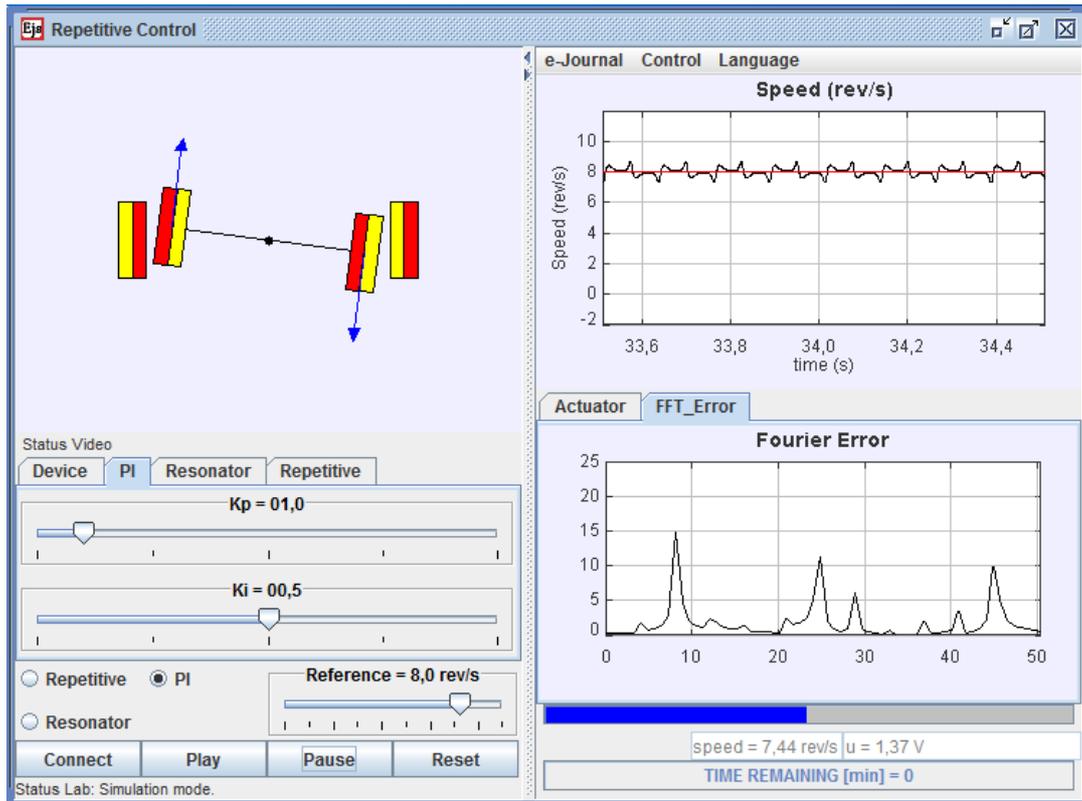


FIGURE 6. PI control (closed-loop experiments): frequency response

The study was carried out by questioning 73 students, belonging to the universities that are in the Automat@bs network (see Subsection 2.1), which used the virtual/remote lab during the academic years 2007/2008 and 2008/2009 in several automatic control courses of graduate level.

The questionnaire was composed of three sets of questions. In the first set, questions dealt with the perception of a learning improvement with respect to traditional methods. In the second set the students answered about the structure of the virtual/remote laboratory, while in the third set they were questioned about the quality of the virtual and remote settings. Table 2 details the questions, while Table 3 shows the results.

Regarding the first block, it is remarkable that not less than a 58% of the students express positive opinions about this learning method and its added value with respect to traditional procedures. Neutral and disagreement answers may have to do with the fact that the students did not had the chance to experiment directly with the real equipment. This could be solved with a hybrid programme in which face-to-face sessions, where students can experiment in situ with the real plant, are combined with sessions promoting distance learning through the virtual/remote laboratory.

The assessment of the second block reveals more than an 83% positive or very positive opinions about the virtual/remote laboratory structure, and more than a 90% of the questioned students believe that it is actually user-friendly. However, additional efforts should be devoted to the improvement of the clarity of the supplied documentation.

Finally, in the third block, the students appreciate (more than a 93%) the usefulness of carrying out simulations previously to real experiments, and the quality of the simulations receives good assessment as well. Improvements here should be focused on the quality of the remote connection and also on the browsing velocity.

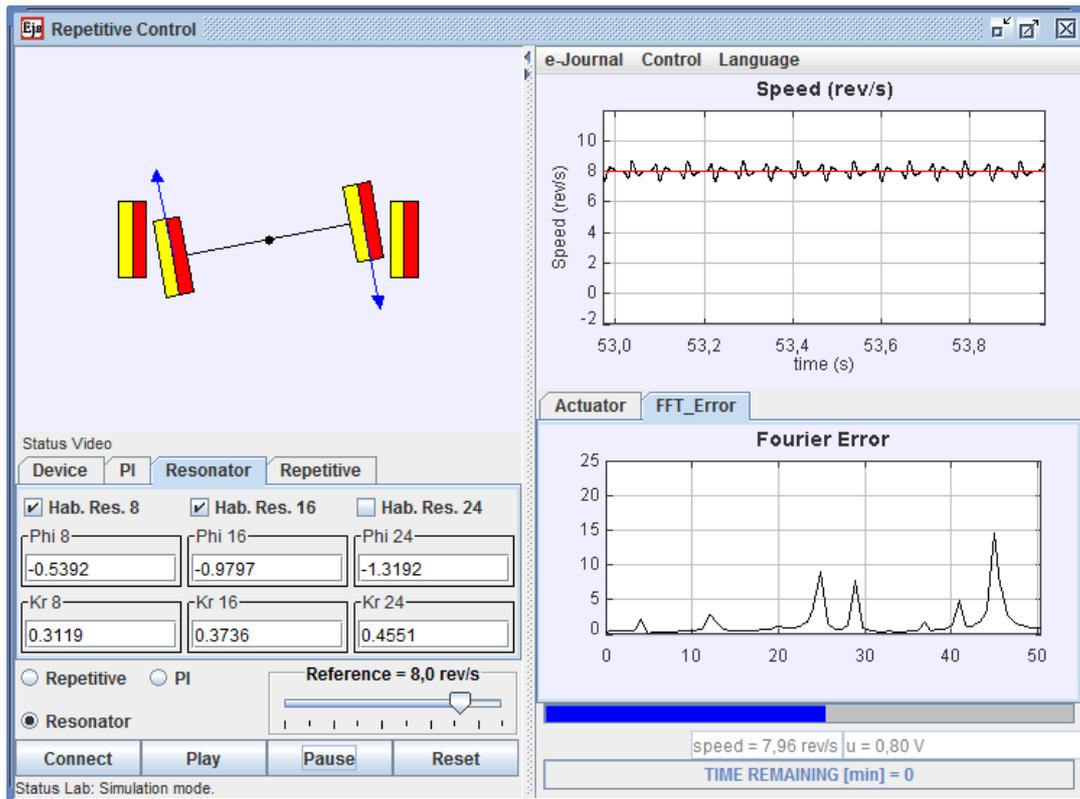


FIGURE 7. Resonant control (closed-loop experiments): frequency response

TABLE 2. Questionnaire

|  |
|--|
| BLOCK 1: LEARNING RESULTS  |
| Q1. I have learned more than with traditional methods              |
| Q2. I have learned faster than with traditional methods            |
| Q3. I am satisfied with this way of doing the practical activities |
| BLOCK 2: LAB STRUCTURE   |
| Q4. The lab is perfectly organized                                 |
| Q5. The lab is user-friendly                                       |
| Q6. The supplied documentation is clear enough                     |
| BLOCK 3: QUALITY AND USABILITY                                     |
| Q7. The simulation clarifies the experiment's targets              |
| Q8. The quality of the simulation is good                          |
| Q9. The quality of the remote connection is good                   |
| Q10. The browsing velocity is appropriate                          |

**7. Conclusions.** An educational approach to the IMP for the tracking/rejection of periodic signals was presented in this paper through resonant control and repetitive control. The pedagogical framework combined the mathematical formulation with practical illustration. For, the article introduced a virtual/remote laboratory used for the analysis, design, implementation and comparative performance assessment of resonant and repetitive controllers. A classic PID strategy was also added, and its performance could be compared with these more advanced design techniques. The presented laboratory contained interactive elements to provide the user of different options: open-loop experiments, PID

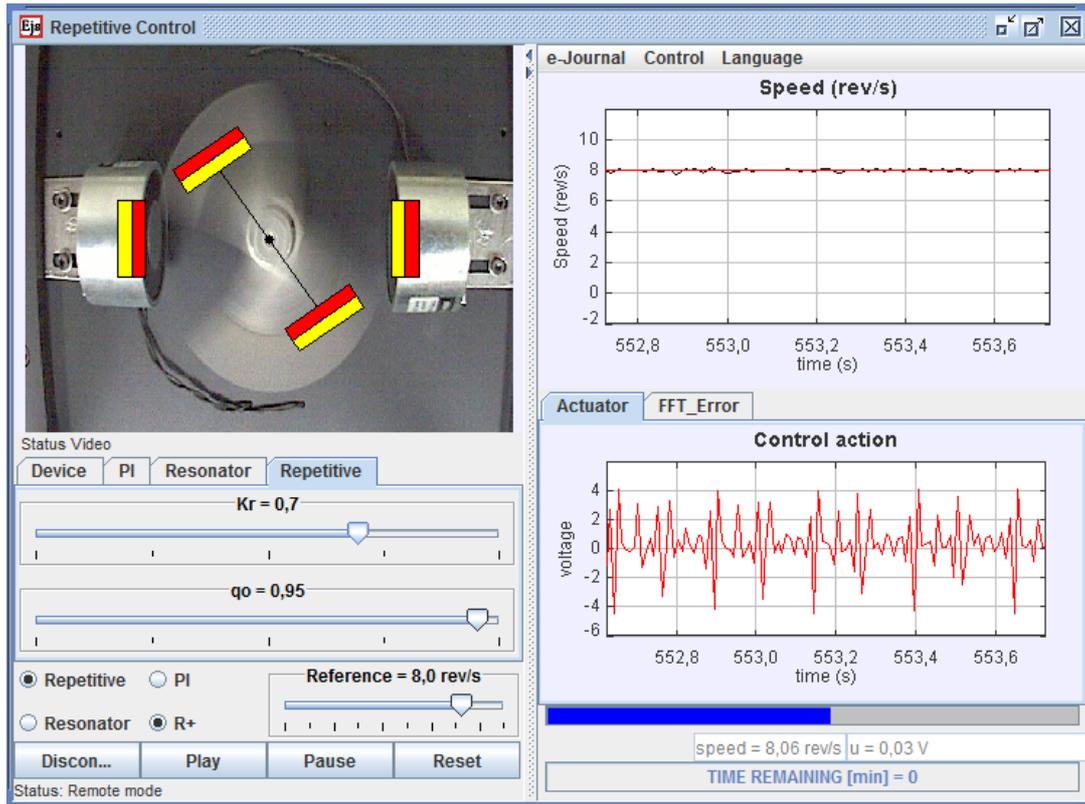


FIGURE 8. Repetitive control in remote setting (closed-loop experiments): time response

TABLE 3. Results

|     | SA (%) | A (%) | N (%) | D (%) | SD (%) |
|-----|--------|-------|-------|-------|--------|
| Q1  | 17.81  | 54.79 | 20.55 | 6.85  | 0      |
| Q2  | 12.33  | 46.58 | 30.14 | 8.22  | 2.74   |
| Q3  | 19.18  | 68.49 | 6.85  | 5.48  | 0      |
| Q4  | 20.55  | 63.01 | 15.07 | 1.37  | 0      |
| Q5  | 23.29  | 67.12 | 9.59  | 0     | 0      |
| Q6  | 8.22   | 12.33 | 75.34 | 4.11  | 0      |
| Q7  | 38.36  | 54.79 | 5.48  | 1.37  | 0      |
| Q8  | 32.88  | 47.95 | 15.07 | 4.11  | 0      |
| Q9  | 20.55  | 31.51 | 20.55 | 8.22  | 1.37   |
| Q10 | 9.59   | 47.95 | 27.40 | 6.85  | 1.37   |

SA: Strongly Agree; A: Agree; N: Neutral; D: Disagree; SD: Strongly Disagree

gain adjustment, resonators frequency selection and variations of the repetitive control parameters, between others. The virtual/remote laboratory, which used a mechatronic educational plant, was built using EJS software and LABVIEW and has been integrated in the Spanish network Automatl@bs.

Students' assessment reported that the virtual/remote laboratory is perceived as a useful and well structured distance learning tool. Furthermore, the possibility of carrying out simulations was seen as a clarifying means regarding the real plant experiment's

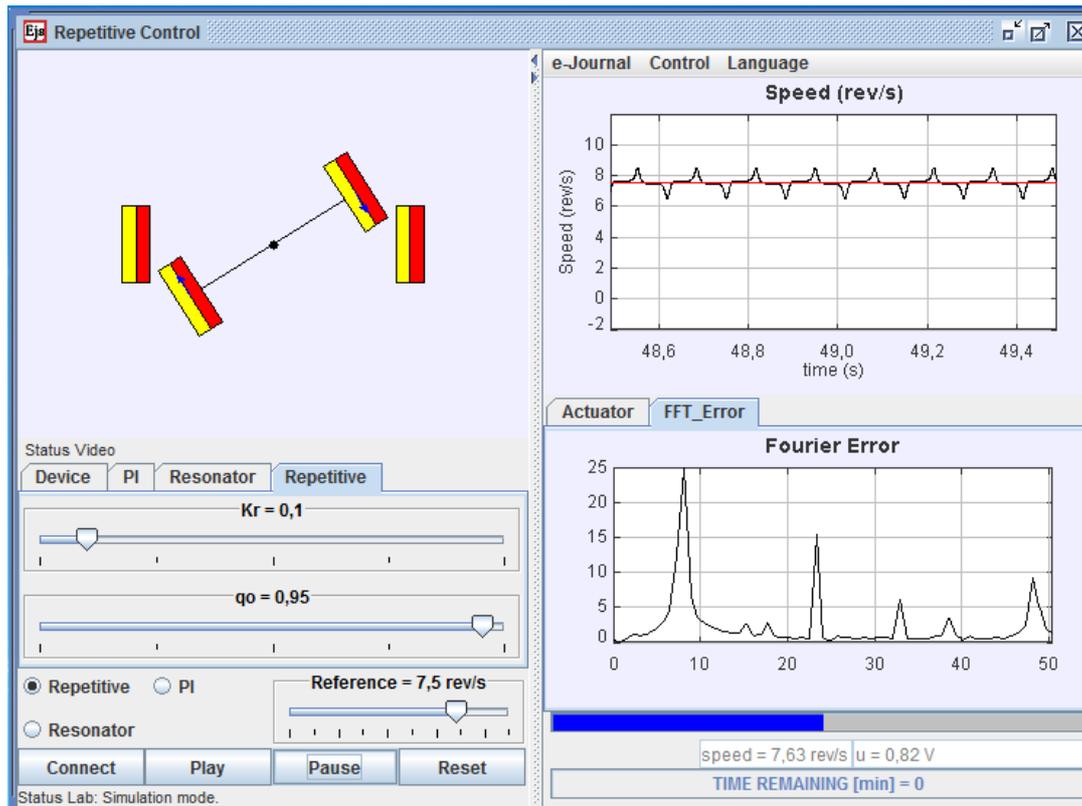


FIGURE 9. Repetitive control with reference different from nominal (closed-loop experiments)

performance and purposes. Main drawbacks were the perception of the physical system from the user's side and the quality of remote connection and browsing velocity.

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