# PI Plus Repetitive Control Design: H-infinity Regions Approach

Martin Goubej
*NTIS Research Centre*
*University of West Bohemia*
Pilsen, Czech Republic
mgoubej@ntis.zcu.cz

Miloš Schlegel
*NTIS Research Centre*
*University of West Bohemia*
Pilsen, Czech Republic
schlegel@ntis.zcu.cz

***Abstract*—The paper deals with a class of plug-in type repetitive controllers intended for servo systems which follow periodic reference signals or compensate periodic exogenous disturbances. Proportional-integral (PI) feedback controller is complemented by an internal model of a generic periodic signal aiming at perfect asymptotic tracking or disturbance rejection. A novel design method is proposed allowing a simultaneous tuning of the PI controller and the repetitive control part. The design requirements can be formulated in the frequency domain as proper loop-shaping inequalities defining constraints on important closed-loop sensitivity functions. These constraints are translated directly into the parametric plane of the controller allowing to derive a complete set of admissible controllers. The proposed method is demonstrated in a case study of a flexible motion system.**

***Index Terms*—repetitive control, periodic disturbance rejection, PI control, loopshaping, H-infinity regions, motion control**

## I. Introduction

Repetitive control methods aim at designing feedback loops capable of compensating generic periodic disturbances or tracking periodic reference signals with high accuracy. The fundamental idea comes from the Internal model principle [5] which states that the model of the exogenous signal generator has to be inserted into the loop in order to achieve zero tracking error asymptotically. It can be shown that a pure time-delay with positive feedback can serve as a minimal model for an arbitrary periodic function. Reference [1] is considered to be a first documented practical application of repetitive control. General analysis of closed-loop stability and performance of repetitive controllers followed later in [2]–[4]. Numerous design method emerged in the last three decades for linear, nonlinear, continuous or sampled-data systems [6]–[10]. Several successful applications were reported in various domains ranging from optical storage systems and disk drives [11], motion controls and robotics [12] to hydraulic manipulators [13] or power electronics [14]. A survey [16] maps the most important results and provides connections to the closely related topics of iterative learning control and run-to-run control.

Most of the relevant literature dealing with general design methods for the repetitive controllers focus on the derivation and parametrization of the part containing the internal model of the exogenous periodic signals plus some other

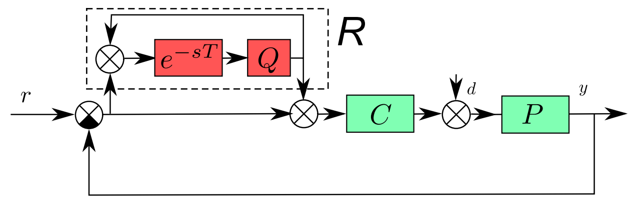


Fig. 1. Considered structure of the repetitive controller, R - repetitive control part in a plug-in scheme, C - feedback compensator, P - controlled plant

dynamic elements necessary for the achievement of stability and performance. The feedback compensator dealing with the stabilization of the closed loop is often assumed to be known in advance. This may lead to suboptimal performance since the insertion of the repetitive control part often leads to significant deterioration of the achievable quality of control. Therefore, it may be advantageous to design the repetitive and feedback control parts in a coordinated manner considering their simultaneous contribution to the overall closed-loop dynamics. From the implementation point of view, a plug-in type scheme may be advantageous [7] as it allows simple (de)activation of the repetitive control part only in specific regimes of operation. Methods capable of designing robust feedback controllers which satisfies some performance constraints in both normal and repetitive control regimes can be beneficial for such scenarios.

The paper proposes a novel design method based on the recent results presented in [15] which dealt with a computational procedure for translation of the frequency domain design requirements directly to the parametric plane of the PI controller. The current work utilizes these results and offers a systematic approach to the synthesis of a class of plug-in type repetitive controllers in a special case where a PI algorithm is assumed to be used as the feedback compensator. A whole set of admissible controllers fulfilling all the important design requirements can be constructed. An example of application to a mechatronic system is given in a use-case study.

The paper is structured as follows. Section II introduces the considered structure of the plug-in type repetitive controller. Section III deals with the proposed design method. Practical example of application to a motion control system is presented in Section IV followed by final concluding remarks.

## II. Structure of the Repetitive Controller

Among several versions of the repetitive control (RC) algorithm, a plug-in type scheme with a parallel connection of the periodic disturbance generator was chosen in our application. This scheme is suitable for practical implementation as it extends a conventional feedback loop with the repetitive control block which can be conveniently enabled or disabled when needed without disturbing the stability of the loop, when properly designed.

The repetitive controller in the parallel form introduces a transfer function into the loop in the form of

$$1 + R(s) = \frac{1}{1 - e^{-sT}Q(s)}, \tag{1}$$

where $R$ is the repetitive control block from Fig. (1) and $Q$ is a suitable shaping filter which is to be derived later. For the particular choice $Q(s) = 1$, the repetitive part generates an infinite number of poles $p_k$ on the imaginary axis at positions given as follows

$$p_k = jk\omega_n;\ \ k = \pm 1, \pm 2, ..., \infty;\ \ \omega_n = \frac{2\pi}{T}. \tag{2}$$

Following from the internal model principle [5], an arbitrary T-periodic exogenous signals $r, d$ can be compensated asymptotically provided that the closed-loop is internally stable.

A sufficient condition of stability for an arbitrary period T can be derived from the Small-gain theorem by isolating the transport delay term and the rest of the dynamics as

$$||Q(s)S(s)||_\infty < 1;\ \ S(s) = \frac{1}{1 + CP}, \tag{3}$$

where $S$ denotes the closed-loop sensitivity function. It is clear that the stability cannot be guaranteed without the $Q$ filter for most practical systems due to the well-known Bode's sensitivity integral theorem. Therefore, the $Q$ is commonly designed as a low-pass filter with the cut-off frequency chosen in such a way that the stability condition (3) holds. This reduces the bandwidth in which the repetitive controller compensates the periodic disturbance. Asymptotically perfect tracking cannot be achieved anymore. However, a significant portion of the error can be reduced at the dominant frequencies within the pass-band of the $Q$ filter. In the algebraic domain, the introduction of the $Q$ filter leads to the retarded spectrum of the internal model leading to an increased stability margin.

## III. H-infinity Loopshaping Design

There are principally three approaches to the design of the repetitive controller:

1) The feedback controller $C$ which stabilizes the loop is designed at first for the nominal plant $P$ without considering the repetitive control part $R$ using any appropriate method. The $Q$ filter structure and parameters as well as the disturbance period $T$ are chosen afterwards in the second step. Usually an iterative procedure of filter retuning while checking the stability condition and any relevant performance criteria for the whole control scheme including the R block is required. This is the most common approach suggested in the literature.
2) The $Q$ filter and period $T$ are chosen and fixed at first followed by the derivation of the feedback compensator $C$ for the modified system $\overline{P} = P(1 + R)$. This part becomes difficult since the repetitive disturbance model introduces an infinite-dimensional time-delay dynamics which complicates the feedback controller design when using standard methods.
3) The repetitive controller $R$ and feedback compensator $C$ are designed in a coordinated manner. The repetitive control bandwidth given by the $Q$ filter as well as the period $T$ are considered to be a part of the design requirements. Multiple design constraints can be formulated both for the nominal plant $P$ (with the RC function deactivated) and the modified plant $\overline{P}$ which acts in the loop after the connection of the RC part. The goal is to derive a suitable controller which satisfies all the requirements simultaneously.

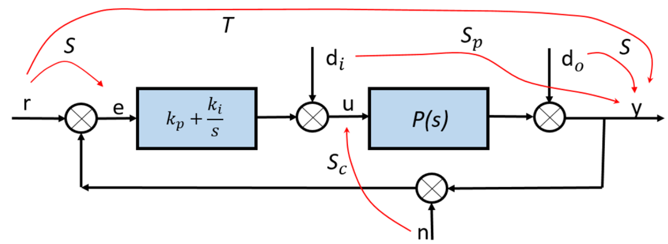


Fig. 2. $H_\infty$ loop-shaping design - formulating the design requirements in the frequency domain by shaping the important closed-loop transfer functions

The last two approaches are attractive from the engineering point of view as they allow to consider the influence of the repetitive control part yet in the phase of the feedback controller design. Moreover, it might be convenient to get an information about the (non)existence of the solution and derive all the admissible controllers when the solution exists.

To accomplish that, a systematic approach is proposed for the derivation of the controller parameters in the special case where C is assumed to be a conventional PI controller. The method can be adapted to the case of PID compensator as well as to other low-order fixed structure controllers with two or three parameters. The PI controller case is chosen as a representative example as it is the most common algorithm used in industrial applications.

### *PI controller design using $H_\infty$ regions method*

The controlled process $P(s)$ is assumed to be a generic LTI system without the poles on the imaginary axis (can be relaxed by adjusting the controller derivation procedure). The feedback compensator $C(s)$ is considered in the standard PI controller form

$$C(s, k) = k_p + \frac{k_i}{s}, \tag{4}$$

where $k$ denotes the parameters vector $[k_p, k_i]$.

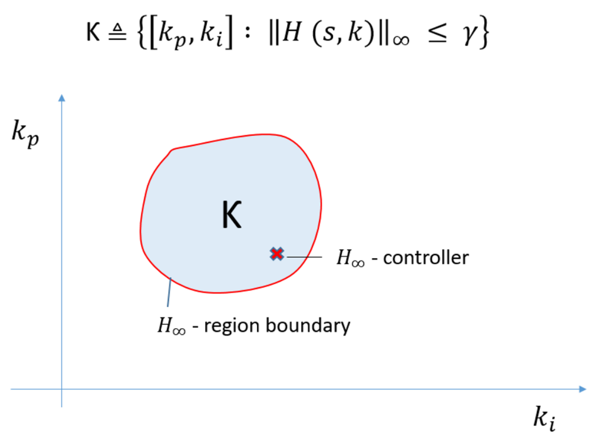


Fig. 3. $H_\infty$ region and the corresponding admissible subset of the parametric $k_i - k_p$ plane of the PI controller

Arbitrary number of design constraints can be formulated in the frequency domain in the form of

$$||H(s,k)||_\infty < \gamma, \tag{5}$$

where $H$ corresponds to an arbitrary closed-loop transfer function which may be formed by injecting a generalized input at any point of the loop, choosing an arbitrary generalized output and include a frequency-dependent weighting in the form of

$$H(s,k) \triangleq W(s)S_*(s), \tag{6}$$

where $S_*(s)$ denotes one of the closed-loop sensitivity functions (sensitivity, complementary-, input- and controller-sensitivity, see Fig. 2) and $W(s)$ introduces arbitrary user-defined frequency-dependent scaling.

Alternatively, a mixed sensitivity constraint can be given in the form which is often used in the robust control theory

$$||H_1||_\infty^2 + ||H_2||_\infty^2 \triangleq ||W_1(s)S_{1*}(s)||_\infty^2 + ||W_2(s)S_{2*}(s)||_\infty^2 < \gamma^2. \tag{7}$$

The goal is to find a controller $C(s,k)$ which together with the given $H(s)$ fulfil the following three conditions

1) $C(s,k)$ internally stabilizes the closed-loop
2) $H(s,k)$ used in the design criterion is stable
3) The H-infinity condition $||H(s,k)||_\infty < \gamma$ or $||W_1(s)S_{1*}(s)||_\infty^2 + ||W_2(s)S_{2*}(s)||_\infty^2 < \gamma^2$ holds

Such controller is called the $H_\infty$ controller. Typically, there is a whole set of the admissible controllers fulfilling the above-mentioned conditions which can be represented directly in the parametric plane $[k_i, k_p]$ (Fig. 3).

This boundary defines a set of admissible controllers. In case the set is nonempty, which means that there exists at least one controller of the given structure for the defined design constraint, one particular parameter combination has to be chosen. One of the possible choices is to select the controller with the highest integral gain which is known to minimize the Integral error criterion

$$IE = \int_0^{+\infty} e(t)\mathrm{d}t = \frac{1}{k_i}. \tag{8}$$

The computation of the $H_\infty$ region and its corresponding set of admissible controllers is a nontrivial task. However, as presented in [15], an explicit solution can be derived in the form of

$$\begin{aligned} k_i(\omega) &= F_i(\omega, x_l, \gamma), \\ k_p(\omega) &= F_p(\omega, x_l, \gamma, A, B, A_1, B_1, w, w_1), \\ &\omega \in [0, \infty), \end{aligned} \tag{9}$$

with the arguments of parametric curves $F_i, F_p$ defined as

$$\begin{aligned} A &\triangleq Re\,(P(j\omega))\,, \;\; A_1 \triangleq \frac{\mathrm{d}A}{\mathrm{d}\omega}, \\ B &\triangleq Im\,(P(j\omega))\,, \;\; B_1 \triangleq \frac{\mathrm{d}B}{\mathrm{d}\omega}, \\ w &\triangleq |W(j\omega)|^2, \;\; w_1 \triangleq \frac{\mathrm{d}w}{\mathrm{d}\omega}, \end{aligned} \tag{10}$$

and $x_l;\; l = \{1,2,3,4\}$ are the real roots of the "companion" polynomial

$$ax^4 + bx^3 + cx^2 + dx + e = 0 \tag{11}$$

with the real coefficients $a, b, c, d, e$ depending explicitly on $\{\omega, x_l, \gamma, A, B, A_1, B_1, w, w_1\}$ (see the reference [15] for the full derivation). The important result is that the derivation of the $H_\infty$ region always leads to 4th order polynomial regardless of the order of the plant or the user-defined weighting functions. Therefore, analytic expression for its roots is available from the Ferrari's method and Cardano formulas. Their careful examination allows a separation of the real roots which lead to the solution of the $H_\infty$ region boundary.

Multiple design constraints may be formulated in the frequency domain for several weighted $H_\infty$ norm of various closed-loop sensitivity functions. The resulting admissible region is then computed from the intersection of the individual regions corresponding to each design constraint.

*Employing $H_\infty$ regions in RC design problem*

The procedure for the derivation of the $H_\infty$ PI controllers can be used conveniently for the repetitive control problems due to the very general form of the feasible design constraints (6,7). A suitable methodology is proposed in the following steps:

1) Formulate **nominal performance requirements** for the plant $P$ without the RC part by setting proper loop-shaping inequalities (6) for the important closed-loop transfer functions or using the mixed-sensitivity criterion (7) and compute the corresponding $H_\infty$ regions. These requirements define the closed-loop behavior with the deactivated RC function in the plug-in scheme (Fig. 1). This may be relevant for transient regimes where the compensation of periodic disturbances is not needed and the $R$ block may be disconnected in order to improve stability and performance of the loop.
2) Choose the **structure and parameters of the $Q$ filter and the disturbance period** $T$, e.g. from the a priori knowledge about the dominant frequency content of the exogenous signals.

3) Formulate the **robust stability condition** $||QS||_\infty < 1$ which fulfills the general form for the design constraints (6). This enforces closed-loop stability for an arbitrary disturbance period $T$. It can be optionally substituted by requirement Nr. 4 when the period is known in advance.
4) Formulate **RC performance and stability requirements** for the modified plant $\overline{P} = P(1 + R)$ and a particular chosen disturbance period $T$. This defines the closed-loop performance including the activated $R$ block providing the repetitive disturbance compensation. As the computational procedure works for arbitrary order of the plant including time-delays, the corresponding $H_\infty$ regions can be computed in the same manner. Multiple period lengths can be considered e.g. in cases with various operating regimes. Internal stability is attained automatically from the principle of the design method.
5) **Compute the intersection of all the obtained $H_\infty$ regions**. In case there exists a non-empty set of admissible controllers, select one particular controller using some secondary design criterion (e.g. the largest integral gain which is optimal with respect to (8)).

The proposed methodology corresponds to the approach Nr. 2) from the discussion at the beginning of Sec. III when considering a single particular period $T$ and $Q$ filter. However, the presented approach may be used in a much more general way by exploiting the fact that *all the design requirements can be transformed directly to the admissible regions in the parametric plane of the PI controller* and the *intersection can be computed automatically giving a set of parameters which fulfill all the requirements simultaneously*. The shape of the resulting regions gives both qualitative and quantitative information about what can be achieved for the given design problem, whether there is a solution and which design requirements are potentially in conflict.

Few suggestions on how to use this in practical design scenarios follow:

- **Multiple different disturbance periods and $Q$ filters can be assumed**, e.g. for the systems operating in various regimes requiring proper adaptation of the RC part of the controller. Also the plant model may change in various operating points. The proposed $H_\infty$ regions allows to derive one robust feedback controller which will work for all the considered situations, if it exists, and all the solutions are obtained at once. If there is no global solution, the computed regions give a suggestion on how to change its parameters accordingly and derive e.g. a gain-scheduled controller.
- The disturbance period $T$ and the structure of $Q$ filter can be fixed, but the **bandwidth of $Q$ may be used as another design parameter**. By computing the regions for various repetitive bandwidth, one may simply derive its maximum feasible value which does not violate the other design constraints.
- **The previous case can be automated** by forming a supervisory optimization loop which varies the repetitive bandwidth $Q$ and searches for its maximum value leading to a non-empty set of admissible PI gains.

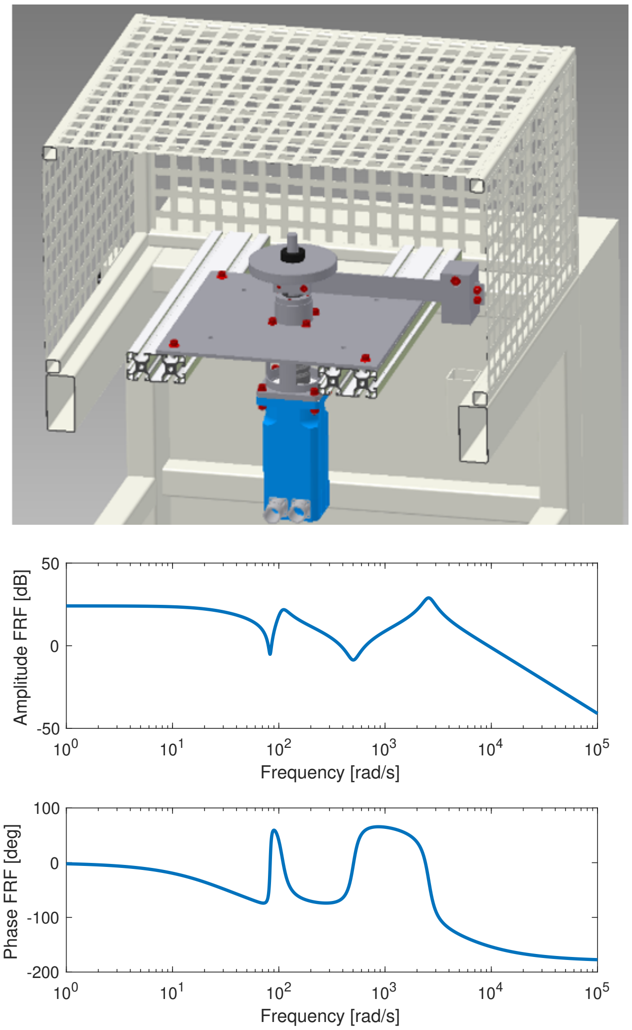


Fig. 4. Flexible arm manipulator - mechanical motion system used for the use case study, top - testbed schematics, bottom - identified frequency response function

The above mentioned scenarios allow a coordinated design of both the RC part and feedback compensator. Therefore, they belong to the case Nr. 3) mentioned in Sec. III. The computation of the regions is nontrivial, but it can be handled using proper software tools. A Matlab toolbox which automates the derivation of the $H_\infty$ regions and their intersections is being developed at our workplace. It will be available to a general public once it is finished.

## IV. Experimental Results

The proposed method for the $H_\infty$ design of PI repetitive controller is demonstrated on the example of a single DoF motion system consisting of a drive and flexible arm (Fig. 4). A model of the system was obtained by means of experimental identification. The resulting frequency response function is shown as well. Two dominant resonance modes due to lateral

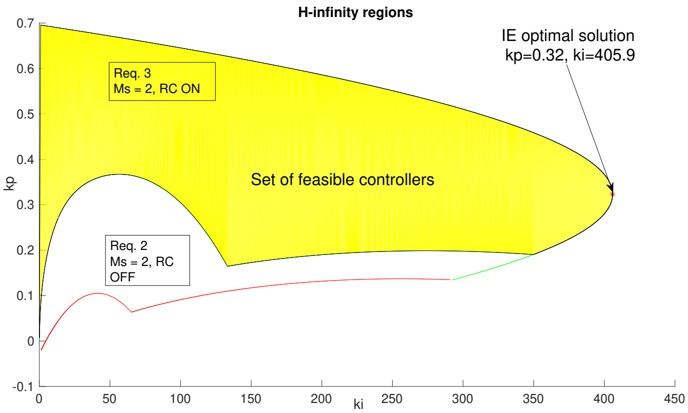


Fig. 5. Computed $H_\infty$ regions in the parametric $k_i - k_p$ plane showing the admissible set of controllers (yellow area) and the selected particular IE optimal solution

dynamics of the arm and flexible motor-arm coupling are present. Parametric transfer function model was derived as

$$P(s) = \frac{\omega(s)}{T_m(s)} = \frac{num(s)}{den(s)}, \tag{12}$$

where $T_m$ denotes the motor torque applied at the input and $\omega$ is the angular velocity of the arm. The numerator and denominator coefficients[1] are given as

$$c_n = \{8.89e7, 1.02e10, 2.31e13, 1.53e14, 1.54e17\},$$
$$c_d = \{1, 4880, 9.54e6, 2.85e10, 1.67e12, 3.45e14, 9.638e15\}. \tag{13}$$

The design requirements were specified as follows:

- Internal stability of the closed loop is required for both nominal and RC mode of operation ($R$ block active or disabled)
- General robustness condition for the nominal plant model $P$ (with the inactive RC part) imposing maximum sensitivity limit
  $M_s = ||S||_\infty < 2$
- Stability and performance requirement for the RC regime (R block active)
  $M_{sr} = ||S_{rc}||_\infty < 2, \ S_{rc} \triangleq \frac{1}{1+\overline{P}C}, \ \overline{P} = P(1+R)$
- Specification of the disturbance period
  $\omega = 10rad/s, \ T = \frac{2\pi}{10} = 0.628s$
- Specification of the RC bandwidth
  $Q(s) = \frac{w_q^2}{s^2+1.4w_q s+w_q^2}, \ w_q = 100rad/s$
- Highest achievable bandwidth in terms of the IE criterion (8), i.e. $\min_{\forall\{k_p,k_i\}}\{IE\} = max(k_i)$ with respect to the previous design constraints.

Other well known control performance criteria such as ISE or ITAE could be used as well in the last design specification. However, their optimal value has to be found numerically by formulating a constrained optimization problem in terms of the computed feasibility region. Experience shows that well chosen frequency domain requirements in conjunction with the IE criterion used in the example work well in most cases. Additional weighted complementary sensitivity or controller sensitivity constraints $||W_1T||_\infty < 1, ||W_2CS||_\infty < 1$ might be used in case that the control action needs to be penalized as well.

The $H_\infty$ regions computed for the formulated design constraints are shown in Fig. (5) for the parametric $k_i - k_p$ plane. The design requirement Nr. 3 ($M_{sr} < 2$) is more restrictive and contains a subset of controllers fulfilling only the nominal performance and stability specification given by constraint Nr. 2 ($M_s < 2$). It can be seen that there is still an infinite number of solutions inside of the yellow area designating the intersection of both regions. All the $k_p, k_i$ parameters combinations inside of this boundary meet all the design requirements simultaneously. A particular solution with the highest integral gain (red point in Fig. 5 corresponding to $k_p = 0.32, k_i = 405.9$) denotes the optimal values with respect to the IE criterion (8). This parameter set was chosen as the final compensator gains.

Figure 6 shows the achieved amplitude response of the closed-loop sensitivity functions $S, S_{rc}$ both for the nominal plant and the extended scheme with the RC part included. The effect of the inserted internal model of the periodic signal is clearly observed from the notch regions in the amplitude response which are generated by the open-loop poles up to the bandwidth of $100rad/s$ imposed by the chosen $Q$ filter. The formulated loop-shaping inequalities $||S||_\infty < M_s, ||S_{rc}||_\infty < M_{sr}$ are met exactly since the optimal controller lies at the boundary of the corresponding $H_\infty$ regions (Fig. 5).

Closed-loop performance was evaluated by means of a numerical simulation. A position-dependent disturbance with three dominant harmonics simulating an unbalanced load or cogging torque of the motor was injected at the plant input in the form of

$$d(t) = \sum_{i=1}^{3} \sin(i\varphi(t)); \ \ \varphi(t) = \int_0^t \omega(\tau)\mathrm{d}\tau. \tag{14}$$

The system was commanded to follow a constant velocity setpoint of $\omega^*(t) = 10rad/s$. Comparison of the closed-loop performance by means of the steady-state tracking error is shown in Fig. (7). The blue line corresponds to the case of the nominal system with the inactive repetitive control module. Steady state error is present due to the periodic input disturbance. The red line shows the performance achieved with the plug-in repetitive controller which was activated at time $t = 5s$. It takes one period of $T = 0.628s$ to learn the corresponding corrective action which suppresses the tracking error significantly. The peak error is reduced approximately by factor of 150.

The functionality of the designed RC controller is validated also experimentally using the aforementioned motion testbed. Figure 8 shows the evolution of the velocity tracking error during a periodic motion task. The plug-in RC part was

[1] The transfer function models are internally stored and handled in the form of a zero-pole-gain model or by means of special orthogonal parameterizations in our application to avoid ill numerical conditioning which may appear for high plant order, no specific treatment was necessary in this particular case

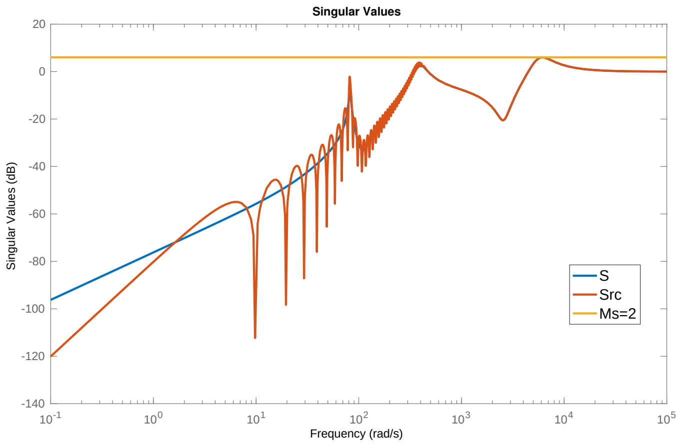


Fig. 6. Resulting sensitivity functions $S, S_{rc}$ for both nominal (RC off) and modified (RC on) plants and the formulated design constraint $M_s = M_{sr} = 2$

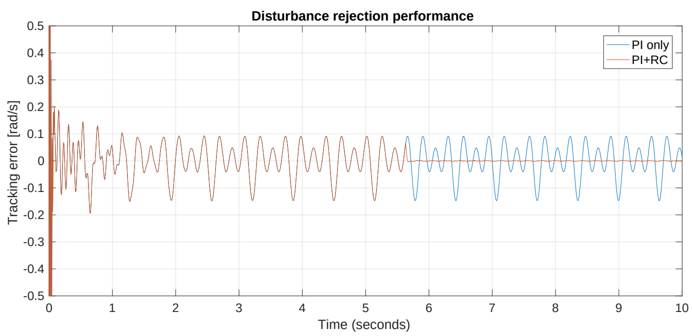


Fig. 7. Closed-loop performance of the designed repetitive controller, evolution of the tracking error

switched at time $t = 5$. Peak error is reduced from $16.1rpm$ to $3.1rpm$ and the root-mean-square value is brought down from $8.3$ to $0.9$.

## V. Conclusion

The paper presents a novel approach to design of a class of repetitive controllers consisting of a conventional PI compensator extended by an internal model of a generic periodic disturbance in the plug-in type topology. Both parts of the control scheme can be tuned either sequentially or simultaneously. The controller parameters are derived in a systematic manner with the use of the $H_\infty$ regions method allowing to translate all the important design constraints directly into the parametric plane of the feedback controller. All the existing solutions are derived at once if they exist. Multiple criteria can be combined easily and the user acquires both qualitative and quantitative insight into the problem. The proposed method can be adapted to other controller types with two or three parameters. Discrete-time formulation is also possible. Future research will cover both new theoretical aspects and implementation of the developed method in the form of Matlab toolbox.

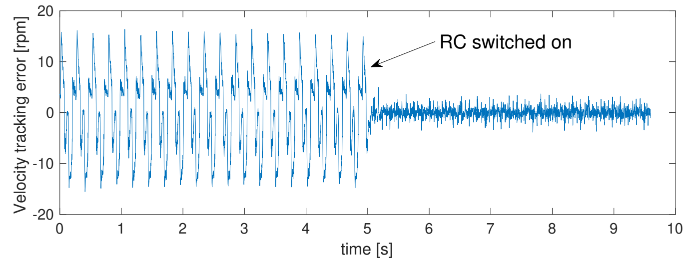


Fig. 8. Experimental validation of the proposed RC controller using the flexible arm testbed

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