International Journal of Industrial Electronics, Control and Optimization © 2018 IECO

Vol. 1, No. 1, pp. 1-8, June (2018)

Two-Degree-of-Freedom Control Scheme for Robust Centralized PI/PID Controller Design Using Constrained Optimization

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ABSTRACT

For a two-input two-output distillation column with heavy interactions and long dead times, a two-by-two PI/PID controller is designed. The design objectives are good setpoint regulation and appropriate load disturbance rejection. The constraints are on degree of robust stability, control effort as well as peaks of the maximum singular value of sensitivity and complementary sensitivity matrices. As this set of design objectives and constraints is often conflicting, a more flexible control structure, a two-degree-of-freedom scheme, is proposed. The design problem is formulated as a constrained optimization problem and is solved by a powerful random-search optimization technique, the so-called vector-based swarm optimization. Next, the performance of the proposed method in controlling a Wood and Berry distillation column is evaluated and compared with that of several well-known design techniques. Because of using a flexible control structure, a powerful optimization algorithm and a comprehensive set of design requirements, the proposed control strategy performs well in coping with conflicting design objectives.

ARTICLE INFO

Keywords:
Load Disturbance Rejection
Robustness
Setpoint Regulation
Two-Degree-of-Freedom Control Structure
Wood and Berry Distillation Column
Article history:
Received February. 13, 2018
Accepted Aprill. 12, 2018

I. INTRODUCTION

Due to its noticeable effectiveness and simple structure, PID is the most popular industrial controller and any improvement in the PID control tuning is valuable[1]. The PID has only three parameters, however, it is not easy to find its optimal values without a systematic procedure[2]. For single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems, a huge number of analytical and numerical techniques for tuning PID controllers have been presented during the past decades[3–5]. In general, the problem of PID control design for MIMO plants can be categorized to 1) multi-loop PID controller design, 2) decentralized PID controller design using a de-coupler, and 3) centralized PID controller design.

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http://dx.doi.org/10.22111/ieco.2018.24006.1007

In this research work, the case study is a two-input two-output (TITO) industrial plant, the Wood and Berry distillation column[6]. Due to strong interactions between its inputs and outputs as well as long dead times, it is a challenging benchmark application. The distillation column should be controlled in such a way that the design specifications are satisfied and the resulting closed-loop system is robust in the face of model uncertainties. Several papers have been published on setpoint regulation and/or load disturbance rejection of this TITO plant. Using a decentralized PI controller, Tavakoli et al.[7] proposed a robust non-dimensional tuning technique to simultaneously obtain good responses to setpoint and load disturbance signals. Based on the direct synthesis method, a centralized PI controller using relative gain array (RGA) and relative normalized gain array (RNGA) was presented[8]. Also, a centralized PI controller based on steady-state gain matrix (SSGM) was designed[9].

In this paper, the design goal is to obtain good responses for both setpoint and load disturbance signals. Also, a number of constraints on degree of robust stability, control effort, and peaks of the maximum singular value of sensitivity and complementary sensitivity matrices are considered. This set of objectives and constraints is often conflicting. In fact, it is a difficult task to find a good trade-off solution using a one-degree-of-freedom (1DoF) control scheme. To obtain better trade-off solutions, a two-degree-of-freedom (2DoF) control scheme is employed. First, the PID control design problem is formulated as an optimization problem. As the resulting problem is challenging, a powerful optimization tool is required to find its optimal solution. To achieve this goal, an easy to use, reliable and robust optimization algorithm, named vector-based swarm optimization (VBSO) is used[10,11].

The paper is organized as follows. In Section II, the proposed two-degree-of-freedom (2DoF) control structure and design requirements are presented. The VBSO is briefly presented in Section III. In Section IV, the Wood and Berry distillation column plant is introduced

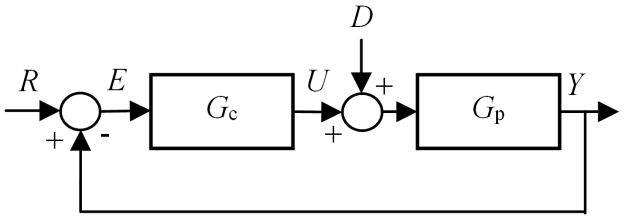


FIG. 1. Block diagram of a 1DoF control system.

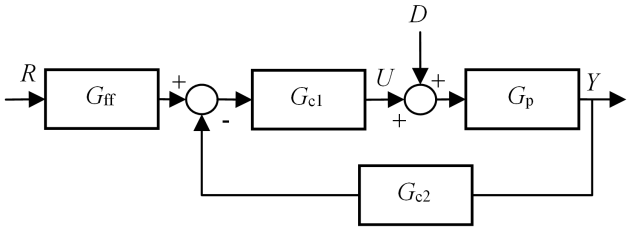


FIG. 2. Block diagram of a 2DoF control scheme.

and the optimal PID parameters are obtained using VBSO. Also, the proposed controllers are compared with other design methods and concluding remarks are provided. Finally, the conclusions of the study are drawn in Section V.

II. CONTROL STRUCTURE AND DESIGN REQUIREMENTS

Block diagram of a 1DoF closed-loop control system is shown in Fig. 1. $G_{\rm p}$ and $G_{\rm c}$ refer to $n \times n$ plant and controller matrices, respectively. R, Y and D are reference input, output and load disturbance vectors, respectively. Also, E and U represent error and control vectors. To design a centralized PID controller with a filter on the derivative action, the elements of $G_{\rm c}$ are defined as $g_{{\rm c}\,ij} = k_{{\rm c}\,ij} + k_{{\rm i}\,ij}/s + (k_{{\rm d}\,ij}s)/(1 + 0.1k_{{\rm d}\,ij}/k_{{\rm c}\,ij}s)$ $i, j \in \{1, ..., n\}$, where $k_{{\rm c}\,ij}$, $k_{{\rm i}\,ij}$, $k_{{\rm d}\,ij}$ are the proportional, integral and derivative gains from j^{th} input to i^{th} output, respectively.

Block diagram of the proposed 2DoF closed-loop control system is shown in Fig. 2, where $G_{\rm ff} = {\rm diag}(g_{{\rm ff}\,1}, g_{{\rm ff}\,2}, \ldots, g_{{\rm ff}\,n})$, b_i is the setpoint weight, $g_{{\rm ff}\,i} = (b_i k_{{\rm c}\,ii} + k_{{\rm i}\,ii}/s + k_{{\rm d}\,ii}s/(1 + 0.1k_{{\rm d}\,ii}/k_{{\rm c}\,ii}s))$, $G_{\rm c1} = \left[g'_{{\rm c}\,ij}\right]_{n\times n}$, $g'_{{\rm c}\,ij} = g_{{\rm c}\,ij}/g_{{\rm c}\,jj}$ and $G_{\rm c2} = {\rm diag}\left(g_{\rm c11}, g_{\rm c22}, \ldots, g_{\rm cnn}\right)$.

It is worth noting that the setpoint weight has a significant influence on the response to setpoint signals. However, it has no influence on disturbance response or robust stably criteria.

According to Fig. 2, the output of closed-loop system is $Y = (I + G_{\rm p}G_{\rm c1}G_{\rm c2})^{-1} G_{\rm p}G_{\rm c1}G_{\rm ff}R + (I + G_{\rm p}G_{\rm c1}G_{\rm c2})^{-1} G_{\rm p}D$. Also, sensitivity and complementary sensitivity matrices are respectively $S = (I + G_{\rm p}G_{\rm c1}G_{\rm c2})^{-1} = (I + L)^{-1}$ and $T = (I + G_{\rm p}G_{\rm c1}G_{\rm c2})^{-1} G_{\rm p}G_{\rm c1}G_{\rm ff}$, where $L = G_{\rm p}G_{\rm c1}G_{\rm c2}$ is the loop transfer matrix. Note that $G_{\rm ff} = G_{\rm c2}$ for $b_i = 1$. In addition, $G_{\rm ff} \approx G_{\rm c2}$ for low and high frequencies. To reach acceptable setpoint regulation over low frequencies, T should be approximately an identity matrix. Therefore, S should be very small as $T + S \approx I$. Hence, the maximum singular value of S, $\bar{\sigma}\left[(I + L)^{-1}\right]$, should be small or the minimum singular value of L, $\underline{\sigma}\,[L]$, should be large. Considering the second term of Y, however, it may not lead to a good disturbance rejection. To reduce sensitivity to modelling errors, the resulting closed-loop system should not be too sensitive to variations in the plant dynamics. To achieve this goal, the maximum singular value of S should be small. The transfer matrix from R to U, a measure of control effort, is defined by $Q = (I + G_{\rm c1}G_{\rm c2}G_{\rm p})^{-1}G_{\rm c1}G_{\rm ff}$.

Here, a well-known method for checking robust stability is used[12,13]. Considering output multiplicative uncertainty, the 2DoF closed-loop system will remain stable under the uncertainty Δ_o if and only if $l(\omega) < 1/\bar{\sigma}\left[(I + L)^{-1}L\right] = \underline{\sigma}\left[I + (L)^{-1}\right]$. As the plant can be modelled more accurately in small frequencies, $l(\omega)$ in $\bar{\sigma}\left[\Delta(j\omega)\right] \leq l(\omega) \leq \gamma$ is small at low frequencies. In fact, γ indicates the degree of robust stability. Similarly, for input multiplicative uncertainties, the closed-loop system will remain stable under the uncertainty Δ_i if and only if $l(\omega) < 1/\bar{\sigma}\left[(I + L_I)^{-1}L_I\right] = \underline{\sigma}\left[I + L_I^{-1}\right]$, $L_I = G_{\rm c1}G_{\rm c2}G_{\rm p}$.

In Fig. 2, the aim of design is to determine the parameters of $G_{\rm c1}$, $G_{\rm c2}$ and $G_{\rm ff}$ so that the outputs follow the reference signals in spite of load disturbances, measurement errors and model uncertainties. In fact, the IAE criteria for unit step changes in setpoint and load disturbance inputs should be minimized.

To obtain a robust controller with good performance, four constraints on $\|S\|_\infty$, $\|T\|_\infty$, $\|Q\|_\infty$ and γ should be considered. In fact, a high degree of robustness is achieved by having large enough values of γ and by avoiding large peaks in $\bar{\sigma}(S)$.

The design procedure has two main phases. In the first phase, setpoint signals are zero and $G_{\rm c1}$ and $G_{\rm c2}$ are determined so that step load disturbance signals are appropriately rejected whereas above-noted constraints are satisfied. In the second phase, load disturbance signals are zero and setpoint weights are tuned to achieve good setpoint responses.

III. VBSO ALGORITHM

Evolutionary and nature-inspired algorithms are increasingly used in numerical optimization problems. These algorithms are less likely to get trapped in local extrema in comparison with single-solution based methods or gradient based methods. To solve a variety of optimization problems, evolutionary and nature-inspired optimization algorithms, such as genetic algorithm (GA)[14], particle swarm optimization (PSO)[15], differential evolution (DE)[16], harmony search (HS) algorithm[17], cuckoo search (CS) algorithm[18] have been widely used in recent

years. Also, their advantages and disadvantages have been identified and several improved strategies have been provided[19–25].

In this paper, a vector-based swarm optimization (VBSO) algorithm with high accuracy and high speed of convergence, proposed by Afroomand & Tavakoli, is used[10,11]. It is an easy to understand, easy to use, reliable and robust optimization algorithm, which performs on the vectors in a D-dimensional search space. Each vector represents a solution. Vectors with appropriate orientation gradually converge to global optimum point. The main idea in VBSO is to use the cooperation operator. It is divided in direct cooperation vector, orienting solutions towards the global optimum point, and differential cooperation vector, responsible for small-scale search around the direct cooperation vector. Differential cooperation vector helps the algorithm to pass local optimums and converge to global one. The direct and differential cooperation vectors are formed using multiplication of VBSO weighting coefficients by suitable vectors. The pseudo code of VBSO algorithm is as follows.

First, an initial population having N_{pop} number of D dimensional vectors is produced randomly. In the initial population, $V_{i,j}[0]$ is the value of j^{th} element of i^{th} vector, where $i \in [1, N_{pop}]$ and $j \in [1, D]$. Also, v_j^{low} and v_j^{up} are lower and upper limits of j^{th} element of corresponding vector, respectively, and *rand* denotes a uniformly distributed random value in the interval $(0, 1)$. Second, each vector is evaluated according to a given cost function. In k^{th} iteration, the cooperation operator, $V_{Co}[k]$, is determined using the direct and differential cooperation vectors, $V_{Dir-C}[k]$ and $V_{Dif-C}[k]$. These cooperation vectors are formed using multiplication of VBSO weighting coefficients, $w_1 - w_9$, by V_c, V_a, V_b, V_{lb} and V_r vectors. The first three vectors represent current solution, average of solutions and current best solution, respectively. Also, V_{lb} is the best vector in the neighborhood of i^{th} vector and V_r is a random vector. Figures 3 and 4 show the contour lines of cost functions in a two-dimensional search space. Fig. 3 shows that suitable V_{Dir-C} can be formed by considering proper portions of V_b and V_{lb}. Also, Fig. 4 illustrates how V_{Dif-C} is made using V_c, V_b and V_{lb}.

To increase the population diversity, a mutation operator is used. Due to using cooperation vectors, VBSO algorithm has an intrinsic mutation capability. Moreover, a polynomial mutation is employed with a mutation probability of 0.4, in which one or two elements of a selected vector are mutated. To make sure new vectors are inside the search space, a boundary check is also required at each step. In addition, the next population is selected from parents and offsprings based on fitness numbers. In

Vector-based swarm optimization algorithm

Set: D, N_{pop}, Number of Iterations (NI), v_j^{low}, v_j^{up}, Iteration=0
$V_{i,j}[0] = v_j^{low} + rand.\left(v_j^{up} - v_j^{low}\right)$, $\forall i = 1, 2, ..., N_{pop}$, $and\, j = 1, 2, ..., D$

While (Iteration≤NI) **do**

for $i = 1, 2, ..., N_{pop}$ **do**

Calculate f(V_i)$\forall i = 1, 2, ..., N_{pop}$, $and\, V = (V_i^1, V_i^2, ..., V_i^D)$

Determine (V_b,V_{lb},V_r,V_a)

Generate weighting coefficients $(w_1 - w_9)$

Direct Cooperation $V_{Dir-C}[k] = w_1 V_c[k] + w_2 V_a[k] + w_3 V_b[k] + w_4 V_{lb}[k] + w_5 V_r[k]$

Differential Cooperation $V_{Dif-C}[k] = w_6.(V_a[k] - V_c[k]) + w_7.(V_b[k] - V_c[k])$
$+w_8.(V_{lb}[k] - V_c[k]) + w_9.(V_r[k] - V_c[k])$

$V_{Co}[k] = V_{Dir-C}[k] + V_{Dif-C}[k]$

Mutation, Boundary Check, Next Generation Selection

end for

Iteration=Iteration+1

end while

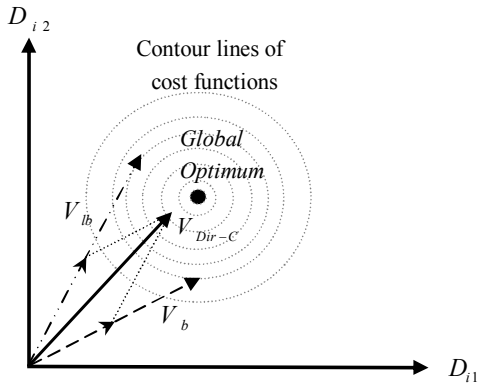


FIG. 3. Formation of the direct cooperation vector[10].

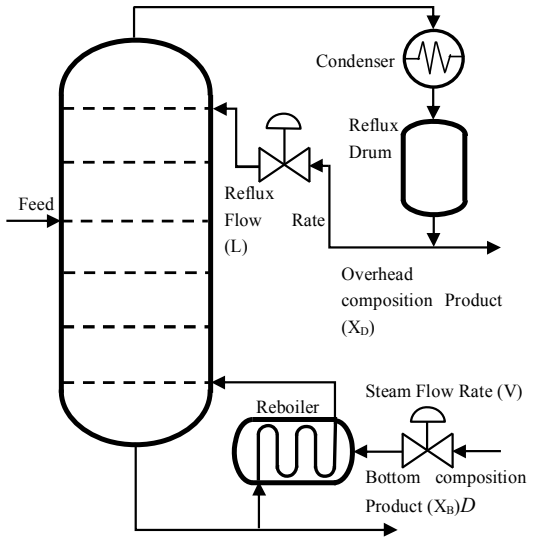


FIG. 5. Simple schematic of a distillation column.

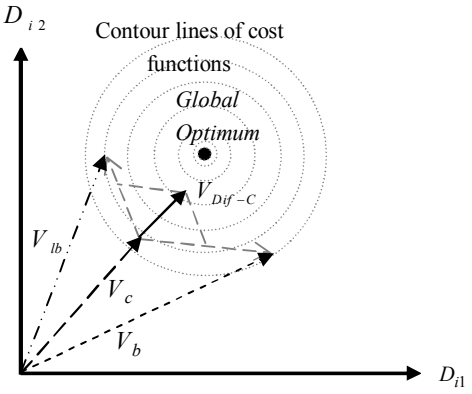


FIG. 4. Formation of the differential cooperation vector[10].

a minimization problem, the parents and offsprings are evaluated and sorted in an ascending order and the first N_{pop} vectors are transferred into the next population.

In the VBSO, there are several weighting coefficient selection strategies[10,11]. In this research work, the weighting coefficients are given by $w_i = 0.5\ rand, i = 1, 3, 4, 5$, $w_i = 0.33\ rand, i = 7, 8, 9$ and $w_i = 0\ rand, i = 2, 6$.

IV. SIMULATION

Most industrial plants are multi-input multi-output systems, in general. As a challenging industrial plant, a distillation column is studied in this section. A distillation column is a process in which a liquid or vapor mixture of two or more substances is separated into its component fractions of desired purity. Having strong interactions between its inputs and outputs, it is the most common separation technique. Fig. 5 depicts a simple distillation column.

The dynamic model of the Wood and Berry (WB) distillation column, is given by

$$\begin{pmatrix} X_D \\ X_B \end{pmatrix} = \begin{pmatrix} \frac{12.8\,e^{-s}}{1+16.7\,s} & \frac{-18.9\,e^{-3s}}{1+21\,s} \\ \frac{6.6\,e^{-7s}}{1+10.9\,s} & \frac{-19.4\,e^{-3s}}{1+14.4\,s} \end{pmatrix} \begin{pmatrix} L \\ V \end{pmatrix} \quad (1)$$

where X_D and X_B represent the percentage of methanol in the distillate and bottom products, respectively. L and V are the reflux and steam flow rates in the reflux drum and reboiler, respectively[6,26].

Applying unit step functions to the reference inputs and step functions of 0.25 to the disturbance inputs, the objective function used is $IAE = IAE_1 + IAE_2$, $IAE_i = \int_0^\infty |e_i(t)|\ dt$ where IAE_i and $e_i(t)$ denote IAE criteria and error signal in the i^{th} output, respectively. To obtain a robust controller with acceptable control effort, we consider $\|S\|_\infty \leq 1.8$, $\|T\|_\infty \leq 1.3$, $\gamma_{in} > 0.65$, $\gamma_{out} > 0.8$, $\|Q\|_\infty \leq 0.3$ for PI controller, $\|Q\|_\infty \leq 0.4$ for 2D-PI controller, $\|Q\|_\infty \leq 1.4$ for PID controller, $\|Q\|_\infty \leq 2$ for 2D-PID controller. Also, γ is computed for a frequency range of 0.01 to 100. Considering 100 vectors and 150 iterations, the VBSO is run for 30 times to find the optimal controller. In all simulations, the decision variables are in the range of $[-1, 1]$. Also, the sample time and simulation time are 0.1 and 300, respectively. The first and second reference inputs are applied at $t = 0$ and $t = 100$, respectively, whereas the load disturbance signals are applied at $t = 200$.

The values of the performance and robustness indices are given by Table I.

The output responses to steps in reference and load disturbance inputs are depicted in Fig. 6.

The PI and PID controller parameters are as follows.

$$k_{\mathrm{cPI}} = \begin{pmatrix} 0.1675 & -0.0274 \\ 0.0286 & -0.0825 \end{pmatrix},$$

$$k_{\mathrm{iPI}} = \begin{pmatrix} 0.0265 & -0.0121 \\ 0.0092 & -0.0125 \end{pmatrix},$$

$$k_{\mathrm{cPID}} = \begin{pmatrix} 0.1178 & -0.0032 \\ -0.0033 & -0.0750 \end{pmatrix},$$

$$k_{\mathrm{iPID}} = \begin{pmatrix} 0.0610 & -0.0374 \\ 0.0217 & -0.0287 \end{pmatrix},$$

$$k_{\mathrm{dPID}} = \begin{pmatrix} 0.3211 & -0.1861 \\ -0.6844 & -0.0793 \end{pmatrix},$$

$$k_{\mathrm{c2DoF-PI}} = \begin{pmatrix} 0.1918 & -0.0814 \\ -0.0326 & -0.1141 \end{pmatrix},$$

$$k_{\mathrm{i2DoF-PI}} = \begin{pmatrix} 0.0626 & -0.0266 \\ 0.0283 & -0.0237 \end{pmatrix},$$

$$b_{i\mathrm{2DoF-PID}} = 0.94, 0.88,$$

$$k_{\mathrm{c2DoF-PID}} = \begin{pmatrix} 0.1769 & -0.0009 \\ -0.0062 & -0.0982 \end{pmatrix},$$

$$k_{\mathrm{i2DoF-PID}} = \begin{pmatrix} 0.0472 & -0.0290 \\ 0.0188 & -0.0273 \end{pmatrix},$$

$$k_{\mathrm{d2DoF-PID}} = \begin{pmatrix} 0.1289 & -0.0764 \\ -0.0899 & -0.0834 \end{pmatrix},$$

$$b_{i\mathrm{2DoF-PI}} = 0.84, 0.75.$$

The stability regions of output and input uncertainties for closed-loop systems are depicted in Fig. 7. In this figure, the region above each curve represents the instability region whereas the region below each curve represents the stability region.

The plots of $\bar{\sigma}(S)$ and $\bar{\sigma}(T)$ for closed-loop systems are given by Fig. 8. They usually have peaks larger than one around the crossover frequencies. For real systems, these peaks are undesirable but unavoidable[13].

A good controller should provide a good compromise between performance and robustness. The controller proposed by SSGM method neither does give a satisfactory degree of robustness nor a good performance index according to Table I and Figures 6 and 7. Table I and Fig. 7 show that RGA and RNGA lead to large enough values of γ_{out}. In addition, the peaks of $\bar{\sigma}(S)$ in Fig. 8 are small enough for these two methods and, therefore, a high degree of robustness is anticipated. According to Table I and Fig. 6, however, they result in big IAE criteria and, hence, unsatisfactory time responses. Moreover, the values of $\bar{\sigma}(S)$ are not small enough in low frequencies and, hence, inferior responses to load disturbance inputs are expected.

According to Table I and Figures 6-8, the results provided by proposed PI controllers are satisfactory in terms of the performance and robustness indices. As expected, the best result is provided by the proposed 2DoF-PI. For PID controllers, Table I along with Figures 6-8 reveal that the results provided by proposed PID controllers are satisfactory. Again, the best result is provided by the proposed 2DoF-PID.

Table I shows that the proposed 2DoF controllers perform better than those in a 1DoF scheme considering both the performance and robustness indices. This is due to using the setpoint weighting. However, it leads to increasing the control effort. In addition, this table shows that the 2DoF-PID controller performs better than the 2DoF-PI controller. However, using an extra controller parameter, namely the derivative action, results in increasing the control effort.

Overall, simulation and comparison results confirm that the proposed method is better than other methods in terms of the performance and robustness. This is due to using a more flexible control structure, a more powerful optimization algorithm and a more comprehensive set of design requirements.

V. CONCLUSIONS

For a two-by-two WB distillation column with strong interactions and long dead times, PI/PID controllers were designed, in this paper. By formulating the design problem as an optimization problem, the VBSO algorithm was used to tune the controller parameters for setpoint regulation and load disturbance rejection, simultaneously. Also, four constraints on peaks of the maximum singular value of sensitivity and complementary sensitivity matrices, degree of robust stability and control effort were considered. Due to using a 2DoF control structure, a powerful optimization algorithm and a comprehensive set of design requirements, the superiority of the proposed control strategy in coping with conflicting design objectives in comparison with several well-known design techniques was confirmed by the simulation results.

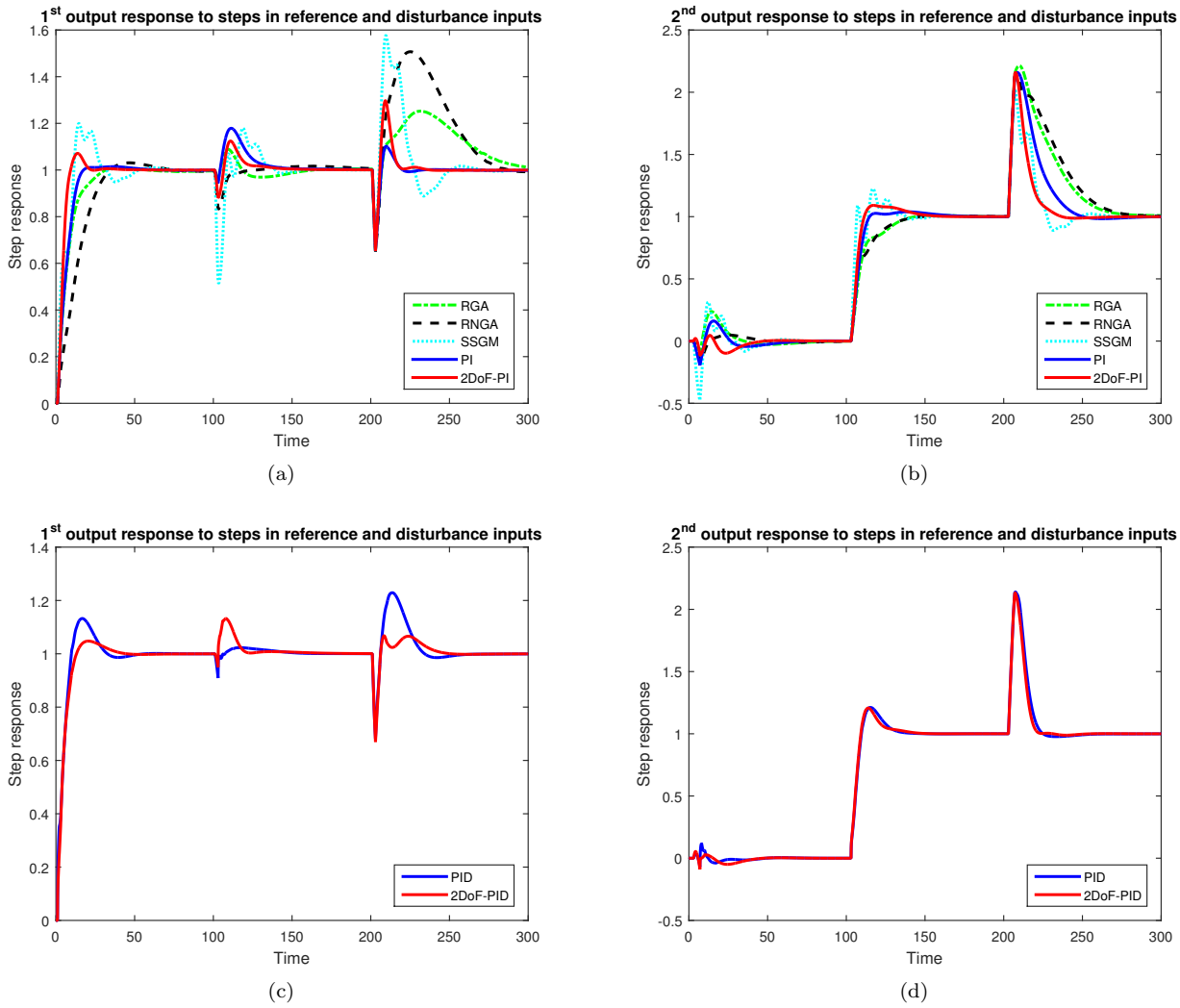


FIG. 6. Output responses to steps in reference inputs and disturbances.

TABLE I. Performance and robustness indices

Method	Performance index		Robust stability			Control effort
	IAE	$\|\|T\|\|_\infty$	γ_{out}	γ_{in}	$\|\|S\|\|_\infty$	$\|\|Q\|\|_\infty$
RGA	69.5	1.02	0.98	0.91	1.58	0.26
RNGA	83.0	1.00	1.00	0.78	1.49	0.24
SSGM	48.8	2.74	0.37	0.51	3.40	1.31
PI	44.5	1.12	0.89	0.75	1.69	0.28
2D-PI	32.9	1.12	0.83	0.68	1.79	0.36
PID	32.6	1.25	0.80	0.74	1.63	1.35
2D-PID	28.9	1.21	0.80	0.68	1.77	1.95

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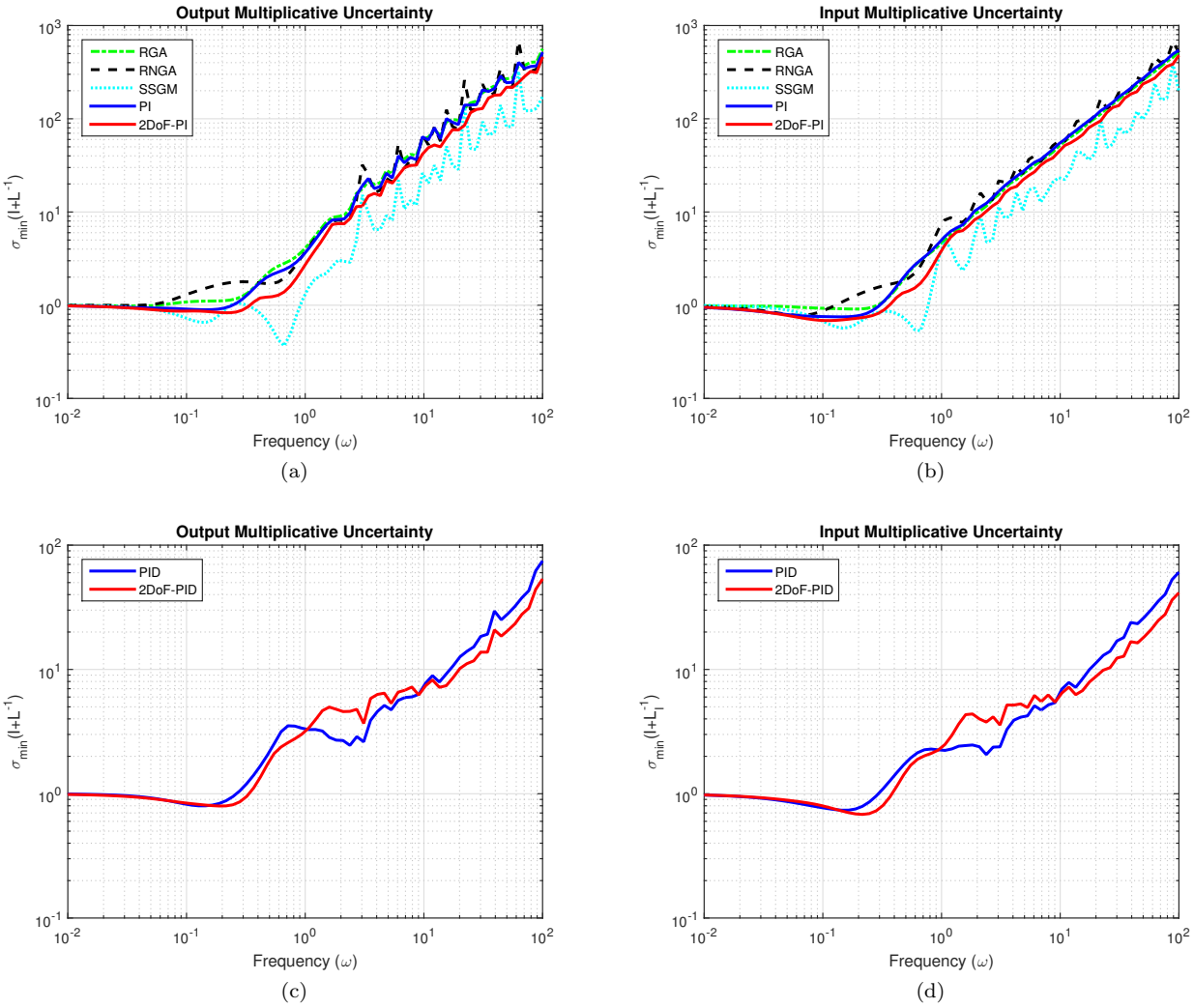


FIG. 7. Stability regions of output and input uncertainties.

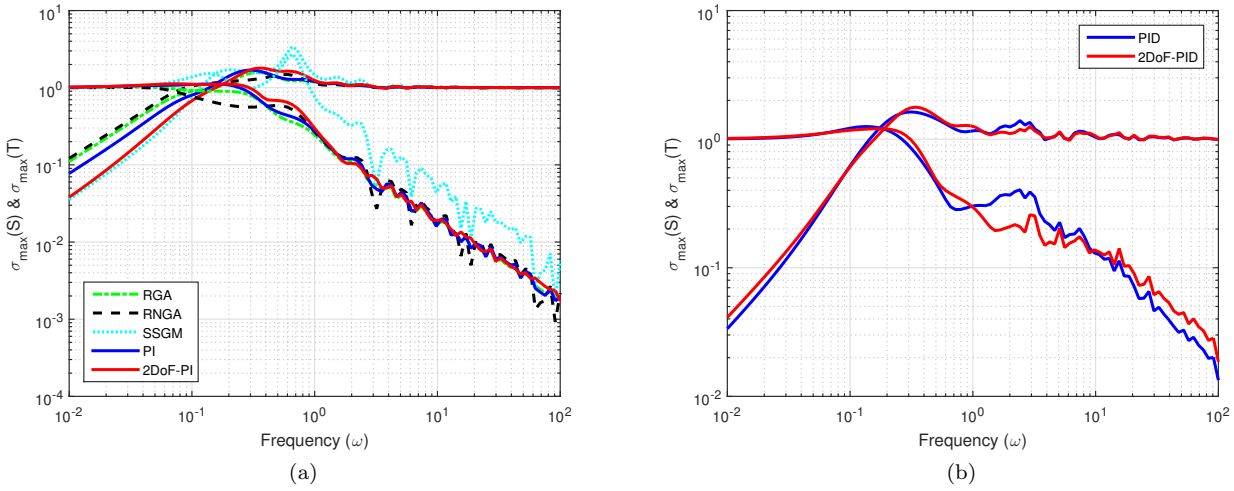


FIG. 8. Maximum singular values of S and T.

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