



Heat Exchanger Performance and Stability Improvement Using H₂ Synthesis Control Design Technique

**Henrietta U. Udeani¹, Hyacinth C. Inyama¹, Kenneth A. Akpado¹
and Chukwudi E. Agbaraji^{2*}**

¹*Department of Electronics and Computer Engineering, Nnamdi Azikiwe University Awka, Nigeria.*

²*Department of Computer Engineering, Federal Polytechnic Nekede, Owerri, Nigeria.*

Authors' contributions

This work was carried out in collaboration among all authors. Author HUU designed the study, performed the simulation and wrote the first draft of the manuscript. Author HCI, KAA and CEA managed the analyses of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2020/v26i1030323

Editor(s):

(1) Dr. Martin J. Bohner, Missouri University of Science and Technology, USA.

(2) Professor, Cheng-Fu Yang, National University of Kaohsiung, Taiwan.

(3) Dr. Suleyman Korkut, Duzce University, Turkey.

Reviewers:

(1) Márcio Avelino Sinoia Luís, Agricultural Research Institute of Mozambique (IIAM), Mozambique.

(2) Xingting Wang, Howard University, USA .

Complete Peer review History: <http://www.sdiarticle4.com/review-history/63101>

Original Research Article

Received 25 October 2020

Accepted 30 December 2020

Published 31 December 2020

ABSTRACT

The heat exchanger is a device that helps to circulate calculated amount of heat in a system. It can be applied in order to reduce the number of heat sources while maintaining a precise level of heat. Heat exchanger is expected to be part of the solution to CO₂ emission and climate issues since its application reduces the sources of heat and cost of production such as in electrical power plant. Due to the critical need for the solution to the enormous emission of CO₂ and the need to reduce cost of running power plants, the study and improvement of the heat exchanger has become very important. The heat exchanger suffers from disturbances due to its harsh environment. In order to maintain desired performance the heat exchanger requires an adequate control measure. Many types of controllers have been designed, however from the review it was observed that most of the controllers produced marginal stability which will not maintain good performance of the system in the presence of significant disturbance. The major objectives of this work are to reduce the tracking error for performance improvement, to reduce the peak sensitivity for better disturbance rejection

*Corresponding author: E-mail: wattchux@gmail.com;

and to improve the stability margins for stability robustness. In this work, an optimal robust control was developed for the heat exchanger using H_2 synthesis technique. From the results, the controlled system trajectory tracking error and overshoot were reduced to zero and the peak sensitivity to disturbance was reduced to 0.189 dB. Gain and phase margins satisfied the robust stability characteristics; gain margin was greater than 20 dB and phase margin was greater 60 dB. This means that the designed optimal controller will guarantee robust performance and stability of the system even in the presence of large disturbance.

Keywords: Heat exchanger; optimal control; controller; robust control; H2 synthesis.

1. INTRODUCTION

Growing demand for environmentally friendly gas-turbine engines with lower emissions and improved specific fuel consumption can be met by incorporating heat exchangers into gas turbines [1]. Environmental issues require gas turbine manufacturers to produce environment friendly gas-turbine engines with lower emissions and higher specific fuel consumption (SFC) ratings. The requirements can be met if heat exchangers are incorporated into gas turbines [1]. Heat exchanger has been applied in many areas that require circulation of specific amount of heat in order to cut down cost of installing many heat sources and also cut down the amount of carbon dioxide emission. In order to achieve the circulation of specific amount of heat, the heat exchanger requires an optimal controller.

In order to control the temperature of outlet fluid of the heat exchanger system a conventional Proportional-Integral-Derivative (PID) controller was used in many works such as in [2,3,4]. Due to inherent disadvantages of conventional control techniques, advanced control measures such as Fuzzy logic controller was employed to control the temperature of outlet fluid of the heat exchanger system in [4,5]. However, in these works the performance of the heat exchanger was not analyzed based on reference tracking on frequency domain and the disturbances and sensitivity of the heat exchanger were not considered. The heat exchanger is a non-linear system that is supposed to be designed to manage the circulation of heat and maintain a particular desired or expected temperature for an optimal industrial processed performance.

Control of a heat exchanger is a complex process due to its non-linear behavior and complexity caused by many phenomena such as leakage, friction, temperature-dependent flow properties, contact resistance, unknown fluid properties etc. [6,7,8,9]. The mathematical model

of the heat exchanger is mostly simplified and linearized in order to achieve the control goal. By so doing, the model suffers from unmodelled dynamics and other forms of uncertainties. As a result of this, an optimal control method such as the H_2 synthesis technique which takes the uncertainties that are contained in the modeling of the system into consideration while enhancing the performance of the system is considered in this work.

2. LITERATURE REVIEW

Sivakumar et al. stated in [5] that temperature control of the shell and tube heat exchanger has characteristics of nonlinear, time varying and time lag. Since the temperature control with conventional PID controller cannot meet a wide range of precision temperature control requirement, the temperature control system of the shell and tube heat exchanger by combining fuzzy and PID control methods was designed in their work. The simulation and experiments were carried out; making a comparison with conventional PID control showing that fuzzy PID strategy can efficiently improve the performance of the shell and tube heat exchanger.

Trafczynski et al indicated in [2] that, for several decades since Ziegler and Nichols proposed their first PID tuning method, the proportional-integral-derivative (PID) controllers are used in many industrial control systems e.g., temperature control at heat exchanger outlet. On the one hand, PID controller structure is simple and its functioning principle is easier to understand than those of other advanced controllers. Different conventional controllers implemented to control the outlet fluid temperature of shell and tube heat exchanger system have been surveyed.

Vasičkaninová and Bakošová [10] opined that heat exchanger can be represented as a system with interval parametric uncertainty, as a result, it requires a robust controller which can take the uncertainties existing in the system into

consideration during design in order to achieve a system that can perform optimally in the presence of the uncertainties. They suggested that fuzzy and neuro-fuzzy controllers can be better alternative to the PID control, although many industrial applications use PID control to maintain constant process variables. However, this method did not address the issue of disturbance rejection or sensitivity of the system to perturbations and also it did not optimize the performance of the heat exchanger as expected and as shown in [10]. In order to address these issues for robustness and optimization of the heat exchanger performance, optimal robust control design was considered. The comparison of H₂ with classical PID control in [11] demonstrates the superiority of the proposed H₂ control especially in the case where the controlled process is affected by disturbances.

3. METHODOLOGY

The control of temperature in a shell-and-tube heat exchanger is demonstrated in Fig. 1, with cold water flowing on the tube side and steam on the shell side [12] where steam condenses and heats the water in the tubes. The controlled variable is the tube-side outlet temperature, and the manipulated variable is the steam flow rate on the shell-side. In order to achieve optimization of the process performance, the controlled variable is measured and fed back to the input, to be compared with the reference input or the desired input in order to produce an error signal. The error signal can then be compensated in order to optimize the plant output. The first step to optimize a system involves the derivation or expression of the mathematical model or representation of the system. However, the mathematical model of any plant cannot be exactly the same with the physical plant. This means that, there exist some differences between the plant model and the plant itself. The difference is actually called uncertainty or error or fault. The flow equation of the heat exchanger is represented as [5]:

$$M_c C_p (T_{in} - T_{out}) = M_s A \tag{1}$$

where M_c , M_s , C_p , T_{in} , and T_{out} and refer to cold water flow rate, steam flow rate, specific heat of water, inlet water temperature, and outlet water temperature respectively.

The dynamics of the process are complex because of various nonlinearities introduced into

the system [5]. The installed valve characteristic of the steam may not be linear [13]. Dead-time depends on the steam and water flow rates, the location and the method of installation of the temperature-measuring devices. To take into account the non-linearity and the dead-time, gain scheduling features and dead-time compensators have to be added. Also, the process is subjected to various external disturbances such as pressure fluctuations in the steam header, disturbances in the water line, and changes in the inlet steam enthalpy and so on [5].

The transfer function of controlled object was derived in [5] and described as the first-order with pure time delay, expressed as follows in equation 2.

$$G_p = \frac{k}{(rs+1)^n} e^{-Ds} \tag{2}$$

where r , k and D refer to time constant, system gain, and delay time respectively.

The heat exchanger can be represented also as a system with interval parametric uncertainty; various step responses were obtained at intervals for values of the gain k , the time constant r and the time delay D as shown in Table 1. The system order $n = 3$.

Table 1. Process dynamics [10]

Time Constant	r_{min}	15
	r_{mean}	19.33
	r_{max}	26
System Gain	k_{min}	3.734E4
	k_{mean}	5.4136E4
	k_{max}	7.8407E4
Delay Time	D_{min}	0.24
	D_{mean}	2
	D_{max}	0.91

3.1 Controller Design

The major objectives of the design in this work are to improve the performance of the system through reference tracking error reduction, to reduce sensitivity to disturbance and to achieve stability robustness [14] using H₂ optimal robust control. The H₂ controller design method here involves the control of the tracking performance of the heat exchanger and its stability with the H₂ weights $W1$ and $W2$ based on the heat exchanger parameters. The weight parameters are varied randomly in order to improve the

iteration results and to improve the performance trajectory response. The weighting functions were chosen based on the industrial performance specifications for H_2 and H-Infinity weights in [15,16]:

3.1.1 The H_2 controller design algorithm

- i. Establish the heat exchanger model $G(s)$
- ii. Apply weight $W1$ to control the plant sensitivity to disturbance
- iii. Apply Weight $W2$ on the control signal u
- iv. Apply weight $W3=0$ on the closed loop system (T) control.
- v. Augment the plant $G(s)$ with weighting functions $W1(s)$, $W2(s)$ and $W3(s)$ to form an "augmented plant" $P(s)$
- vi. Apply H_2 synthesis and generate the controller, K
- vii. Develop the loop gain: $L = K \times P$
- viii. Develop the system Sensitivity function: $S=(1+L)^{-1}$
- ix. Develop the Complementary Sensitivity function: $T=1-S$
- x. Analyze L , S and T for tracking error and stability for the heat exchanger

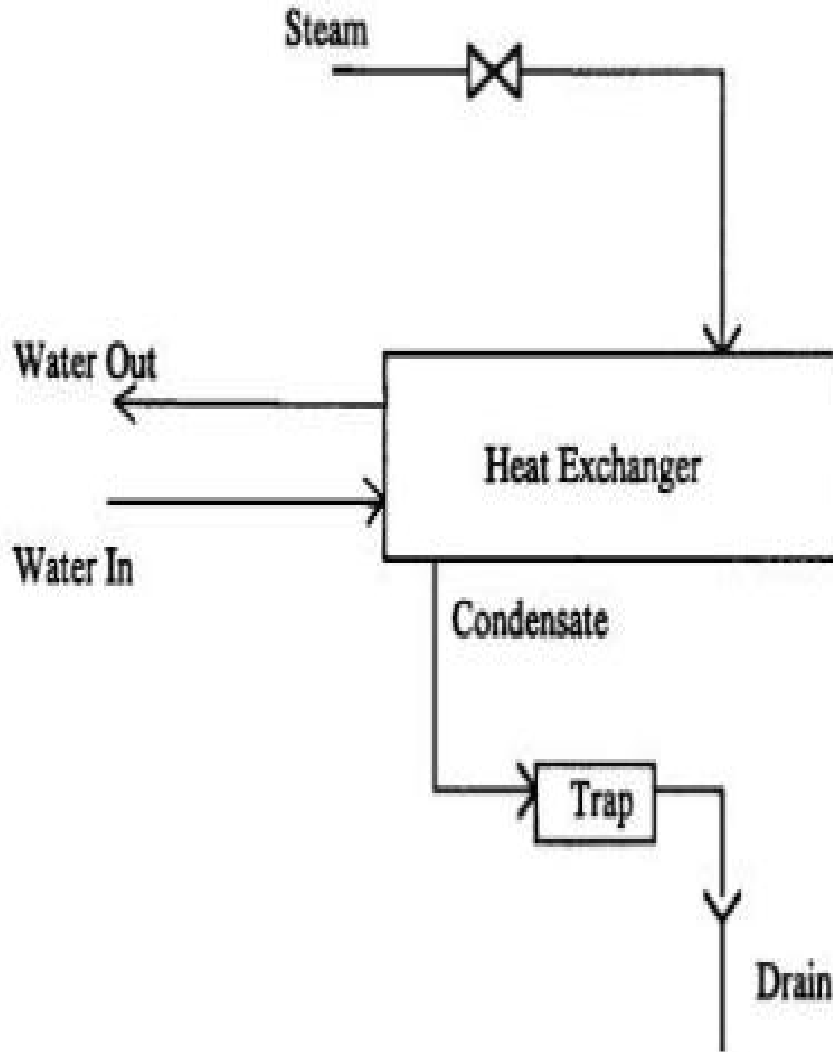


Fig. 1. Shell-and-tube heat exchanger [5]

4. RESULTS AND DISCUSSION

The controller was designed following the three experiment or scenarios of the existing parameters adopted in this work.

4.1 For System Parameter Minimum Values Experiment

In Fig. 2, the complementary sensitivity T, graph recorded zero dB peak gain at low frequencies and recorded values less than zero at high frequencies. This shows that the system can track the input signal without error, thereby producing desired performance and also attenuate noise very well. The sensitivity S, graph recorded low values less than zero at low frequencies. This signifies that the system will be able to reject disturbances. It also recorded peak

sensitivity of 0.348 dB. This means that the system can perform optimally even in the presence of disturbances. The state space model of the controller K, was achieved for the minimum value experiment as follows:

$$a = \begin{bmatrix} -0.471 & -0.8341 & -1.484 & 0.4095 \\ 0.125 & 0 & 0 & 0 \\ 0 & 0.0625 & 0 & 0 \\ 0 & 0 & 0 & -1e-06 \end{bmatrix},$$

$$b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001953 \end{bmatrix}$$

$$c = [-0.01694 \quad -0.04547 \quad -0.09039 \quad 0.02559]$$

$$, d = [0]$$

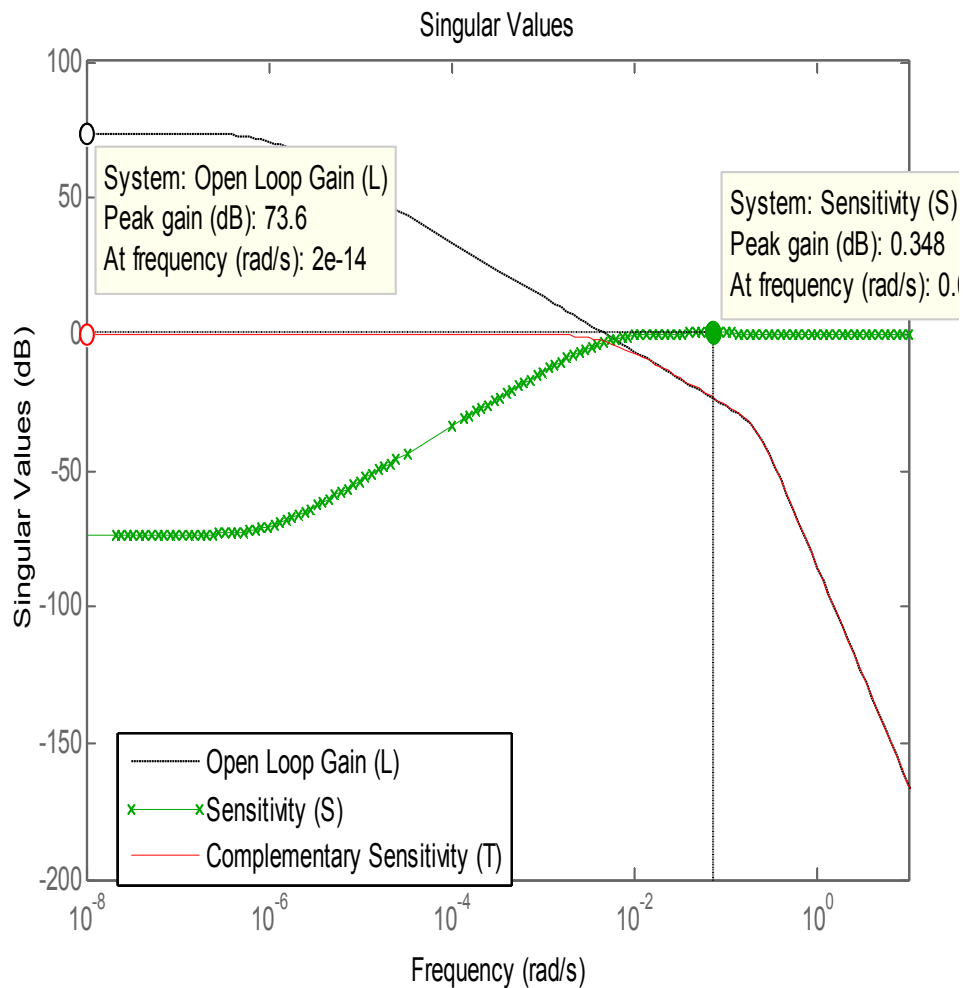


Fig. 2. T, S and L graphs for the system minimum value experiment

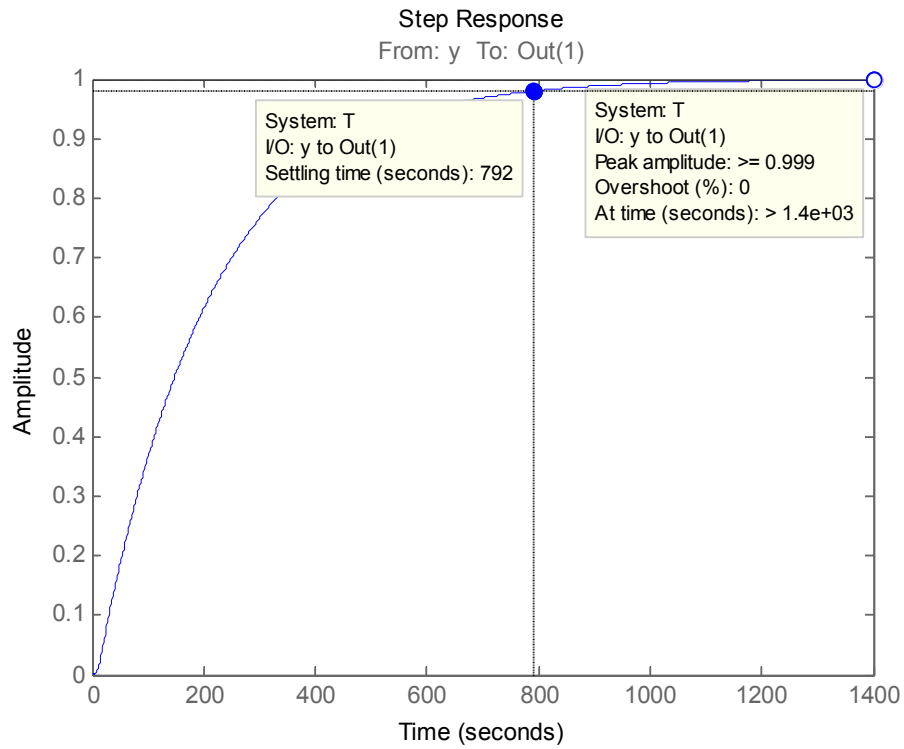


Fig. 3. Step response graph of the system minimum value experiment

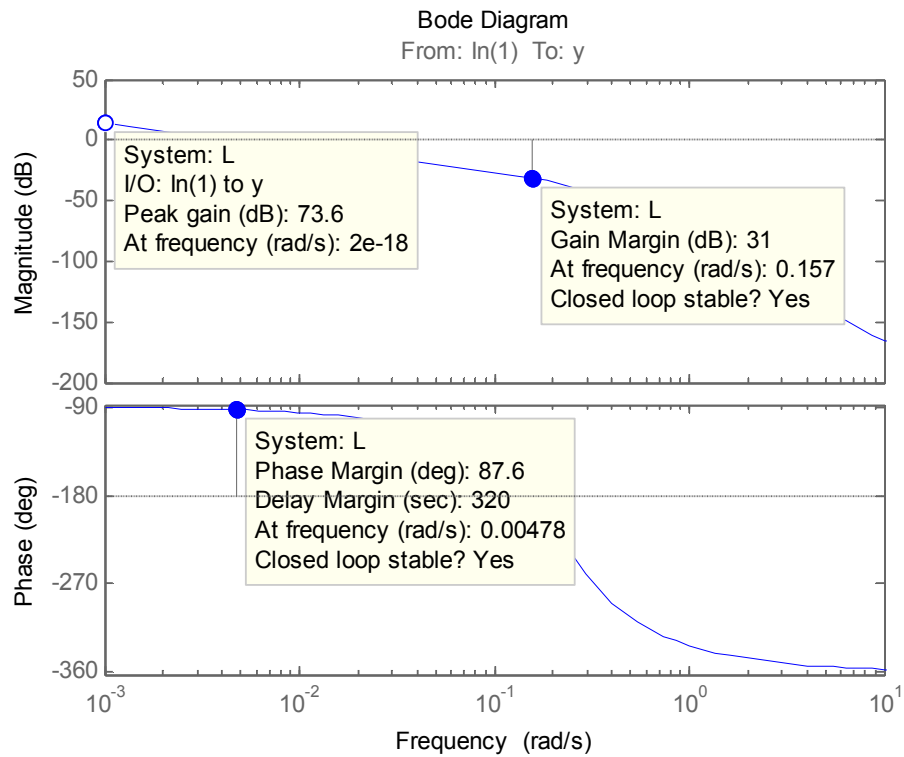


Fig. 4. Bode plot of the system minimum value experiment

4.2 For Plant Parameter Mean Values Experiment

In Fig. 5, the T, graph recorded zero dB peak gain at low frequencies and also recorded values less than zero at high frequencies. This means that the controlled system can track the input signal without error, thereby producing desired performance and also attenuate noise. The S, graph recorded low values less than zero at low frequencies. This specifies that the system will be able to reject disturbances. It also recorded peak sensitivity of 0.189dB. This means that the system can perform optimally even in the presence of disturbances. The state space model of the controller K, was achieved for the mean values experiment as follows:

$$a = \begin{bmatrix} -0.8546 & -2.889 & -19.64 & 0.819 \\ 0.125 & 0 & 0 & 0 \\ 0 & 0.03125 & 0 & 0 \\ 0 & 0 & 0 & -1e-06 \end{bmatrix},$$

$$b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001953 \end{bmatrix}$$

$$c = [-0.02186 \quad -0.08828 \quad -0.6128 \quad 0.02559],$$

$$d = [0]$$

4.3 For Plant Parameter Maximum Values Experiment

In Fig. 8, the T, graph recorded zero dB peak gain at low frequencies and recorded values less than zero at high frequencies. This means that the controlled system can track the input signal without error, thereby producing desired performance and also attenuate noise. The S, graph recorded low values less than zero at low frequencies. This implies that the system will be able to reject disturbances. It also recorded peak sensitivity of 0.222 dB. This means that the system can perform optimally even in the presence of disturbances. The state space model of the controller K, was achieved for the maximum values experiment as follows:

$$a = \begin{bmatrix} -0.7185 & -4.094 & -23.49 & 1.638 \\ 0.0625 & 0 & 0 & 0 \\ 0 & 0.03125 & 0 & 0 \\ 0 & 0 & 0 & -1e-06 \end{bmatrix},$$

$$b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001953 \end{bmatrix}$$

$$c = [-0.009423 \quad -0.06286 \quad -0.3665 \quad 0.02559],$$

$$d = [0]$$

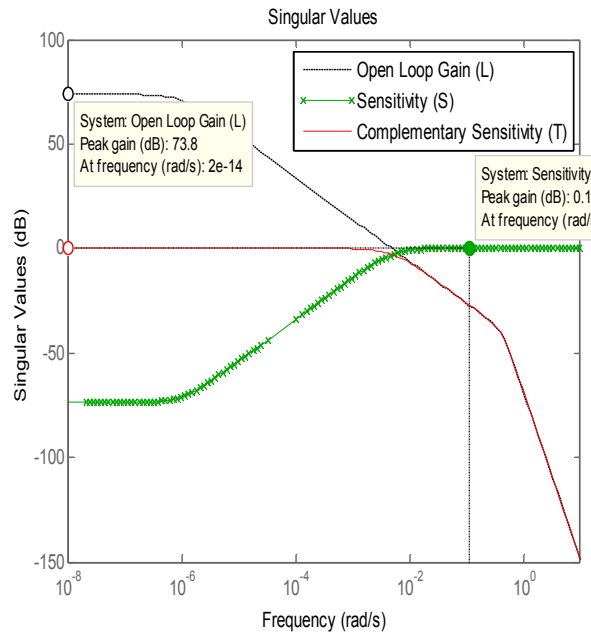


Fig. 5. T, S and L graphs for the system mean values experiment

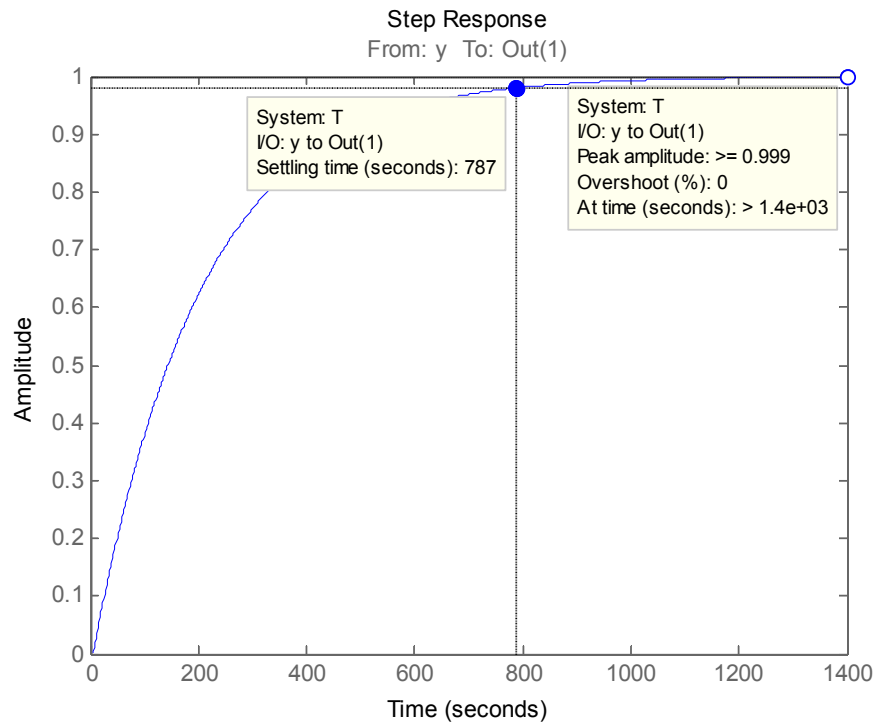


Fig. 6. Step response graph of the system mean values experiment

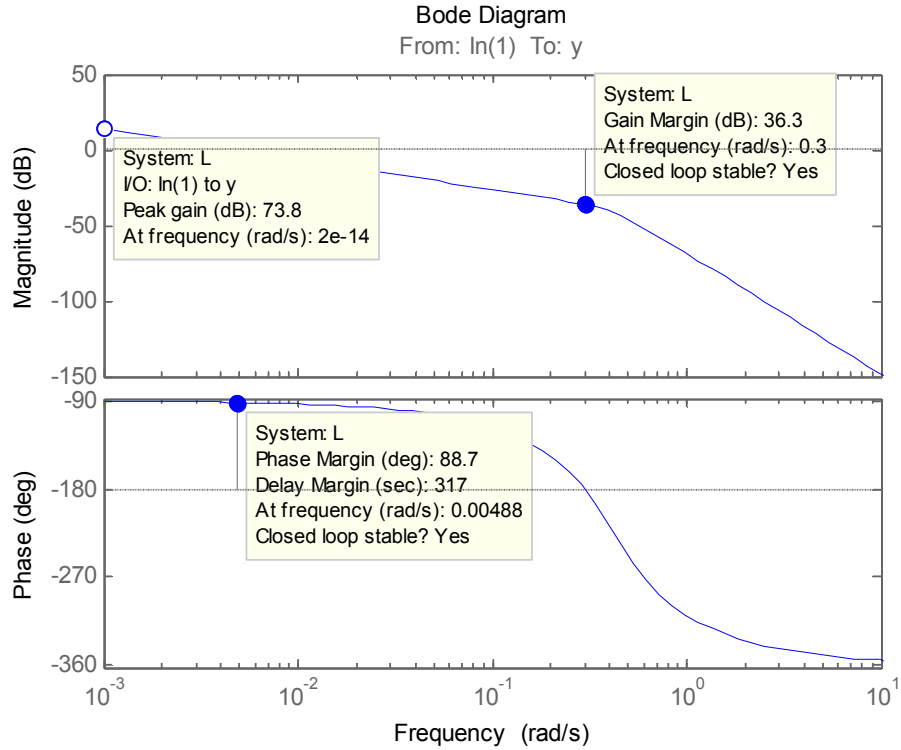


Fig. 7. Bode plot of the system mean value experiment

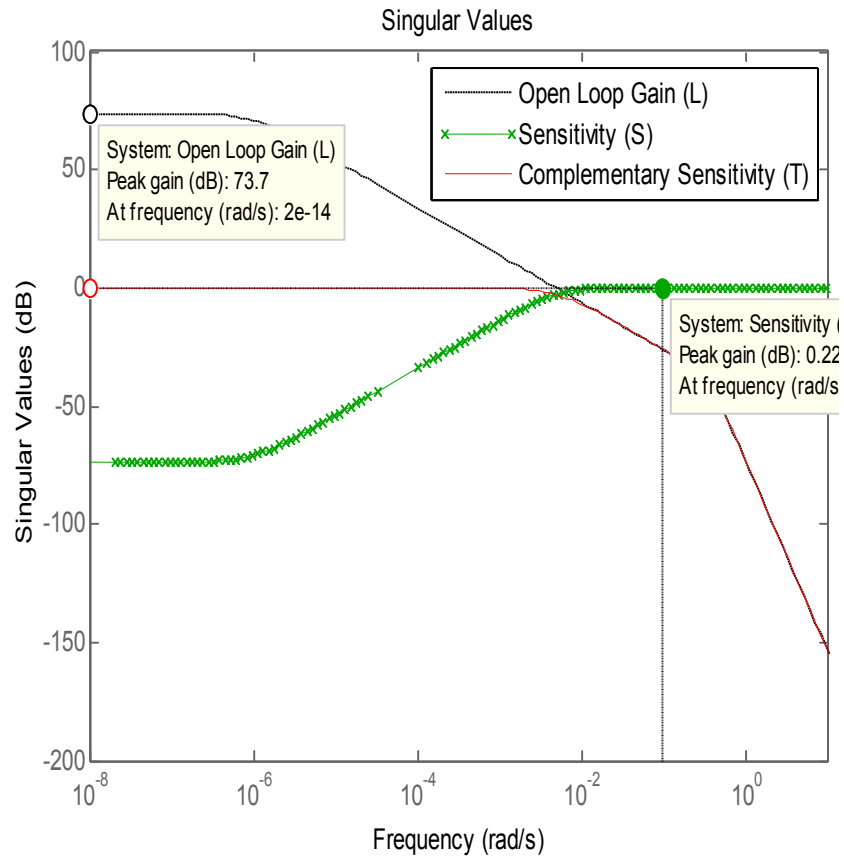


Fig. 8. T, S and L graphs for the system maximum value experiment

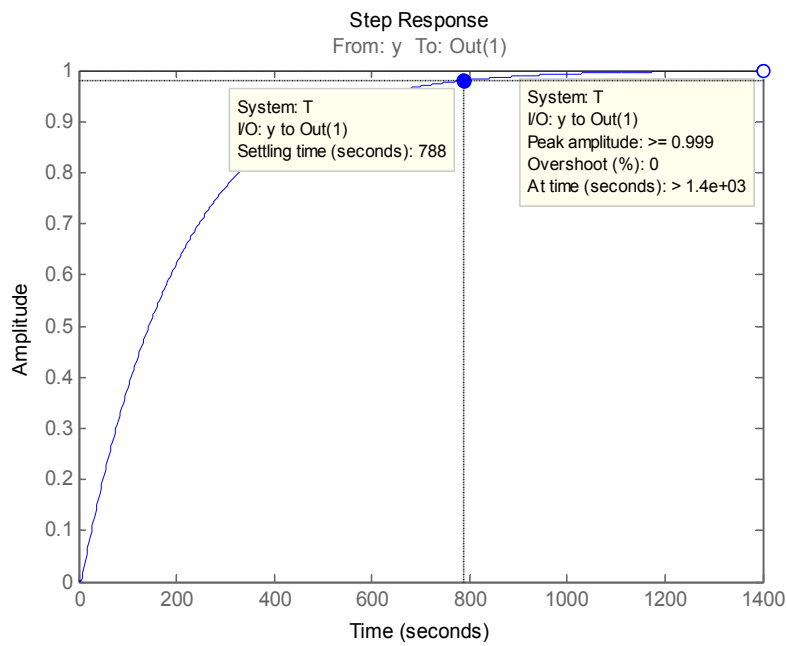


Fig. 9. Step response graph of the system maximum values experiment

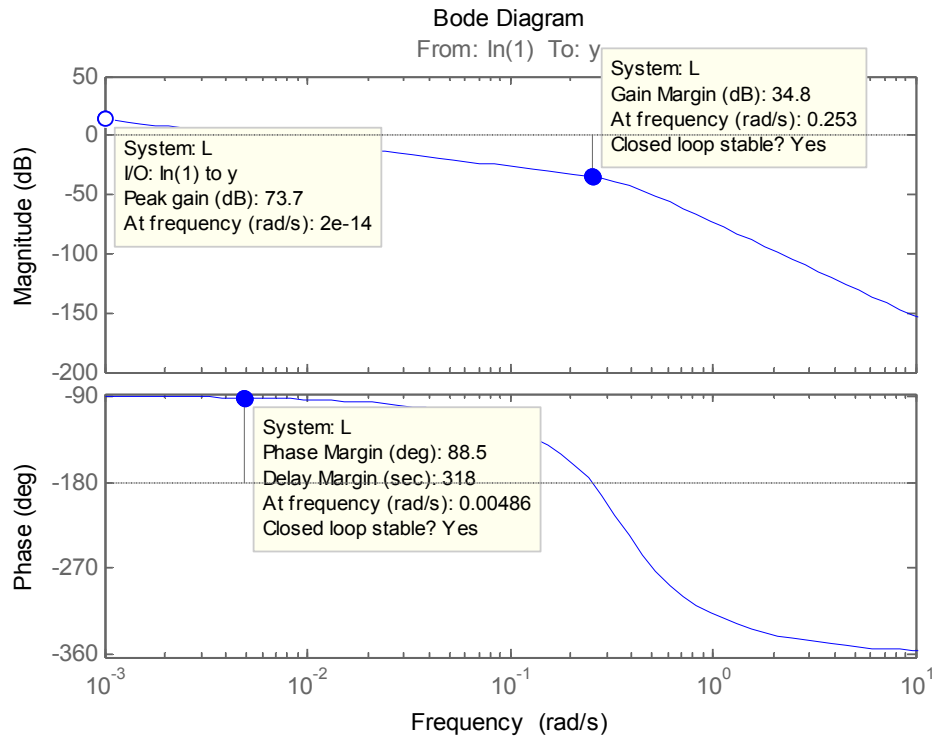


Fig. 10. Bode plot of the system maximum values Experiment

Table 2. The results of controller design using H₂ synthesis

Performance and stability specifications	For minimum values	For mean values	For maximum values
Loop Gain	73.6 dB	73.8 dB	73.7 dB
Sensitivity	0.348 dB	0.189 dB	0.222 dB
Reference Tracking Error	0	0	0
Overshoot	0	0	0
Gain Margin	31 dB	36.3 dB	34.8 dB
Phase Margin	87.6 dB	88.7 dB	88.5 dB

The results of the controller design using H₂ synthesis for the heat exchanger system based on the minimum, mean and maximum plant parameter values are summarized in Table 2.

5. CONCLUSION

The aim of this research work which was to design an optimal controller that can improve the performance and stability of the heat exchanger system was successfully achieved. The heat exchanger control designs was reviewed and it was found that it achieved marginal stability in most works which does not guarantee optimal performance because it will not be able to withstand significant disturbance. Since the heat exchanger is located in a harsh environment where there are

significant disturbances which affect its parameters, it becomes imperative to design a controller that considers the presence of disturbance in order to achieve a robust system that can function optimally with such disturbances. From the controller design results, the system reference tracking error and overshoot were reduced to zero and the sensitivity to disturbance was reduced to 0.189dB. From the results, the controlled system trajectory tracking error and overshoot were reduced to zero and the peak sensitivity to disturbance was reduced to 0.189dB. Gain and phase margins satisfied the robust stability characteristics; gain margin was greater than 20dB and phase margin was greater 60dB. This means that the designed optimal controller will guarantee robust performance and stability of the

system even in the presence of large disturbance. The results also show that gain and phase margins satisfied the robust stability characteristics: gain margin is greater than 20 dB and phase margin is greater 60dB. This means that the optimal robust controller designed using H₂ synthesis control achieved performance and stability robustness improvement for the heat exchanger.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Min JK, Jeong JH, Ha MY, Kim KS. High temperature heat exchanger studies for applications to gas turbines. Springer-Verlag Heat Mass Transfer. 2009;46:175–186.
2. Trafczynski M, Markowski M, Alabrudzinski S, Urbaniec K. Tuning parameters of PID controllers for the operation of heat exchangers under fouling conditions. Chemical Engineering Transactions. 2016;52:1237-1243.
3. Wakitani S, Deng M, Yamamoto T. Design of a data-driven controller for a spiral heat exchanger. IFAC symposium on dynamics and control of process systems. Norway. 2016;342-346.
4. Srivastava N, Tanti DK, Ahmad MA. Matlab simulation of temperature control of heat exchanger using different controllers. Automation, Control and Intelligent Systems. 2014;2(1):1-5.
5. Sivakumar P, Prabhakaran D, Kannadasan T. temperature control of shell and tube heat exchanger by using intelligent controllers-case study. International Journal of Computational Engineering Research. 2012;2(8):285-291.
6. Janna WS. Engineering heat transfer, Third edition, The University of Memphis, Tennessee, USA; 2009.
7. Al-Mutairi EM. Optimal design of heat exchanger network in oil refineries. Chemical engineering transactions. 2010;21:955-960.
8. Panjeshahi MH, Joda F, Tahouni N. Pressure drop optimization in multi-stream heat exchanger using genetic algorithms. Chemical Engineering Transactions. 2010;21:247-252.
9. Pan M, Bulatov I, Smith R, Kim JK. Improving energy recovery in heat exchanger network with intensified tube-side heat transfer. Chemical Engineering Transactions. 2011;25:375-380.
10. Vasičkaninová A, Bakošová M. Robust control of heat exchangers. Chemical Engineering Transactions. 2013;29:1363-1368.
11. Vasickaninova A, Bakosova M. Application of H₂ and H_∞ approaches applied to the robust controller design for a heat exchanger. Chemical Engineering Transactions. 2012;35:463-468.
12. Yamashita H, Izumi R, Yamaguchi S. Analysis of the dynamic characteristics of cross-flow heat exchangers with both fluids unmixed. Bull. JSME. 1978;21(153):479-485.
13. Alsop AW, Edgar TF. Non-linear heat exchanger control through the use of partially linearised control variables, Chein. Eng. Commn. 1998;75:155–170.
14. Agbaraji CE. Robustness Analysis of a closed-loop controller for a robot manipulator in real environments. Physical Science International Journal. 2015;8(3):1-11.
15. Filardi G, Sename O, Voda AB, Schroeder HJ. Robust H-Infinity control of a DVD drive under parametric uncertainties. Paper ID: 632:1-6.
16. Agbaraji CE, Udeani UH, Inyama HC, Okezie CC. Robust control for a 3DOF articulated roboticmanipulator joint torque under uncertainties. Journal of Engineering Research and Reports. 2020; 9(4):1-13.

© 2020 Udeani et al.; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
<http://www.sdiarticle4.com/review-history/63101>