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Performance and Stability Analysis of a Heat Exchanger

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Abstract
This research work focuses on the performance and stability analysis of the heat exchanger based on the time and frequency domain functions. The analysis was carried out to study the behavior of the heat exchanger without a controller in order to determine the particular control method suitable for optimal performance. From the simulation results of the heat exchanger model analysis, the system achieved good overshoot of 0% in the three scenarios of simulation experiments. It recorded settling time of 113sec, 145sec and 196sec respectively for the experiments. This means that its performance is very poor. The system recorded gain margin of -73.8dB, -78.9dB and -80.7dB respectively for the three experiments. It recorded phase margin of -115deg, 50.4deg and 172deg respectively for the three experiments. This means that the system did not satisfy the stability criteria. Therefore, it was concluded that the heat exchanger is not stable for the three scenarios of model parameters. The heat exchanger requires an optimal controller which can help to improve its performance and stability by reducing the reference tracking error and increase the stability margins respectively.

Keywords: Heat Exchanger, System Performance, Stability, Gain Margin, Phase Margin

1. Introduction

Direct Electric Heat Exchangers, also called circulation heaters, are used to calculatedly circulate heat in a system without direct contact between the source and the heated medium. Heat exchanger is commonly used in industrial processes to transfer heat from the hot fluid through a solid wall to a cooler fluid. There are different types of heat exchanger used in the industry but most of the industry use shell and tube type heat exchanger system (Srivastava, Tanti & Ahmad 2014). Shell and tube heat exchangers are probably the most common type of heat exchangers applicable for a wide range of operating temperatures and pressures. In shell and tube heat exchanger one fluid flows through the tubes and a second fluid flows within the space between the tubes and the shell (Sodja, Zupancic & Sink 2009). The outlet temperature of the shell and tube heat exchanger system has to be kept at a desired set point according to the process requirement.

Heat exchangers are used in a variety of applications. They are used to heat gases like nitrogen, hydrogen and hydrocarbons, as well as liquids such as water, oils, acids, solutions and other fluids (Long 2012). Electrical heat exchangers have become the principle component of many recent technologies which has brought about great change in the technological development in the industries and standalone systems.

Growing demand for environmentally friendly aero gas-turbine engines with lower emissions and improved specific fuel consumption can be met by incorporating heat exchangers into gas turbines (Min et al. 2009). This means that with the application of heat exchanger system, the number of heat sources will be reduced because the heat exchanger is capable to transfer or circulate a specific amount of heat to the required points from one or two heating sources.

However, 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. (Janna 2009; Al-Mutairi 2010; Panjeshahi, Joda & Tahouni 2010; Pan et al. 2011). The mathematical model of the heat exchanger is mostly simplified and linearized in order to achieve the control goal. Therefore, by so doing, the model suffers from unmodelled dynamics problem and other forms of uncertainties.

In this work, the heat exchanger performance and stability was analyzed based on the time and frequency domain function as stated in (Agbaraji 2015) in order to ascertain the type of control measure that can help it maintain equilibrium in its function even in the presence of disturbances.

2.0 Literature Review

In many industrial process and operations, heat exchanger is one of the simplest and an important unit (Thal-Larsen 1960) for the transfer of thermal energy in a calculated and controlled manner. Heat exchangers are commonly used in a variety of plant processes to transfer energy from one fluid or gas to another without mixing the two substances. As integral parts of comfort and process heating and cooling applications, they expected, in most cases, to perform efficiently and effortlessly for years. However, because they are parts of larger systems, they are often installed and forgotten, leading to problems down the road or less-than-optimum performance. A little knowledge about heat exchangers, how they operate and the problems limiting their performance can help plant engineers make better choices and install and maintain these devices more appropriately and cost effectively. There are different types of heat exchangers used in industries; the shell and tube heat exchanger system being most common. The main purpose of the application of exchanger is to maintain specific temperature conditions in a complex system, which is achieved by controlling the exit temperature of one of the fluids (mainly hot fluid) in response to variations of the operating conditions. The temperature control of heat exchanger plant is nonlinear, time varying and time delay system (Sivakumar, Prabhakaran & Kannadasan 2012).

Trafczynski et al (2016) stated that heat exchanger may be affected by fouling which builds up on the heat transfer surface. They opined that, in a real-life plant, possible consequences of fouling include burning extra fuel to compensate for reduced heat recovery, reducing plant output when the exchangers are cleaned and generating costs of cleaning interventions. In recent years, various approaches to the mitigation of fouling effects in industrial heat exchangers and exchanger networks have been reported in (Trafczynski et al. 2016). Apart from fouling-induced reduction of steady-state heat recovery (Liu et al. 2015), transient states of heat exchangers (Ansari & Mortazavi 2006) and inefficient control of both individual exchangers (Khare & Singh 2010) and entire networks (Varga, Hangos & Szigeti 1995) may also have a detrimental effect on the overall Heat Exchanger Network (HEN) performance.

Sahoo, Radhakrishnan & Rao (2017) in their research work “Modeling and control of a real time shell and tube heat exchanger” explained that the process industries generate large amount of heat that needs to be transferred. Heat exchangers are extensively used in industries for utilization of the heat energy generated from different processes. For definite utilization of this energy, the temperatures of the hot and cold fluids passing through the heat exchanger should be monitored and controlled efficiently. A proper model of heat exchanger is required for the purpose of analysis and control of the system.

3.0 Analysis of the Existing System Parameters

In this system model parameter analysis, the system characteristics for performance and stability were examined using adopted existing parameters. Three set of parameters of the existing system model were used: minimum (min), mean (mean) and maximum (max). This may be because; the heat exchanger is mostly located in extreme condition environments where some of its parameters may undergo some changes in their internal conditions. Thus, the simulation experiments were carried out in three scenarios covering the three set of parameters.

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

1: Process dynamics (Vasickaninova & Bakosova 2013)

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

The mean values of the parameters are considered to be nominal. While the min and max represent the minimum and maximum values of the system parameters. The analysis was carried out in MATLAB by executing the MATLAB codes in m-file. The experiment for the analysis was carried out for the three stages of the parameter values: minimum, mean and maximum.

For Minimum Parameter:
The simulation experiment results for the minimum parameter as presented in figures 1 and 2 were summarized in table 2.

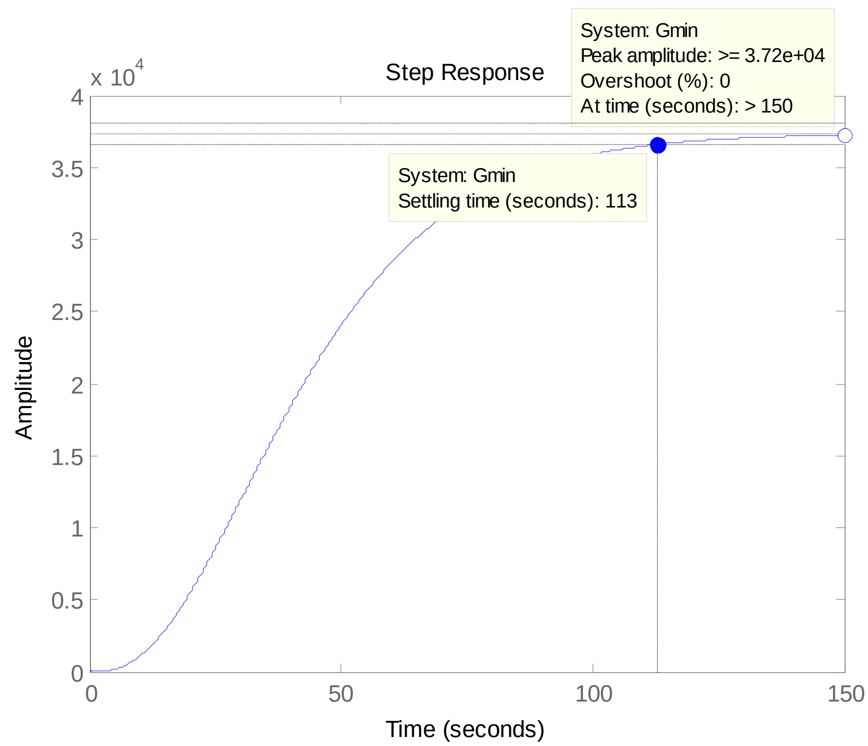

Figure 1: Step response of the heat exchanger for the minimum parameters

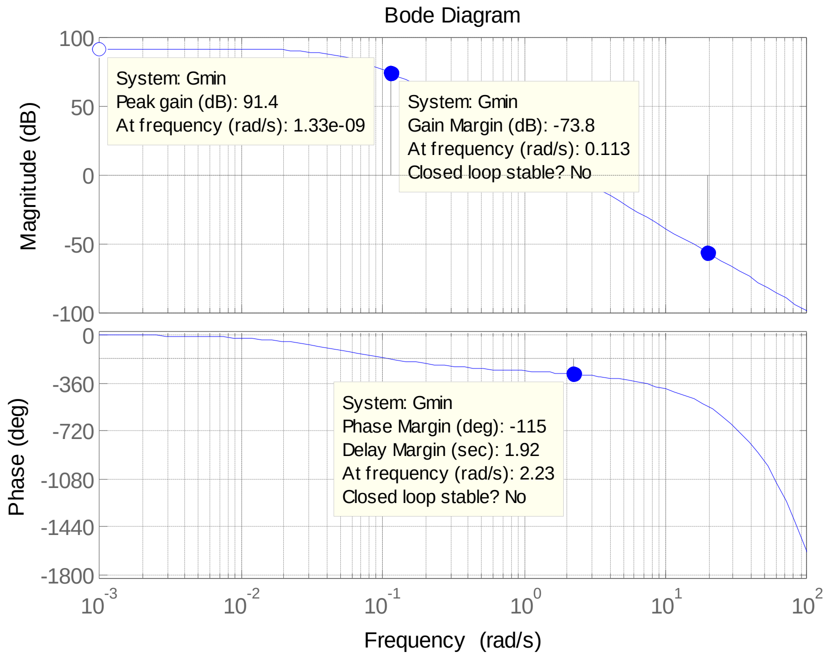

Figure 2: Bode plot for the minimum parameter value experiment

Table 2: Performance and stability functions values for minimum parameters

Performance and stability Functions	**Values**
Overshoot (%)	0
Settling time (sec)	113
Gain margin (dB)	-73.8
Phase margin (deg)	-115

For Mean parameters:

The simulation experiment results for the mean parameter as presented in figures 3 and 4 were summarized in table 3.

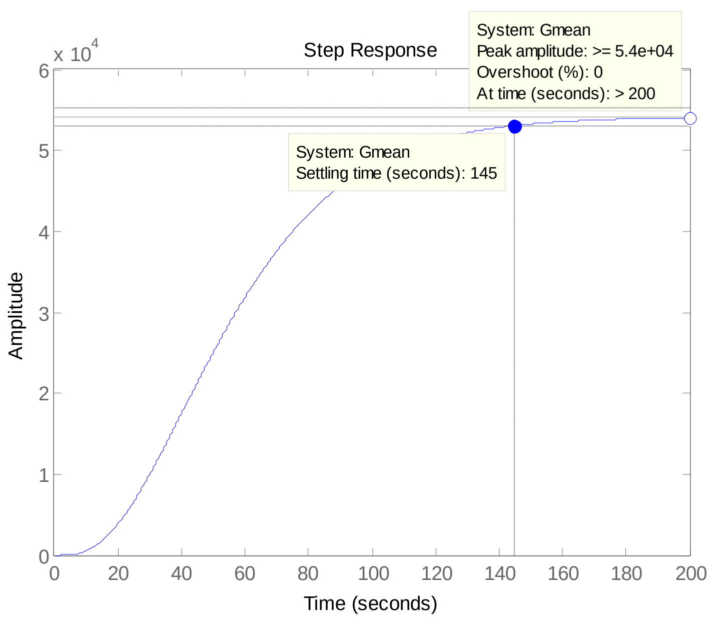

Figure 3: Step response of the heat exchanger model for the mean parameters

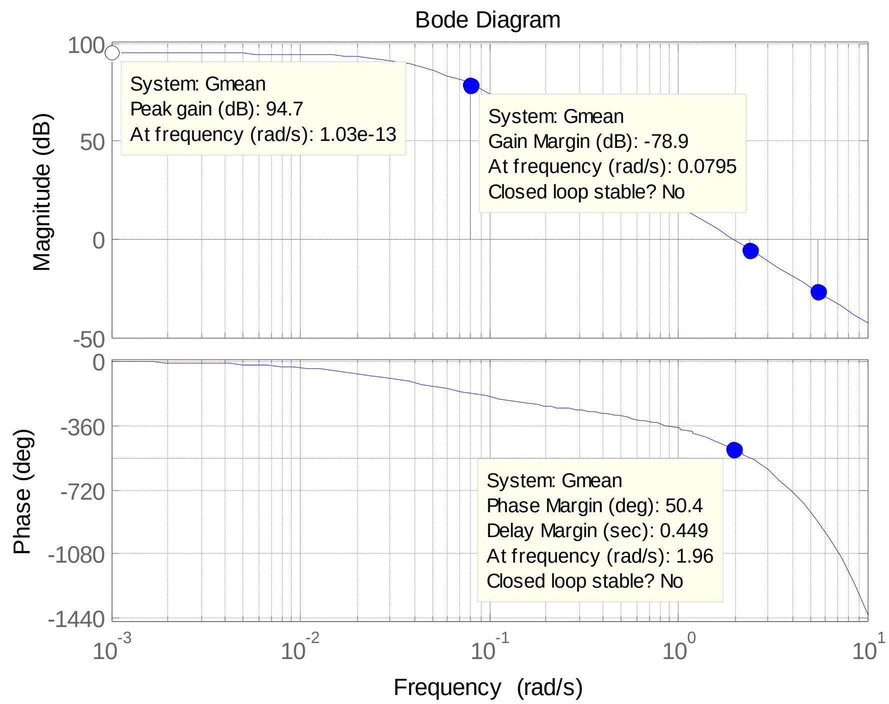

Figure 4: Bode plot for the mean parameter value experiment

Table 3: Performance and stability functions values for mean parameters

Performance and stability Functions	**Values**
Overshoot (%)	0
Settling time (sec)	145
Gain margin (dB)	-78.9
Phase margin (deg)	50.4

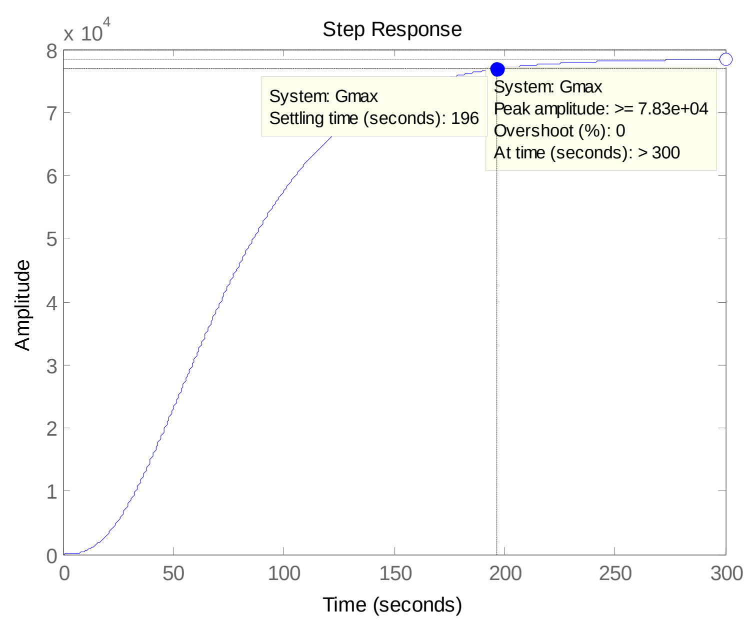

Figure 5: Step response of the heat exchanger model for the maximum parameters

For Maximum parameters:
The simulation experiment results for the maximum parameter as presented in figures 5 and 6 were summarized in table 4.

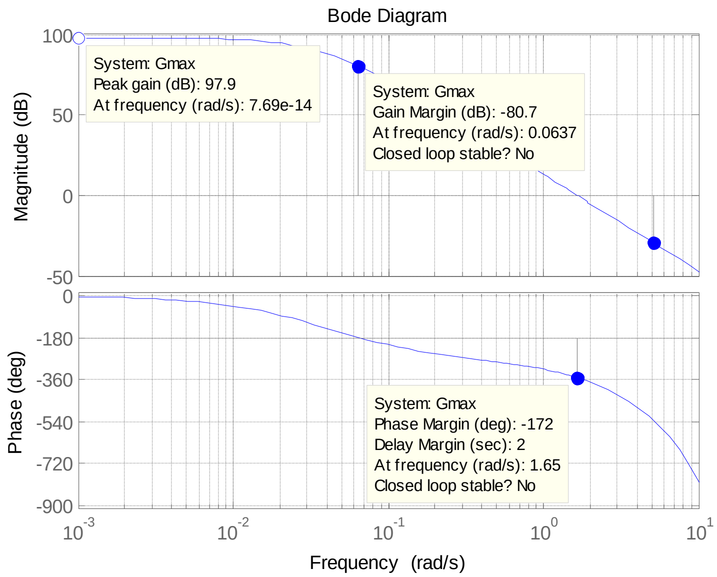

Figure 6: Bode plot for the maximum parameter value experiment

Table 4: Performance and stability functions values for maximum parameters

Performance and stability Functions	**Values**
Overshoot (%)	0
Settling time (sec)	196
Gain margin (dB)	-80.7
Phase margin (deg)	-172

The simulation results show that the system performance was poor with a high settling time and also the system is not stable for the three set of existing model parameter values as adopted and analyzed in this work.

4.0. Conclusion

The analysis of existing heat exchanger plant model parameters was successfully carried out based on time domain and frequency domain functions using step function input in MATLAB software. This was carried out in order to study the behavior of the heat exchanger system without a controller. The heat exchanger is a device that undertakes a very vital role in most production processes. It circulates calculated amount of heat in the larger system, which helps to reduce the number of heat sources in the system, thereby reducing the amount of emitted air pollutants and also cost of production. With its functions in the electric power generation, it continuously circulates amount of heat in the system. The extreme environmental conditions at the location of the heat exchanger and its heat management functions makes it more prone to suffer from parameter value changes and other forms of uncertainties.

From the simulation results of the heat exchanger model analysis, the system achieved good overshoot of 0% in the three scenarios of simulation experiments. However, it recorded settling time of 113sec, 145sec and 196sec respectively for the experiments. This means that its performance is very poor. The system recorded gain margin of -73.8dB, -78.9dB and -80.7dB respectively for the three experiments. It recorded phase margin of -115deg, 50.4deg and 172deg respectively for the three experiments. This means that the system did not satisfy the stability criteria and therefore is not stable for the three scenarios of model parameters.

An optimal control was therefore recommended in this work which can help to improve the performance of the system and also improve its stability based on the stability robustness specification. Since the system suffers from high level of uncertainties, it should be designed to be robust enough in order to function optimally even in the presence of model uncertainties and other extreme environmental conditions. The optimal controller improves performance and stability of a system by reducing or cancelling its reference tracking error and increasing the stability margins. Reference tracking error is the difference between the actual output and the desired output of the system, while stability margins are the gain and phase margins. These characteristics determine the performance and stability of the system.

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