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Design a robust quantitative feedback theory controller for cyber-physical systems: ship course control problem

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One of the most critical problems in all practical systems is the presence of uncertainties, internal and external disturbances, as well as disturbing noise, which makes the control of the system a challenging task. Another challenge with the physical systems is the possibility of cyber-attacks that the system's cyber security against them is a critical issue. The systems related to oil and gas industries may also be subjected to cyber-attacks. The subsets of these industries can be mentioned to the oil and gas transmission industry, where ships have a critical role. This paper uses the Quantitative Feedback Theory (QFT) method to design a robust controller for the ship course system, aiming towards desired trajectory tracking. The proposed controller is robust against all uncertainties, internal and external disturbances, noise, and various possible Deception, Stealth, and Denial-of-Service (DOS) attacks. The robust controller for the ship system is designed using the QFT method and the QFTCT toolbox in MATLAB software. Numerical simulations are performed in MATLAB/Simulink for two case studies with disturbances and attacks involving intermittent sinusoidal and random behavior to demonstrate the proposed controller.

Key words: quantitative feedback theory, Denial-of-Service, robust control, cyber-physical systems

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1. Introduction

One area often threatened by cyber-attacks is the oil and gas industry. The economies in many countries are highly dependent on the oil and gas field production. The research, therefore, needs to address the security threats to overcome this problem. Ships play an essential role in the oil and gas industry, and their security protection is critical [1]. Several attacks (such as DOS attacks, Deception attacks, Stealth attacks, etc.) can occur on the physical systems, which can cause interference with the system control process [2–5]. The DOS attack causes interference in sensors' reception and data transmission [6]. A Deception attack occurs on the plant and can involve stealing data and generating an error in the system data [7]. A Stealth Attack on sensors causes interference with the measurement process of the system [7]. Figure 1 shows the impact and location of attacks on a system.

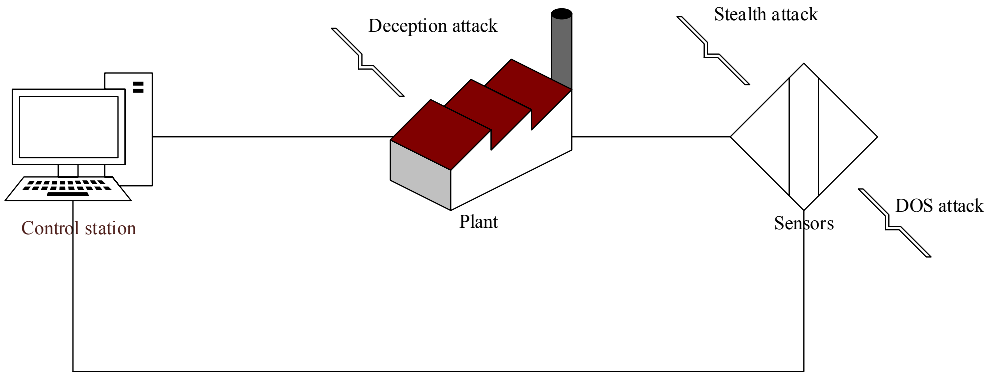

Figure 1: Various attacks in the physical systems

Cyber-Physical Systems (CPS) have become a critical issue with many groups having a malevolent intent [8–10]. This issue has been introduced as a branch of science by incorporating three science of control, communications, and computing [7]. Power systems, transportation systems, industrial networks, and communication systems involve such systems [11–15]. In [16], energy systems have been controlled using a hybrid adaptive law. In [17], the control of the Traffic Light has been investigated as a CPS application. In [18], the CPS control has been addressed with an application in smart grid and in [19], Multi-Agent Systems have been evaluated.

Uncertainties, internal and external disturbances, and measurement noise in most physical systems are unavoidable. Robust control methods are available to eliminate the effects of this type of phenomenon, such as Sliding Mode Control (SMC) [20–23], adaptive control [24–27] as well as H_2 and H_∞ methods [28, 29]. The SMC is one of the robust control methods which is used for control of different applications [30–33]. One of the studies in the field of robust control is published by Vesely and Osysky, in this study, two robust control methods are introduced which are useful for Single-Input-Single-Output and Multi-Input-Multi-Output systems [34]. In [35] an optimal control technique is presented. This method is tested for the robust control of an aircraft subject [35].

Quantitative Feedback Theory (QFT) method is a robust control method which has been used for the control of various systems. This method was introduced by Professor Isaac Horwitz in 1963 and has been developed extensively in recent years. In [36], the QFT has been used for controlling an under-actuated hovercraft system. In [37], the fourth-order boost DC-DC converter has been controlled by this method. In [38], the non-diagonal controller has been designed for multi-input and multi-output systems. In the third section of the article, this control method is described.

In this paper, a control system is designed using QFT to control the ship for reference trajectory tracking in the presence of various uncertainties, internal and external disturbances, noise, and cyber-attacks. Then, two illustrative examples are provided to illustrate the evaluation of the proposed controller.

The remainder of this note is organized as follows. The second section describes the ship system's model and problem. In the third section, the QFT method is briefly introduced. In the fourth section, the controller for the ship system is designed. The fifth section tests the proposed controller in two modes of intermittent sinusoidal and random attacks, disturbances, and noises using MATLAB/Simulink. Finally, conclusions are drawn in the last section.

2. Ship cyber-physical system

2.1. Ship model

In [39–41], the Nomoto model ship system has been presented as follows

$$T\ddot{\psi} + \dot{\psi} = K\delta\,, \tag{1}$$

where T is the set of time constants, and K is the system gain. δ is the control input, and ψ is the pitch angle of the ship. The transfer function of the system can be written as follows

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1+Ts)}\,. \tag{2}$$

The uncertainties of the system parameters are as $T \in [-107.59\ \ -199.81]$, $K \in [-0.0133\ -0.0247]$, and their nominal values are $T_0 = -153.7$, $K_0 = -0.019$.

2.2. Attacks, internal and external disturbances

In addition to the uncertainties described in the previous section, it is assumed that the proposed system is subjected to internal and external disturbances, noises, Deception, Stealth, and DOS attacks. This study aims to design a robust controller against all these attacks, disturbances, and noises using the QFT approach (see Fig. 2).

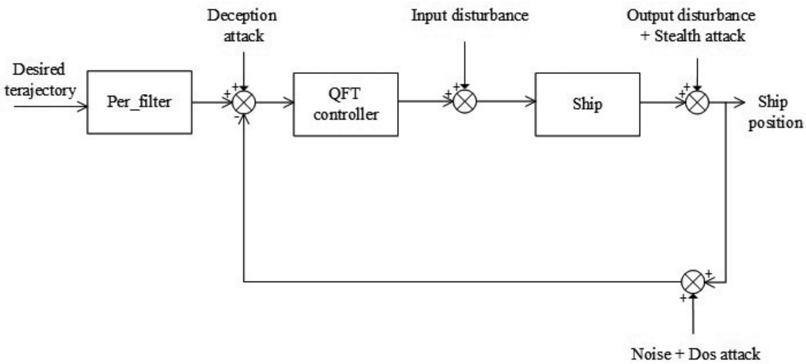

Figure 2: Ship system in the presence of a variety of disturbances and attacks

As shown in Fig. 2, various attacks and disturbances are considered. The controller and pre-filter are designed using the QFT control method to track the reference path and be robust against uncertainties, disturbances, noise, and various types of attacks.

The model considered for the external disturbances, noises, and possible attacks is described in (3).

$$\begin{cases} \text{Input disturbances + Deception attack} = \dfrac{1}{0.107s^2 + 13.91s + 107}, \\ \text{Output disturbances + Stealth attack} = \dfrac{s}{s+2}, \\ \text{Noise + DOS attack} = \dfrac{1}{138.3s + 1}. \end{cases} \tag{3}$$

Assuming the conditions stated, the controller and pre-filter for the ship system are designed by the QFT method in the next section.

3. Quantitative Feedback Theory (QFT) method

The QFT control method is a robust method for controlling physical systems. This method was presented by Horwitz in 1963 and has been developed in subsequent years [42]. The Nichols charts are fundamental concepts for designing the QFT controllers. It makes it possible to design controllers that are robust against all kinds of noises, disturbances, and uncertainties [43]. The design by using the QFT method is step-by-step and has a regular design procedure.

The QFT method is based on system's phase and frequency. Initially, this control method was developed for Single-Input and Single-Output (SISO) systems. Horwitz and colleagues then generalized it to various non-linear systems, Multi-Input and Multi-Output (MIMO) systems, delayed systems, etc. [44].

To design the controller using the QFT method, the following steps usually are followed [45]:

a) Determine the models of the desired tracking.

b) Determine the models of the desired behavior of disturbances.

c) Determine the set of system models that model system behavior for uncertain parameters.

d) Specify the appropriate frequency range and plot uncertainty templates in the Nichols chart.

e) Choose the nominal transfer function of the system

f) Determine the boundary of system stability on the Nichols chart.

g) Determine the tracking bound on the Nichols chart.

h) Determine the disturbance bounds on the Nichols chart.

i) Insert the desired bounds on the Nichols chart.

j) Design of the nominal loop transfer function.

k) Design the pre-filter.

l) Analysis of the resulting design.

The steps above have become more accessible by using the recently developed toolboxes. Professor Mario Garcia-Sanz introduced the toolboxes such as QFT and QFTCT. This paper uses the QFTCT toolbox to perform the above steps.

4. Design QFT controller for ship CPS

In this section, the twelve design steps for the QFT method are followed for the ship system, and the QFTCT toolbox is used to simulate the steps.

Step 1: Determine the models of the desired tracking

The considered tracking models for the ship system in this paper are as Eq. (4)

$$T_{R_U} = \frac{0.6584s + 19.753}{s^2 + 4s + 19.753}, \qquad T_{R_L} = \frac{120}{0.02s^4 + 1.34s^3 + 18.64s^2 + 84.4s + 120}. \tag{4}$$

Step 2: Determine the models of the behavior of disturbances.

The desired models are defined in Eq. (3).

Step 3: Determine the set of system models which model all system behaviors for uncertain parameters.

This set is described in Eq. (2) and the subsequent description.

Step 4: Specify the appropriate frequency range and plot uncertainty templates in the Nichols chart.

The considered frequency range for the design is as $\omega \in [0.001, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 50, 100, 1000]$. The uncertainty templates are plotted as the Fig. 3.

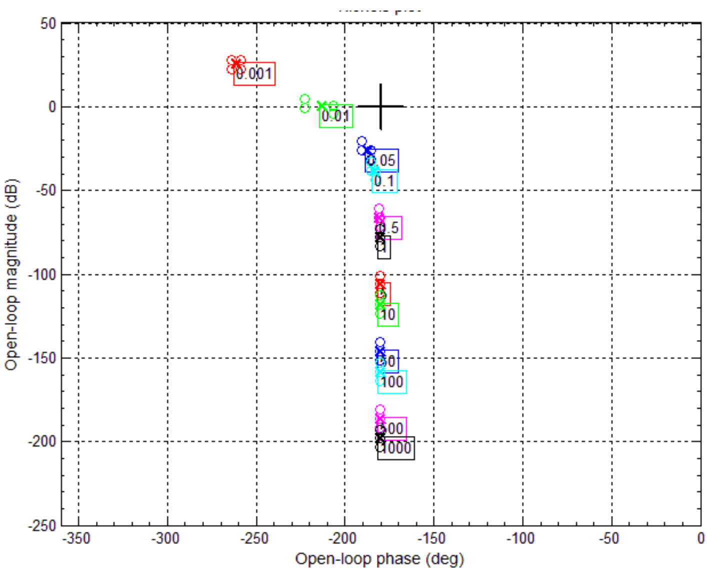

Figure 3: Ship system templates at desired frequency points

Step 5: Choose the nominal system transfer function.

The nominal ship transfer function is as $P_0(s) = \dfrac{-0.019}{s(-153.7s + 1)}$.

Steps 6 to 9: Determine the desired bounds on the Nichols chart. By assuming robust stability bound equal to 1.36, in consequence, the gain margin and the phase margin are as Gain-Margin = 2.5 dB, Phase-Margin = 43 degree. Optimal bounds are shown in Fig. 4.

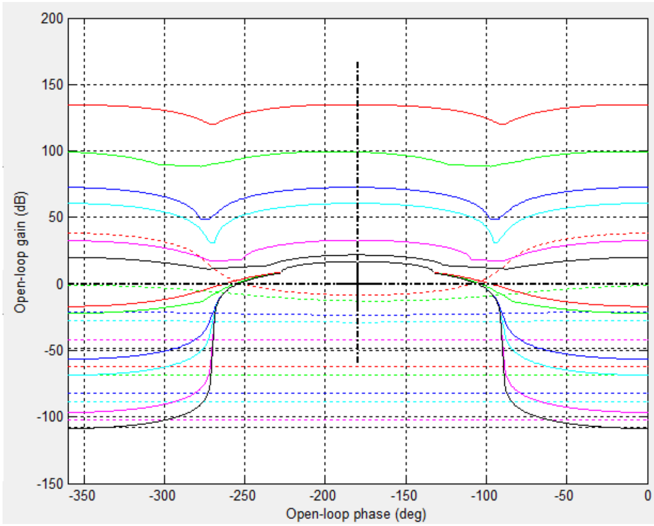

Figure 4: Desired bounds

Step 10: Design of the nominal loop transfer function. The nominal ring transfer function is designed as follows:

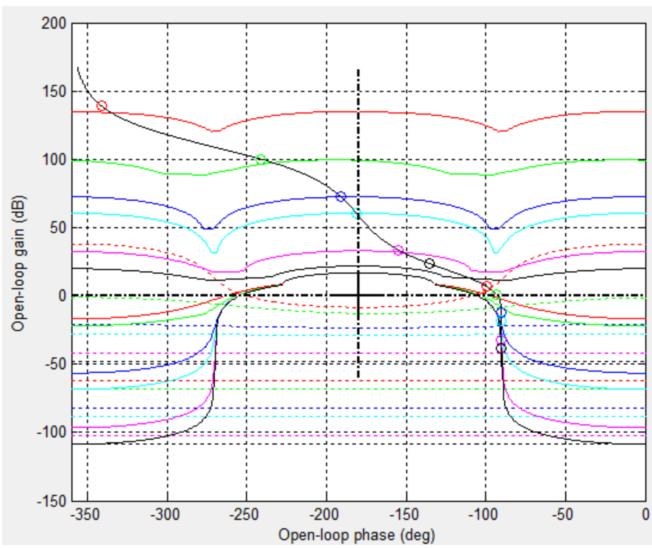

Figure 5: The nominal ring transfer function

As a result of this design, the QFT controller is obtained as Eq. (5).

$$C(s) = \frac{\left(9.717s^3 + (1.058 \times 10^5)s^2 + 2.144s + (5.734 \times 10^{-6})\right)}{(8.61 \times 10^{-5})s^3 + s^2 + 2s}. \tag{5}$$

Step 11: Design the pre-filter

The pre-filter is designed as shown in Fig. 6.

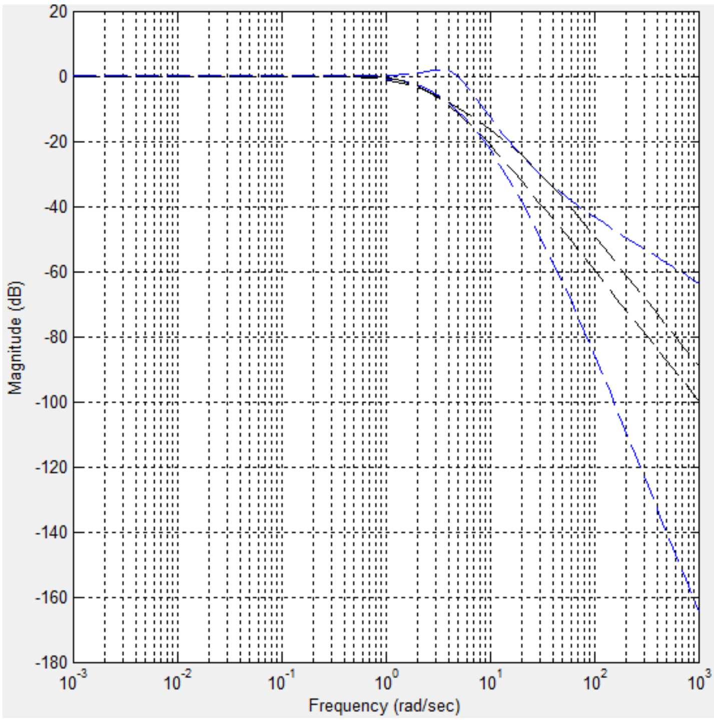

Figure 6: The designed pre-filter

As a result of this design, the pre-filter equation is obtained as follows:

$$F(s) = \frac{1}{2.4306} \times \frac{1}{(6.414{\times}10^{-10})s^3 + (9.745{\times}10^{-6})s^2 + 0.03707s + 0.411}. \tag{6}$$

Step 12: Analysis

For analysis of the designs, the Nichols Chart, the system stability response, and step response of the selected reference trajectory tracking are shown in Figs. 7 and 8, respectively.

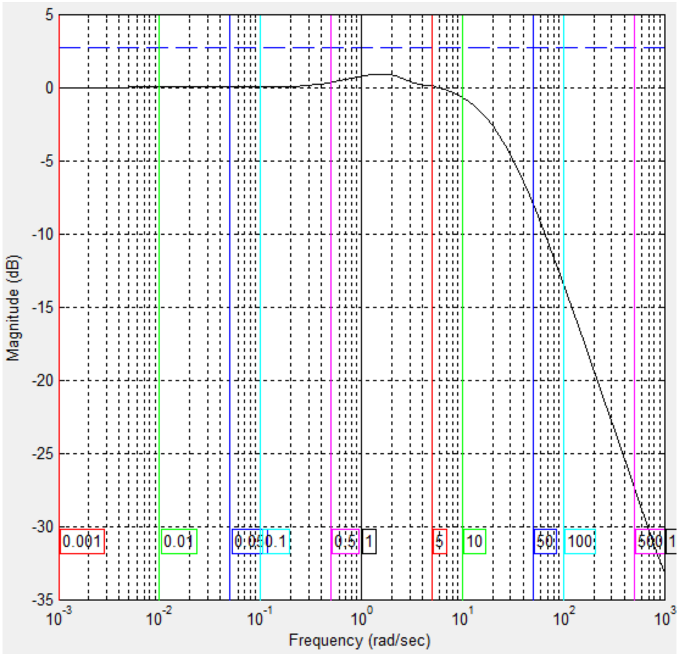

Figure 7: The Nichols Chart the system stability response

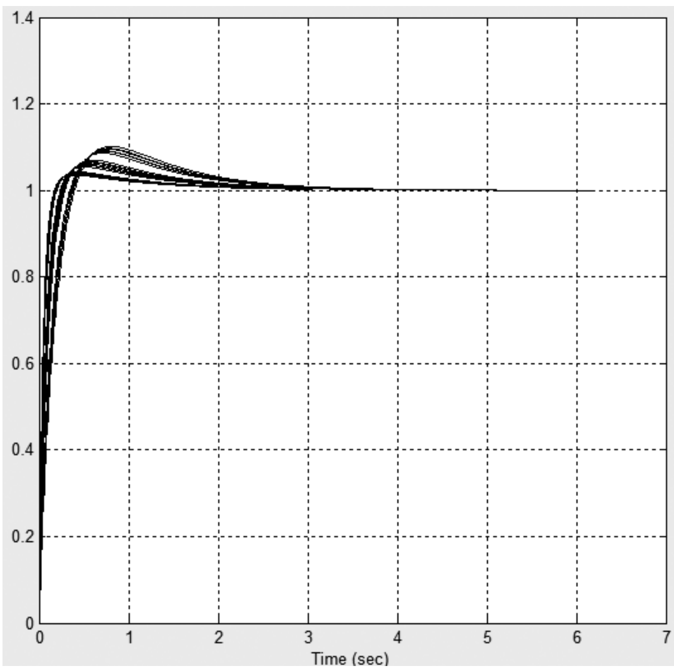

Figure 8: Step response of the reference trajectory tracking

5. Two case studies

This section aims to conduct the numerical simulation in MATLAB/Simulink with the numerical solver ode14x for the ship system and consider the above designs (previous section). The disturbances, noises, and attacks are considered in two modes intermittent and random. Also, the simulation is performed for one of the modes of the uncertainties. For simulation, the system transfer function is assumed as: $\frac{\psi(s)}{\delta(s)} = \frac{-0.0133}{-107.59s^2 + s}$ and the reference input is as $\psi_d = \sin(0.1t) + \cos(0.2t)$.

5.1. First case study

For the first case study, the simulation is performed by considering intermittent mode for the noises, disturbances, and attacks. The model of noises and disturbances and attacks are chosen in the form of Eq. (7)

$$\begin{cases} \text{Deception Attack} = 0.01\sin(0.01t), \\ \text{Input Disturbances} = 0.02\sin(0.3t), \\ \text{Output Dis} + \text{Stealth Attack} = 0.01\sin(0.2t), \\ \text{Noise} + \text{DOS Attack} = 0.01\sin(0.5t). \end{cases} \tag{7}$$

Figure 9 represents the reference trajectory tracking along with the ship trajectory. Figure 10 shows the disturbances, noise, and attacks.

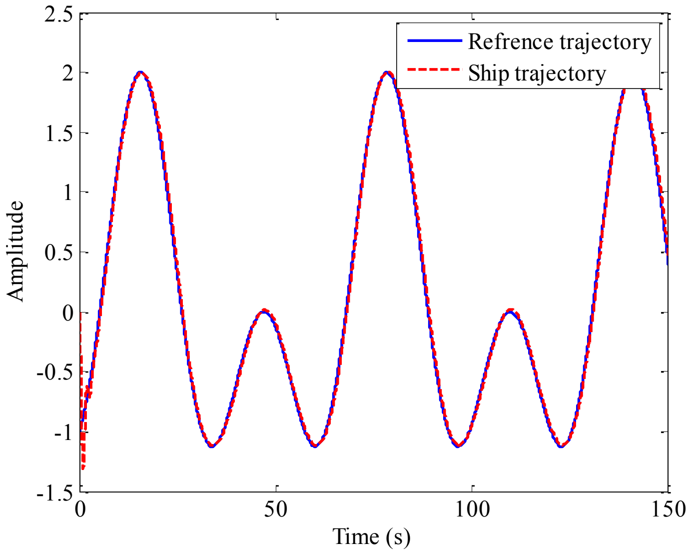

Figure 9: The ship trajectory with the intermittent sinusoidal model of the disturbances and noises and attacks

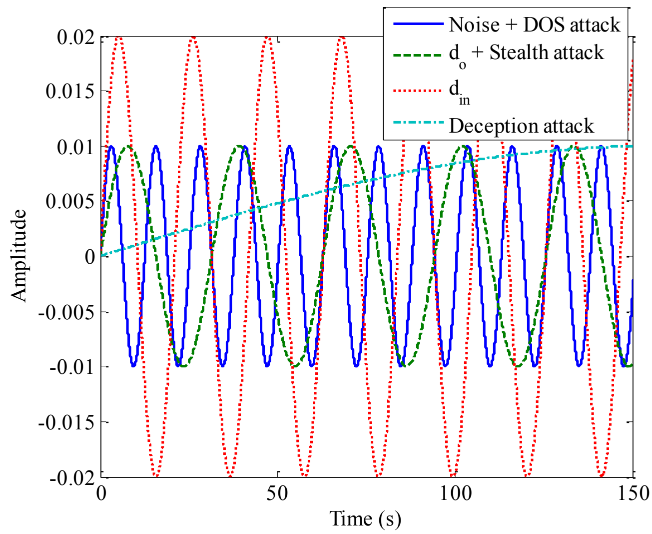

Figure 10: The noises and disturbances, and attacks of the first case study

5.2. Second case study

For the second case study, the numerical simulation is performed for the ship system with the random mode of the noises and disturbances and attacks. Figure 11 shows the reference trajectory tracking along with ship trajectory. Figure 12 represents the noise, disturbances and attacks.

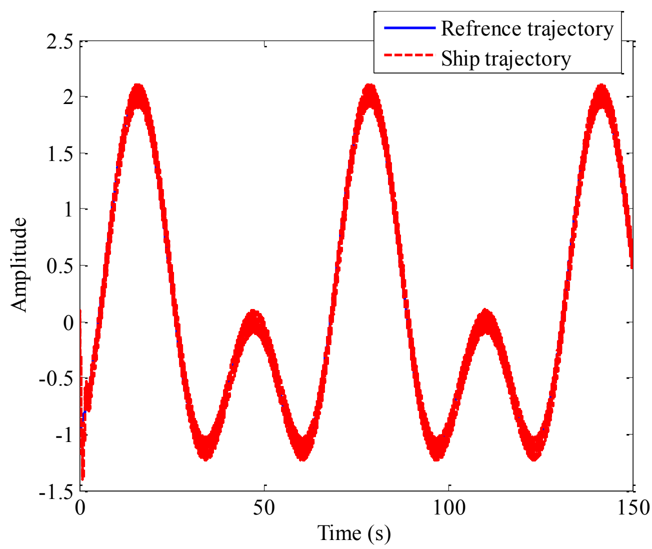

Figure 11: The ship trajectory with the random mode of the disturbances and noises and attacks

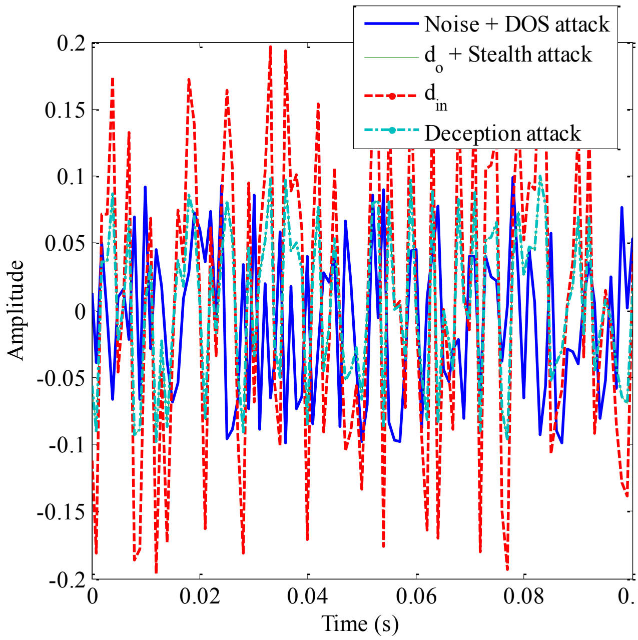

Figure 12: The noises and disturbances, and attacks of the second case study

6. Conclusions

In this paper, a robust controller is designed using the QFT design method for a ship system in the presence of noise, disturbances, and cyber-attacks. The proposed ship system has parametric uncertainties. The proposed controller is tested in two modes, intermittent and random, of the noise, disturbances, and attacks. After designing the controller and pre-filter by the QFT method, as expected from the tracking response stage, the system can track the reference trajectory tracking precisely, which was the objective. The system was subjected to three types of DOS, Stealth and Deception attacks, various types of internal and external disturbances, and noise. The robust controller proposed for the system dealt well with all these uncertainties. Two illustrative examples were presented using MATLAB/Simulink.

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