Hindawi
Shock and Vibration
Volume 2019, Article ID 3818539, 9 pages
https://doi.org/10.1155/2019/3818539

Research Article

A New Scheduling Quantitative Feedback Theory-Based Controller Integrated with Fault Detection for Effective Vibration Control

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Received 4 March 2019; Accepted 31 March 2019; Published 7 May 2019

Academic Editor: Mario Terzo

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In this work, a new integrated fault detection and control (IFDC) method is presented for single-input/single-output systems (SISOs). The idea is centered on comparing the closed-loop output between the faulty system and fault-free one to schedule/switch the feedback control once the fault occurs. The problem addressed in this work is the output disturbance rejection. The set of feedback controllers are designed using quantitative feedback theory (QFT) for fault-free and faulty systems. In the context of QFT-based IFDC, the proposed active approach is novel, simple, and easy to implement from an engineering point of view. The efficiency of the proposed method is assessed on a flexible smart structure system featuring a piezoelectric actuator. The actuator and sensor faults considered are the multiplicative type with both fixed and time-varying magnitudes. In the fixed magnitude fault case, the actuator/sensor output delivering capability is reduced by 50% (multiplying a factor of 0.5 to its actual output), while in the time-varying magnitude case, it becomes 60% to 50% for a particular time interval. In both cases, the proposed control method identifies the fault and activates the required controller to satisfy the specification with less control effort as opposed to the passive QFT design featured by faulty system design alone.

1. Introduction

It is necessary to design control systems that are reliable, fault tolerant, and safe operation of modern and advanced technological systems including flexible structures. The goal of fault-tolerant control systems (FTCSs) is to maintain the performance and stability in the presence of system and sensor/actuator faults. There are two approaches known in the literature such as the passive and active methods, respectively [1]. In passive FTCSs, the design is performed offline using the robust control methods with respect to uncertainty and faults. Active FTCSs involve automatic controller reconfiguration (or) switching mechanism using a fault detection and identification (FDI) module. The passive FTCSs can result in very conservative design during the fault-free phase, especially when the hardware is fully checked a priori by the engineer before start-up [2]. And also when the number of fault scenario increases, the passive FTCSs performance become less and less effective for each fault [3]. This is the main motivation for the active method-based FTCS designs. Active FTCSs use a model-based FDI strategy which has received increasing attention in recent years [1, 3]. A model-based FDI uses a mathematical model of the system and online measurement to draw conclusions about the faults on the system. The core concept of a model-based FDI is to generate a so-called "residual" which are signals that are zero in the fault-free case and nonzero otherwise [4]. In practice, the system is uncertain and the characteristics of the disturbances/noise are unknown, so the residuals are never zero [5]. One of the widely adopted approaches is to choose a so-called threshold value for the fault detection (FD) purpose [6, 7]. This enables us to make a reliable decision in the sense that the false alarm rate due to the model uncertainty/disturbances becomes small. These steps are known as residual generation and evaluation in an FDI module [1, 5]. In [8], the robust dissipative FTC of a discrete time system is addressed. Recently in [9], a randomly occurring actuator fault in complex dynamical networks is considered. It is noted here that the idea to identify the state between the fault-free and faulty model is to monitor the closed-loop output. If the closed-loop output is within the user-defined tolerance, the considered model is a fault-free model.

In this work, the problem of integrated fault detection and control is addressed using quantitative feedback theory (QFT). Basically, QFT is a frequency-domain-based robust control method and uses two-degree-of-freedom (2-DOF) structure to satisfy the performance specifications such as robust tracking/disturbance rejection and also robust stability requirements [10]. The main objective of QFT is to reduce the effects of plant parametric uncertainties with the help of feedback. And the amount of feedback is directly related to the extent of plant uncertainty and unknown external disturbances. The plant uncertainties may be the result of modeling error or linearization of a plant around different operating conditions and/or occurrence of faults. Both QFT and H_∞ performance problems have a common design philosophy except one significant difference being in the representation of uncertainty [11]. The inherent conservatism in H_∞-based design can lead to high-order controller design unlike the QFT-based low-order controller (use of both loop gain and phase in the loopshaping). So far, QFT has successfully been applied to many engineering applications [11–17]. For the past few decades, QFT-based FTC has drawn considerable attention in the QFT community. A brief review of the existing literature relating the QFT-based passive and active FTCSs is now presented. The QFT-based passive FTCS has been applied to a flight control system with the control surface damage [18, 19]. QFT-based position controller design for an electrohydraulic actuator (EHA) with a faculty position sensor and servo valve is presented in [20]. They account the sensor calibration gain fault by using redundant sensors. A passive QFT-based fault-tolerant position controller is designed for the servo-hydraulic positioning system in the presence of fluid leakage across the actuator piston seal. Recently, another application of QFT to passive FTC is presented for the position control of EHA with a faulty cylinder position seal in [21]. They further designed a QFT-actuating pressure controller for an EHA system with a leaky piston seal [22]. For a comprehensive list of QFT-based FTC work, the reader can refer the papers given in the reference of [21–23]. As far as the application of QFT to active FTC design is concerned, the work in [23] proposed a fault tolerant QFT position controller for electrohydraulic actuators against actuator piston fault. The idea is to design a bank of QFT controllers for the multiple linear models obtained from different leakage levels (piston orifice area) and then apply the aggregated control action by switching based on the smooth Gaussian function. It is remarked that multiplicative type of faults such as actuator and sensor faults are handled by the proposed fault model. In practice, the actuator delivering capability is reduced either by internal or external fault. Similarly, the sensor readings can be erroneous due to internal or external fault.

In fact, the idea of FDI-based QFT was initiated in [24]. The approach is centered on designing the feedback controller to satisfy the robust performance/stability at low-frequency range and maximize the faults (actuator/sensor) for FD purpose at the high-frequency range where the faults are likely to be concentrated. The FD filter design is posed as a model matching problem wherein the filter has to track the prespecified residual reference model. The main difficulty is the selection of the reference model of significant physical meaning for the FD point of view [6]. On the contrary, the study on the integrated fault detection (IFD) and QFT-based control for the multivariable system was undertaken in [2]. In this work, FD objective has been formulated as a constraint on sensitivity maximization over the high-frequency range wherein the fault energy is concentrated. In particular, the sensitivity function with a multiplicative fault (actuator/sensor) was chosen for the fault direction. It has been shown that control performances are fair, but the limitation of the formulations occurred in terms of the feedback cost in the high-frequency gain which can cause excessive control effort. Therefore, in order to resolve the above limitation, a novel IFDC method is proposed in this work. Consequently, the main technical contributions are summarized as follows:

(i) A novel IFDC with scheduling QFT is proposed for SISO uncertain system to solve the output disturbance rejection problem.

(ii) The faults are detected based on the difference between the closed-loop response of the faulty system and fault-free system (or) tolerance whichever is maximum. To the best of the author's knowledge, the proposed approach is first of its kind wherein the systematic integration of IFDC with the scheduling QFT controller is presented.

(iii) A flexible smart structure system is used to demonstrate the effectiveness of the proposed approach. Both actuator and sensor multiplicative faults with fixed and varying magnitude are considered for vibration control.

(iv) The stability of the scheduling QFT controller is analyzed using the existing frequency-domain condition. The proposed method gives the less control effort with the better vibration-control performance as compared to the QFT-based passive FTC.

The paper is organized as follows. Section 2 states the problem statement and key components of the proposed IFDC followed by the frequency-domain stability condition for the scheduling/switching controller. The proposed design procedure for IFDC is given in Section 3 with the validation example of the smart flexible structure featuring the piezoelectric actuator and sensor. Section 4 presents control results with comparative works between the proposed method and existing approach in the time domain. The conclusion of the work is drawn in Section 5.

2. Problem Formulation

The problem to be solved is closed-loop stability and limit cycle avoidance in systems with actuator input amplitude saturation taking into account uncertainty in the plant. The problem to be solved is output disturbance rejection/stability and fault detection in systems taking into account uncertainty in the plant. Our method can be viewed as a complement to [2, 24].

The following specifications are considered for the QFT-based feedback controller design.

2.1. Robust Stability. The robust stability of the closed-loop system with the fault is ensured by designing the feedback controller such that the nominal loop transmission function ($L_0 = k_a k_s P_0 G_f$) does not penetrate the universal high frequency bound at $\omega = [0, \omega_h]$:

$$\left|\frac{k_a k_s P G_f}{1 + k_a k_s P G_f}\right| \le W_s, \quad \forall P \in \mathscr{P}, \ \omega \in [0, \omega_h], \tag{1}$$

where k_a and k_s represent the actuator and sensor fault magnitude, respectively.

2.2. Robust Output Disturbance Rejection. The closed-loop output disturbance transfer functions should fall below a priori defined disturbance specification within $[0, \omega_l]$ in order to minimize the effects on the output. The closed-loop system should satisfy the following inequality:

$$\left|\frac{1}{1 + k_a k_s P G_f}\right| \le B_d, \quad \forall P \in \mathscr{P}, \ \omega \in [0, \ \omega_l]. \tag{2}$$

For the fault-free case, the actuator and sensor fault magnitudes become $k_a = k_s = 1$ in the specification inequalities (1) and (2).

The key component of the proposed approach is fault detection. The concept involved for fault detection here is simple and direct one. From the specification (2), the closed-loop output response always lies below a user-defined tolerance (B_d) for any plant element from the uncertainty ($\mathscr{P}$). So, the idea is to compare the maximum of the tolerance (B_d) and the worst case fault-free closed-loop output (y_{max}) with that of the actual closed-loop system (y_f). If the actual output is more than the maximum of (B_d, y_{max}), then the fault occurs otherwise there is no fault. The reason for considering the maximum of (B_d, y_{max}) instead of B_d alone is that the worst case output (fault-free system), sometimes, may exceed the tolerance B_d by a very small value especially at the steady state. This is due to the fact that there is no direct translation from the frequency domain to the time domain and vice versa [10]. Because of this, the chances of detecting this as a fault become satisfactorily small due to the model uncertainty. The goal of robust residual evaluation in FDI also emphasizes this point of reliable decision-making [5].

The following condition captures the proposed idea for the IFDC:

$$\begin{aligned} &\text{If } y_f > \max(B_d, y_{max}) \Longrightarrow \text{fault} \Longrightarrow \text{controller} = G_f, \\ &\qquad\qquad \text{else} \Longrightarrow \text{no fault} \Longrightarrow \text{controller} = G, \end{aligned} \tag{3}$$

where y_f and y_{max} are denoted as faulty and fault-free (worst case) closed-loop outputs, respectively. And the corresponding feedback controllers are denoted as G and G_f, respectively. This is similar to the model-based FDI wherein residual generation and evaluation is used to identify and isolate the faults. But, here we use it for scheduling/switching between the feedback controllers in order to reduce the fault effect on the output as opposed to the FD purpose (switch ON the alarm) alone.

In this work, we consider the multiplicative fault (actuator/sensor) as it affects the stability of the closed-loop system depending on its size. So, the stability of the closed loop can be analyzed using the following result from the paper [25] for the switching controller. The stability of the two closed-loop systems with tracking transfer functions $T_1(s) = L_1(s)/1 + L_1(s)$ and $T_2(s) = L_2(s)/1 + L_2(s)$ under switching is given by the following inequality:

$$\left|\arg\{1 + L_2(j\omega)\} - \arg\{1 + L_1(j\omega)\} + \arg\left\{\frac{D(j\omega) + \Delta\, D(j\omega)}{D(j\omega)}\right\}\right| < \frac{\pi}{2}, \tag{4}$$

where the loop transmission function of systems 1 and 2 are denoted by $L_1(s) = N(s)/D(s)$ and $L_2(s) = N(s) + \Delta N(s)/D(s) + \Delta\, D(s)$, where $N(s)$ and $D(s)$ denotes the numerator and denominator polynomials, respectively.

Remark. In QFT, the tolerance (B_d) can be specified as a discrete magnitude (dB) at each discrete performance frequency. Condition (3) checking to identify the fault becomes difficult one as it is required to compare the output continuously. To resolve this issue, it is suggested to compare the magnitude of y_{max} with y_f.

3. Design Procedures for IFDC

3.1. Design of Feedback Controller Using QFT Principle. Design a set of linear feedback controllers (G and G_f) for fault-free and faulty systems, respectively, to satisfy the desired specifications (step 1) using the loopshaping technique. The nominal loop transmission function (fault-free case, $L_0 = P_0 G$ and faulty case $L_{0f} = k_a k_s P_0 G_f$) is shaped such that it should lie on or above the open bounds (performance bounds) and lies outside the closed (stability) bounds at each design frequency. For this purpose, MATLAB QFT toolbox [26] or QFTCT software [27] provides an interactive environment.

3.2. Integrated fault Detection and Control. Next, the actual closed-loop system (with controller G) output is continuously compared with the maximum of (B_d, y_{max}), as explained in Section 3 to identify the faults. Once the fault occurs, then activate the controller G_f into the feedback loop. The proposed design strategy is shown in Figure 1.

In order to implement the proposed control method, vibration control of systems [28–31] associated with the piezoelectric actuator and sensor is considered. Especially, to clearly represent the external disturbance, vibration control of a flexible smart structure system shown in Figure 2 is adopted in the work [32].

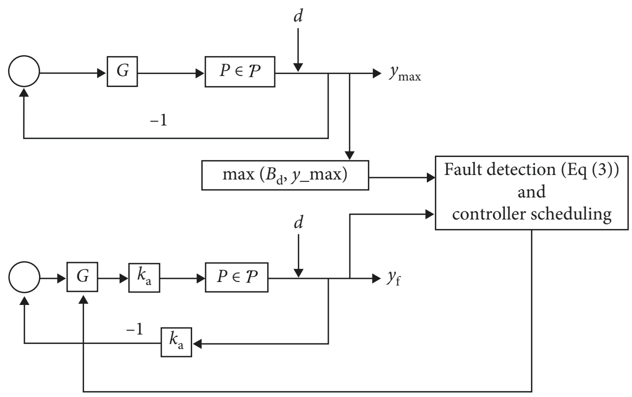

Figure 1: Proposed integrated fault detection and control.

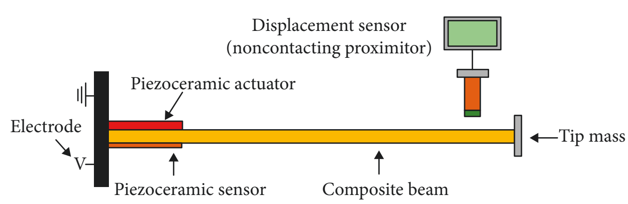

Figure 2: Schematic diagram of the smart structure.

A flexible cantilevered composite beam (glass/epoxy) has the piezoactuator bonded on its upper surface, while the piezosensor on the other surface as a colocated pair. A noncontacting displacement sensor (proximitor) is used to measure the output displacement. For a complete description about the plant modeling and the mechanical properties of the smart structure, readers can refer the paper [32]. In this study, we consider the first and second flexible modes while designing the QFT controller. The plant transfer function which relates the control voltage (input) and the displacement (output) is given by

$$P(s) = \frac{k\left(\left(s^2/\omega_3^2\right) + \left(2\xi_3 s/\omega_3\right) + 1\right)}{\left(\left(s^2/\omega_1^2\right) + \left(2\xi_1 s/\omega_1\right) + 1\right)\left(\left(s^2/\omega_2^2\right) + \left(2\xi_2 s/\omega_2\right) + 1\right)}, \tag{5}$$

where $k \in [0.2, 0.8]$, $\omega_1 \in [30, 36]$, $\omega_2 \in [121.6, 122.7]$, $\omega_3 \in [71.5, 80]$, $\xi_1 \in [0.03, 0.044]$, $\xi_2 \in [0.09, 0.11]$, and $\xi_3 \in [0.05, 0.059]$. The chosen design frequency set $\omega = [0.1, 0.25, 0.5, 1, 1.5, 2, 3, 5, 10, 20, 30, 50, 71.5, 100, 122, 500, 1000]$. The following design specifications are considered.

3.3. Robust Stability Margin. The closed-loop system with fault is robustly stable provided it satisfies the M-circle magnitude of 1.6 dB, and this is specified as

$$\left|\frac{k_a k_s P(j\omega) G_f(j\omega)}{1 + k_a k_s P G_f}\right| \leq 1.6\,\text{dB}, \quad \forall P, \forall \omega. \tag{6}$$

3.4. Robust Output Disturbance Rejection. The closed-loop should reject the effects of the output disturbance or fault within 2 sec, and it is captured as

$$\left|\frac{1}{1 + k_a k_s P(j\omega) G_f(j\omega)}\right| \leq B_d = \left|\frac{j\omega}{j\omega + 2.5}\right|, \quad \forall P,\ \omega \in [0,\ 2]. \tag{7}$$

As mentioned in Section 2, for the fault-free system, $k_a = k_s = 1$ in the above specification inequalities (6) and (7). Fault magnitude affects the actuator/sensor output delivering capabilities. We consider the multiplicative fault magnitudes of the actuator and sensor vary as $k_a \in [0.4, 0.6]$ and $k_s \in [0.4, 0.6]$, respectively. This implies that the actuator can deliver 40 to 60% of the demanded control input. And, the sensor can give the correct measured signal (y_m) 40 to 60% due to the calibration or gain drift or any wear and tear.

4. Feedback Controller Design

4.1. Fault-free System. After formulating the desired specifications, the feedback controller design is carried out for the fault-free system. For this purpose, the closed-loop specifications (inequality (6)-(7) with $k_a = k_s = 1$ and $G_f = G$) are translated into a set of bounds on the nominal loop transmission function (L_0) at each design frequency. The feedback controller (G) is designed by adding the poles/zeros and complex poles/zero such that the L_0 lies on or above the open bounds (disturbance rejection specification) and outside the closed bounds (stability margin) as shown in Figure 3. The designed controller is given as follows:

$$G(s) = \frac{13.5\left(\left(s^2/233.5^2\right) + \left((2 \times 0.189s)/233.5\right) + 1\right)\left(\left(s^2/27.89^2\right) + \left((2 \times 0.1992s)/27.89\right) + 1\right)}{\left(\left(s^2/188^2\right) + \left((2 \times 0.3126s)/188\right) + 1\right)\left(\left(s^2/3490^2\right) + \left((2 \times 0.6715s)/3490\right) + 1\right)}. \tag{8}$$

4.2. Faulty System. The bounds are generated by converting the closed-loop specifications (inequality (6)-(7)) at each design frequency. The nominal loopshaping is carried out to design the fault tolerant controller (G_f) as shown in Figure 4. The feedback controller respects the bounds at each design frequency and given as follows:

$$G_f(s) = \frac{83\left(\left(s^2/233.5^2\right) + \left((2 \times 0.189s)/233.5\right) + 1\right)\left(\left(s^2/27.89^2\right) + \left((2 \times 0.1992s)/27.89\right) + 1\right)}{\left(\left(s^2/188^2\right) + \left((2 \times 0.3126s)/188\right) + 1\right)\left(\left(s^2/3490^2\right) + \left((2 \times 0.6715s)/3490\right) + 1\right)}. \tag{9}$$

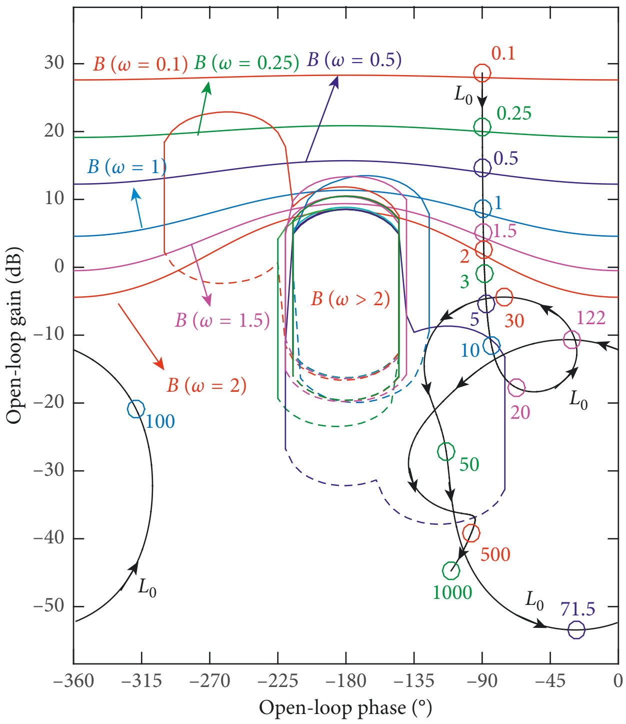

FIGURE 3: The nominal loopshaping plot for a fault-free system. B (ω) denotes the bounds at each design frequency ω.

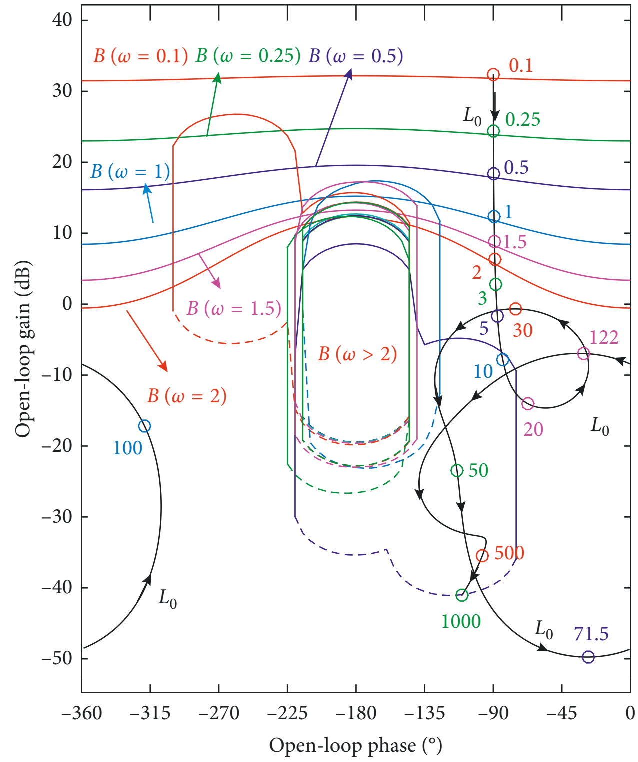

FIGURE 4: The nominal loopshaping plot for a faulty system. The bound at each design frequency ω is represented as B (ω).

Here, the controller (G_f) gain is more than the fault-free controller (G) gain in order to accommodate both the fault effect and disturbance rejection on the output as opposed to the disturbance rejection specification alone.

5. Controller Validation

5.1. Frequency-Domain Validation. The frequency-domain validation of the designed closed-loop system with/without fault is shown in Figure 5. Here, the worst case of the closed-loop system satisfies the tolerance (B_d) at each performance design frequency $\omega \in [0,\ 2]$.

5.2. Scheduling/Switching Stability Condition. To analyze the stability of the closed-loop system while switching the controller when the fault occurs, the condition (inequality 4) is verified as shown in Figure 6. The condition is satisfied for every design frequency, so we can conclude the system under switching/scheduling is stable.

5.3. Time-Domain Validation. Two cases of multiplicative faults (actuator/sensor) are considered for the performance evaluation, i.e., fixed magnitude fault and varying magnitude faults. In the fixed magnitude fault, the actuator and sensor fault magnitudes are constant, i.e., $k_a = k_s =$ constant. Time-varying faults (at sensor/actuator) are introduced by varying the magnitudes of k_a and k_s between certain values for a time interval, say, $t = [t_1,\ t_2]$ sec.

5.3.1. Case (i): Fixed Magnitude Fault. The closed-loop responses of the system (for 128 random plants from P), for a step disturbance of 0.1 unit at time $t = 0.5$ sec, with the fault-free design and faulty design (passive FTC) and proposed scheduling design are shown in Figure 7. All methods can reject the disturbance, and the displacement of the tip is within the tolerance B_d (dashed blue line). At time $t = 5$ sec, the multiplicative actuator and sensor faults occur with the magnitude of $k_a = 0.5$ and $k_s = 0.5$. It means that the actuator and sensor can deliver only 50% of its actual outputs, respectively. Because of the insufficient control input (voltage)/sensor output, the displacement of the tip varies more in the case of fault-free QFT design and it violates the desired tolerance (solid magenta line) as shown in Figure 7. At the same time, the responses due to passive FTC and the proposed scheduling design satisfies the tolerance because it demands the required control (from the design) in order to counter the fault. The zoomed view between the time $t = 5$ to 6.5 sec is shown in Figure 8 for illustrative purpose.

The control envelope shown in Figure 9 gives the minimum and maximum values of the control effort for the passive FTC and the proposed scheduling QFT design. For the sake of simplicity, we do not consider the fault-free design as it violates the tolerance. From Figure 9, it is seen that the proposed scheduling QFT control requires less control effort especially in the fault-free time (i.e., $t < 5$ sec) as compared to the conservative passive FTC design.

5.3.2. Case (ii): Time-Varying Magnitude Fault. Similar to the fixed magnitude fault case, during the fault-free time, all

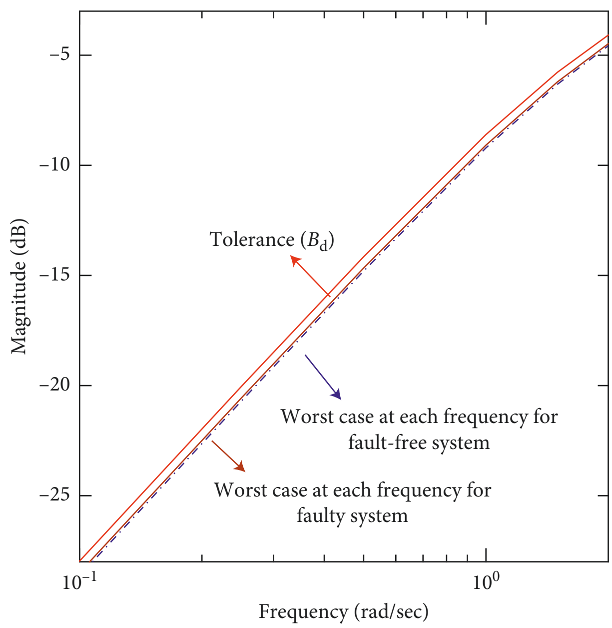

Figure 5: Frequency-domain validation of the robust output disturbance rejection specification.

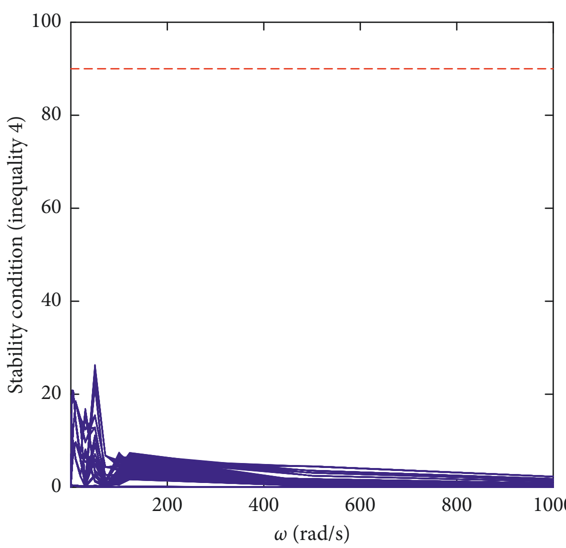

Figure 6: Stability condition (inequality 4) for the switching controller.

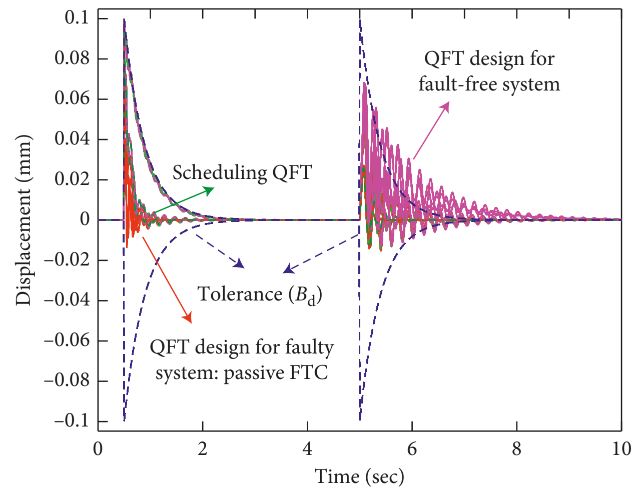

Figure 7: The closed-loop responses of the system (128 randomly selected plant from the plant set (5)) with the fixed fault at time $t = 5$ sec for case (i). "Magenta solid line" represents the fault-free design (G), "red dashed line" represents the faulty system controller (G_f) response, and "green dashed-dotted line" represents proposed scheduling QFT.

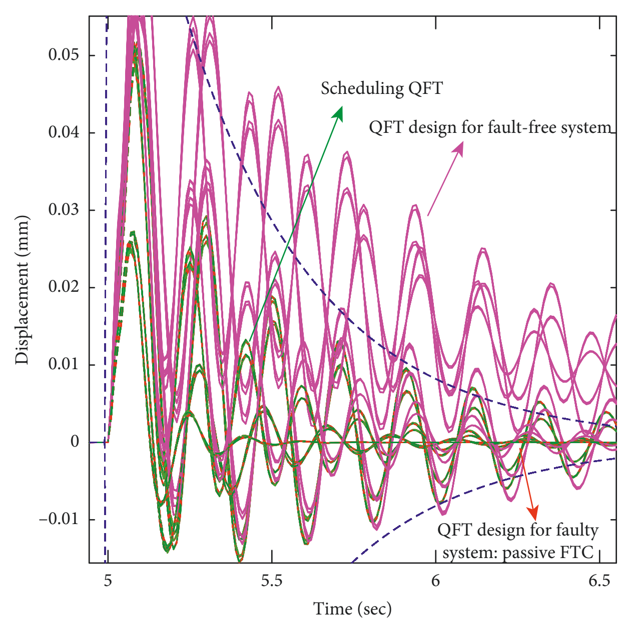

Figure 8: The zoomed-in view of Figure 7 between the time instant $t = 5$ sec and 6.5 sec.

of mentioned design satisfies the disturbance rejection tolerance as shown in Figure 10. In this case, the actuator fault with the magnitude varying between $k_a = 0.6$ and 0.5 for a period of 1 sec starting from $t = 5$ sec to $t = 6$ sec is considered. The sensor fault is also varying similar to the actuator fault. This implies that the actuator/sensor can only deliver 60% to 50% of its outputs, respectively, between the time interval $t = [5, 6]$ sec. Figure 10 illustrates the response of the different design, and it confirms the similar observation as described for case (i).

The control envelope shown in Figure 11 illustrates the passive FTC design requires more control effort than the proposed scheduling QFT during the fault-free time, i.e., time $t < 5$ sec. The norms of control efforts for the proposed IFDC and passive FTC QFT designs are tabulated in Table 1. It is observed that the norms for proposed IFDC-based scheduling controller are smaller than that of the passive FTC controller. The 1-norm gives the measure of availability of the total resource in the signal which is lesser in the proposed approach as compared to the existing passive one. The computed 2-norm shows that the proposed controller requires less energy to control the vibration as opposed to the passive FTC.

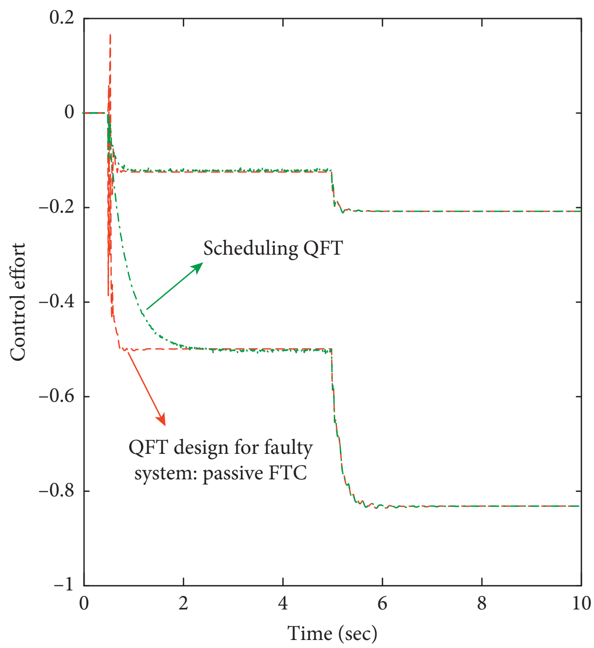

Figure 9: Control envelope for the fixed fault case using the passive FTC and the proposed scheduling design.

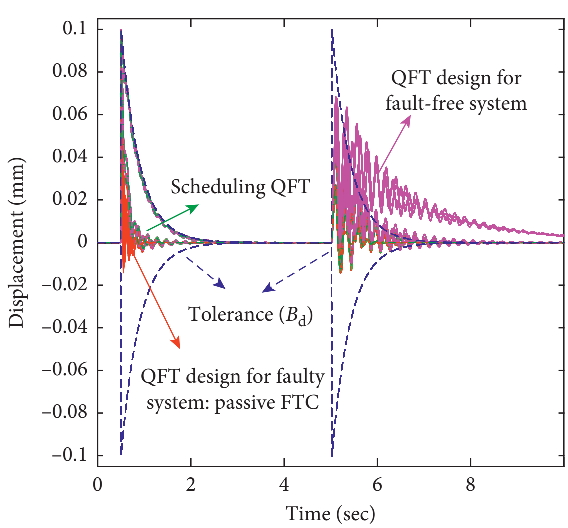

Figure 10: The closed-loop responses of the system (128 randomly selected plant from the plant set (5)) with the time-varying fault occurring at time $t = 5$ sec for case (ii). Here, the responses for fault-free design, the design for faulty system, and the proposed scheduling approach are represented by "magenta solid line," "red dashed line" and "green dashed-dotted line," respectively.

6. Conclusion

A novel approach for IFDC with scheduling QFT for SISO uncertain system has been proposed in this paper. The stability of the scheduling QFT design was analyzed using the available frequency-domain condition. The proposed IFDC approach is analog to the existing model-based FDI approach, but here, we use it for control purpose also as opposed to the FD purpose alone. A challenging flexible smart structure system featuring the fault of the piezoelectric actuator and sensor has been used to demonstrate the effectiveness of the proposed approach. It has been validated that the proposed method requires less control effort to satisfy the desired specifications as compared to the existing QFT-based passive FTC methods. In the controller implementation, both the actuator and sensor multiplicative faults (with fixed and time-varying magnitudes) are considered at the same time. In the fixed magnitude fault case, the actuator/sensor can deliver only 50% of its actual outputs. Despite this insufficient control input (voltage)/sensor output, the tip displacement satisfies the tolerance with less control effort for the proposed design as compared to the passive FTC QFT design. In addition, it has been demonstrated that the actuator/sensor can deliver only 60 to 50% of its output in the time-varying magnitude showing that the proposed design requires less control effort to satisfy the specification. It is noted that a comparative work between QFT-based FTC and non-QFT-based FTC methods will be undertaken as a future work.

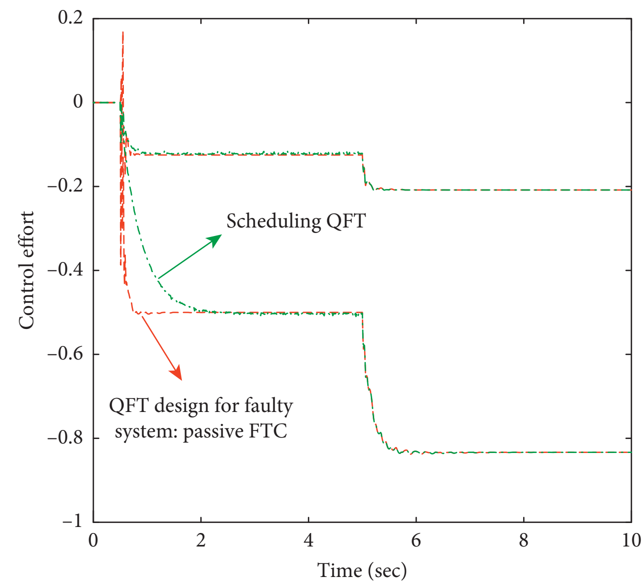

Figure 11: Control envelope for the time-varying fault case using the passive FTC and the proposed scheduling design.

Table 1: Comparison of norms of control efforts with the passive FTC and the proposed method.

Norm	Passive FTC QFT		Proposed IFDC with scheduling	
	Fixed fault	Varying fault	Fixed fault	Varying fault
1	634.5	707.2	620	693
2	21.23	24.2	20.98	23.9

Data Availability

All data to achieve the results are available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Dr. R. Jeyasenthil formulated the integrated fault detection and control (IFDC) model to enhance the effectiveness of vibration control for the actuator/sensor fault system and performed the simulation works to demonstrate the benefit of the proposed control approach. Prof. Y. S. Lee made a great effort to check all equations and rectified some typos of the main equations, and he rephrased the motivation of this work in the preparation of the final version after acceptance. Prof. S. B. Choi created the idea of the IFDC and established the problem formulation considering the bound of the robust stability and disturbance rejection.

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