ONLINE TIME DELAY AND DISTURBANCE COMPENSATION FOR LINEAR NON MINIMUM PHASE SYSTEMS

MİNİMUM FAZ OLMAYAN DOĞRUSAL SİSTEMLER İÇİN ÇEVRİMİÇİ GECİKME VE BOZUNUM TELAFİSİ

ÖZLEM DEMİRTAŞ

PROF. DR MEHMET ÖNDER EFE

Supervisor

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To my family who always supports me,

To my love who taught me to believe,

To all the women that inspire me.

ABSTRACT

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Özlem DEMİRTAŞ

Master of Science, Department of Computer Engineering

Supervisor: Prof. Dr. Mehmet Önder EFE

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Disturbances often occur in real systems and this has a negative effect on system stability and performance. In the past, a number of remedies have been proposed to enhance the stability and performance characteristics of feedback control systems.

The classical disturbance observer estimates disturbances acting on the system utilizing a proper inverse model and eliminates the disturbance from the control channel. However, the model inversion for non minimum phase systems leads to unstable control loops, which require a special treatment for the right half plane zeros. This undesired situation narrows down both the simplicity and the capabilities of disturbance observer.

Although researchers try to make the system robust by using more complex controllers due to restrictive effect of classical disturbance observers, the designed controllers often achieve one control target, making the system robust against disturbances yet sacrificing other control objectives.

In addition to external disturbances, inherent time delays are also inevitable facts observed in dynamic systems, and similar to disturbances, they disrupt the system's stability and deteriorate its operation. Smith predictor is often used to restore the stability of such systems. In this approach, negative feedback is made from the controller output to input by using delay time model and the delay becomes a multiplier of the delay free closed loop transfer function. However, in order to design the delay time model, the actual delay time must be measured precisely, which is usually not possible in practice.

In this study, both the disturbance observer for non minimum phase systems and the adaptive Smith predictor design for systems with time delay are proposed to eliminate the negative effects of disturbances and time delays, concurrently. According to the results, it is seen that the controller alone is not capable of maintaining the stability under time delay and disturbances. On the other hand, for non minimum phase and time delay systems, the response of the system is stable and it resembles the nominal system behavior with proposed time delay and disturbance estimation methods.

Keywords: Disturbance Observer, Recursive Least Squares, Smith Predictor, Non Minimum Phase Systems, Time Delay.

ÖZET

MİNİMUM FAZ OLMAYAN DOĞRUSAL SİSTEMLER İÇİN ÇEVRİMİÇİ GECİKME VE BOZUNUM TELAFİSİ

Özlem DEMİRTAŞ

Yüksek Lisans, Bilgisayar Mühendisliği Bölümü

Tez Danışmanı: Prof. Dr. Mehmet Önder EFE

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Gerçek sistemlerde genellikle bozunumlar görülür ve bunlar sistem kararlılığı ile performansı üzerinde olumsuz etkilere sahiptir. Geçmişten bu yana, geri beslemeli kontrol sistemlerinin kararlılık ve performans karakterini iyileştirmek üzere bazı çözümler üretilmektedir.

Klasik bozunum gözlemcileri sisteme etkiyen bozunumları uygun bir ters modelden faydalanarak kestirmekte ve kontrol edilen kanaldan temizlemektedir. Lakin, minimum-fazda olmayan sistemlerde modelin tersini alma, sağ yarı-düzlem sıfırlarının özel olarak ele alınmasını gerektiren kararsız kontrol döngülerine neden olmaktadır. Bu arzu edilmeyen durum, bozunum gözlemcilerinin hem sadeliğini hem de kabiliyetlerini sınırlandırmaktadır.

Araştırmacılar, klasik bozunum gözlemcilerinin yetersizliğinden dolayı, daha karmaşık kontrolcüler kullanarak sistemi gürbüz hale getirmesine rağmen; tasarlanan kontrolcüler genellikle tek amaç doğrultusunda sadece sistemi gürbüz hale getirmekle kalmakta ve diğer tasarım hedeflerinden feragat etmektedir.

Harici bozunumlara ek olarak, zaman gecikmeleri de dinamik sistemlerin doğasında var olmakta ve bozunumlara benzer bir şekilde sistem kararlılığı ve operasyonunu zedelemektedir. Bu gibi durumlarda sistem kararlılığını geri kazanabilmek için sıklıkla Smith tahmincileri kullanılmaktadır. Bu yaklaşımda, kontrolcü çıktısından girdisine bir negatif geri besleme ile zaman gecikmesi modeli kullanılmakta ve bu gecikme ise gecikmesiz kapalı döngü transfer fonksiyonunun bir çarpanı haline gelmektedir. Ancak, böyle bir zaman gecikmesi modeli tasarımı için, pratikte pek de mümkün olmayan, gerçek gecikme değerinin hassas bir şekilde ölçümünün yapılabiliyor olması gerekmektedir.

Bu çalışmada bozunum ve zaman gecikmelerinin olumsuz etkilerini eşzamanlı olarak ortadan kaldırmaya yönelik, minimum-fazda olmayan gecikmeli sistemler için bozunum gözlemcisi ve adaptif Smith tahmincisi tasarımları öne sürülmektedir. Elde edilen sonuçlara göre, kontrolcü tek başına zaman gecikmesi ve bozunumlar altında sistem kararlılığını sağlatmakta güçlük çekmektedir. Öte yandan öne sürülmekte olan gecikme ve bozunum kestirimi yöntemleri ile minimum-fazda olmayan ve gecikmeli sistemlerde, sistem cevabı kararlılığını korumakta ve nominali yansıtacak şekilde davranmaktadır.

Anahtar Kelimeler: Bozunum Gözlemcisi, Özyinelemeli En Küçük Kareler, Smith Öngörücü, Minimum Faz Olmayan Sistemler, Zaman Gecikmesi.

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I would like to thank deeply to my colleague and love Oğuz Han ALTINTAŞ for the trust and support he gave me. I conclude this thesis thanks to the happiness, joy, valuable advice and knowledge he has given me. He is one of those to whom this thesis is dedicated, and I believe that one day he will achieve all his goals with his intelligence, diligence and kindheartedness.

I would also like to thank to my beloved parents Fatma and Özgür DEMİRTAŞ and my brother Fatih Can DEMİRTAŞ for their endless patience and love. Thanks to the great family life they gave me, I was able to achieve all the good things that have happened in my life like this thesis.

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CONTENTS

FIGURES

ABBREVATIONS

DOB	Disturbance Observer
NMP	Non Minimum Phase
MP	Minimum Phase
SP	Smith Predictor
CDOB	Communication Disturbance Observer
RLS	Recursive Least Squares
RLSWF	Recursive Least Squares with Forgetting Factor
LS	Least Squares
RHP	Right Half Plane
SMC	Sliding Mode Control
APF	All Pass Filter
ND	Network Disturbance
MRA	Model Reference Adaptive
KF	Kalman Filter
EKF	Extended Kalman Filter
RLSWVF	Recursive Least Squares with Variable Forgetting Factor
LHP	Left Half Plane

1 INTRODUCTION

1.1 Motivation

Internal and external disturbances in the dynamic systems affect the system response negatively by disrupting the operation of the system. For this purpose, developers have turned to additional designs that will eliminate these disturbances affecting the system when the system controller is not sufficient. Although these designs cannot completely eliminate disturbances of all magnitudes and frequencies, they improve the system response.

DOB is an effective structure that improves system response by estimating disturbances affecting the system. Although it was first presented in 1983 by Ohnishi [1], it has an ongoing development process since the mid-1960s. The classical DOB design is shown in the Figure 1.1. As can be seen from the figure, the control signal subject to disturbance enters the plant via the control channel. The output signal enters to the nominal system dynamics and Q-filter, respectively, and the estimated value of the disturbance is obtained. Then, estimated disturbance is eliminated from the control signal.

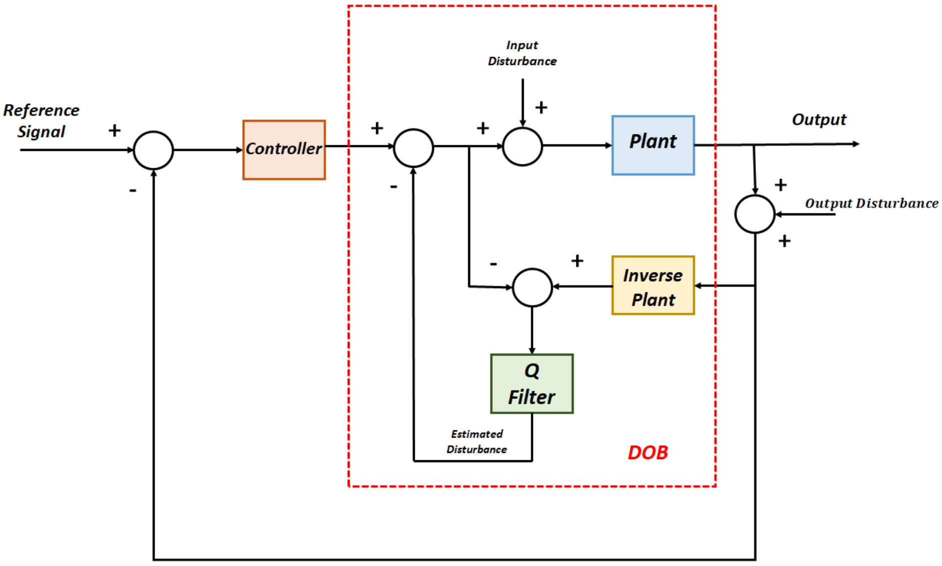

Figure 1.1. Classical DOB structure.

There are two criteria that determine the performance of classical DOB design: selection of Q-filter coefficients and inversion of the plant. Generally, to eliminate disturbances, Q-filter is chosen as 1 at low frequencies and 0 at high frequencies [2]. Q-filter selection is made not only depending on the frequency of disturbance, but also according to other performance constraints of system. In [3] and [4], different Q filter designs that ensure system stability are proposed. The difficulty in reversing the system arises if the system to be taken is NMP. The inverse of NMP systems causes instability [5]. Therefore, different methods have been developed to apply the classical DOB design to NMP systems. Generally, these methods are divided into two parts. In the first type of method, the system is enabled to show MP behavior by designing a parallel filter to the NMP system. In the second type of method, MP system approximation of the NMP system is estimated by using optimization methods.

In addition to the disturbances affecting the system, the time delay problem also negatively affects the system instability and disrupts the system response. Therefore, in addition to the system controller, different designs are developed and the negative effect of the time delay on the response is tried to be eliminated. SP is often used to restore the stability of such systems. The classic SP design is shown in Figure 1.2. In this approach, negative feedback is made from the controller output to input by using delay time model and the delay becomes a multiplier of the delay free closed loop transfer function. However, in order to design the delay time model, the actual delay time must be measured precisely, which is usually not possible in practice. In addition, if the disturbances affecting the system are not eliminated, the SP design is also negatively affected, and the time delay on the system cannot be compensated. The CDOB, which is a modified version of the classical DOB, is also used for time delay elimination. This design reduces the negative effect of the time delay on the response by accepting the delay as a disturbance affecting the system. However, although it can operate without the need for measurement of delay value, this design requires the inverse of the nominal system model, as in the classical DOB design, and this situation creates a constraint for NMP systems [6].

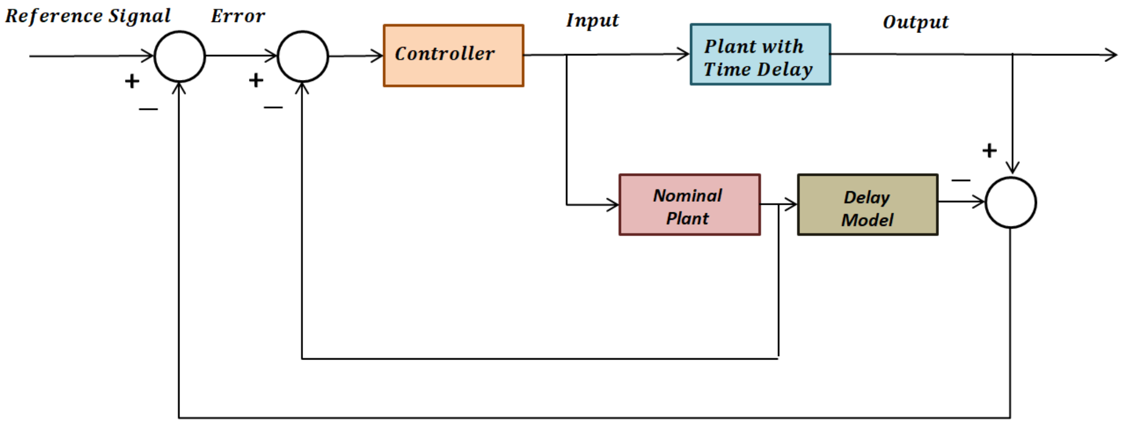

Figure 1.2. SP structure.

In summary, in cases where the system controller is not sufficient, an additional control structure is needed to provide both time delay and disturbance elimination in linear NMP systems. Although DOB provides disturbance elimination, the fact that classical DOB design cannot be used for NMP systems poses a major constraint. Similarly, although SP provides simple and effective delay compensation, the need for precise measurement of the delay value affects the flexibility of the design.

1.2 Aims of Proposed Research

In the proposed thesis, it is provided to combine the classical DOB and SP by eliminating their design constraints.

In the first step, the design of a DOB for NMP systems is performed. The MP approximation of the system is found by using a constrained optimization approach, and the inverse of the system is obtained by using this approximation. Then, artificial disturbances are fed to the system and the effect of the DOB on the system performance is observed. In the second step, the adaptive SP design using RLSWF method is proposed as shown in Figure 1.3. In this phase, it is assumed that the nominal model of the system is known and the real system dynamics with delay are estimated using RLSWF. In this way the disruptive effect of delay on the system is eliminated in an online manner without the need for precise measurement of the time delay.

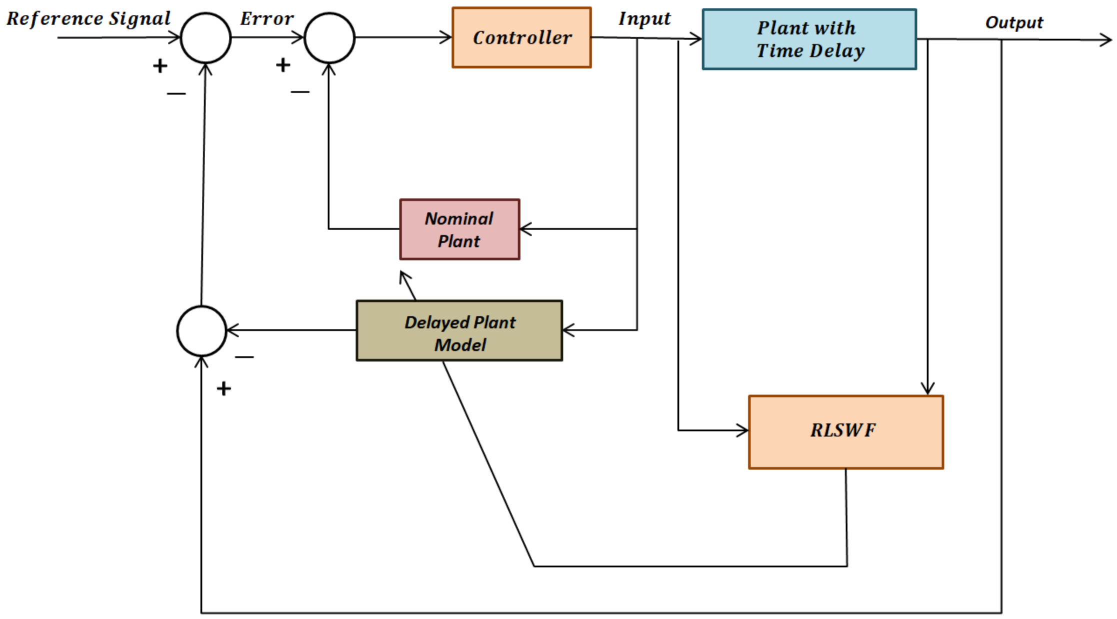

Figure 1.3. Novel adaptive SP design.

In the last phase, the studies done in the previous steps are combined to observe how the system stability is maintained for cases where the disturbance and delay are effective simultaneously. Then the closed loop system with uncertain elements is investigated with and without the presence of combination of proposed methods. As a result of the study, three practical and up-to-date designs that can be used both independently from each other and in combination presented to the developers to eliminate disturbance and delay in system.

1.3 Originality and Main Idea of the Proposed Research

The proposed research consists of three different parts.

In the first part, DOB design was created for NMP systems, and the limitation of classical DOB design for these systems was removed. When the studies in the literature are examined, it is seen that generally two different types of methods are used in NMP-DOB design. In the first type of method, a filter parallel to the NMP system is designed to ensure that the system shows MP behavior [7][8][9]. The process of reversing the system in the DOB design is performed through the combination of the NMP system and the parallel filter, preventing the DOB from exhibiting an unstable performance.

The design steps of this structure are shown in the Figure 1.4. and Figure 1.5., respectively [9]. In the figures, C is the system controller, P is the actual system, P_n is the nominal system, Q is the low-pass filter, R is the reference signal, Y is the output signal, d is the input disturbance, σ is the measurement noise and V is the parallel filter.

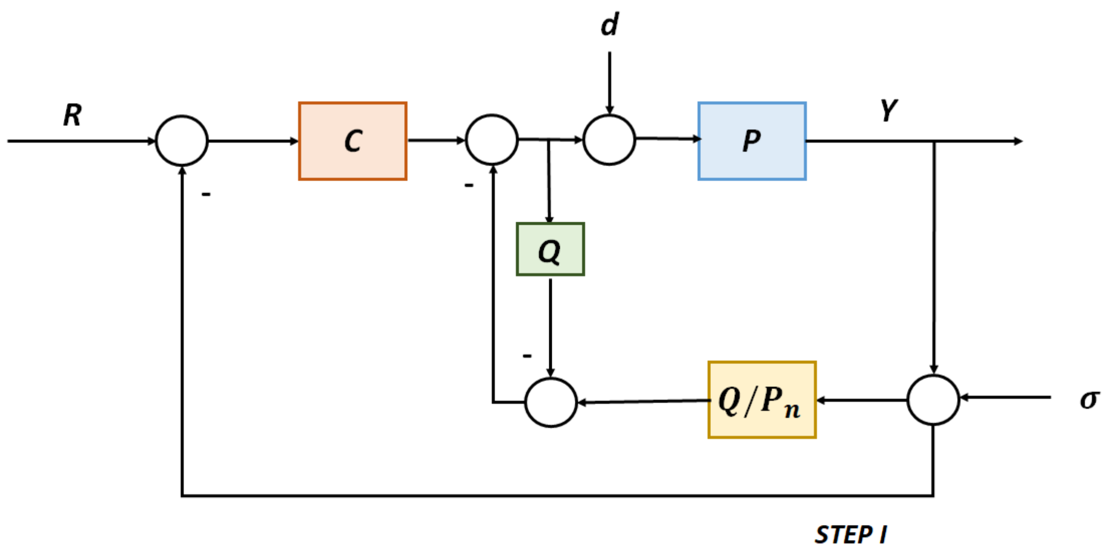

Figure 1.4. Classical DOB design in closed loop system.

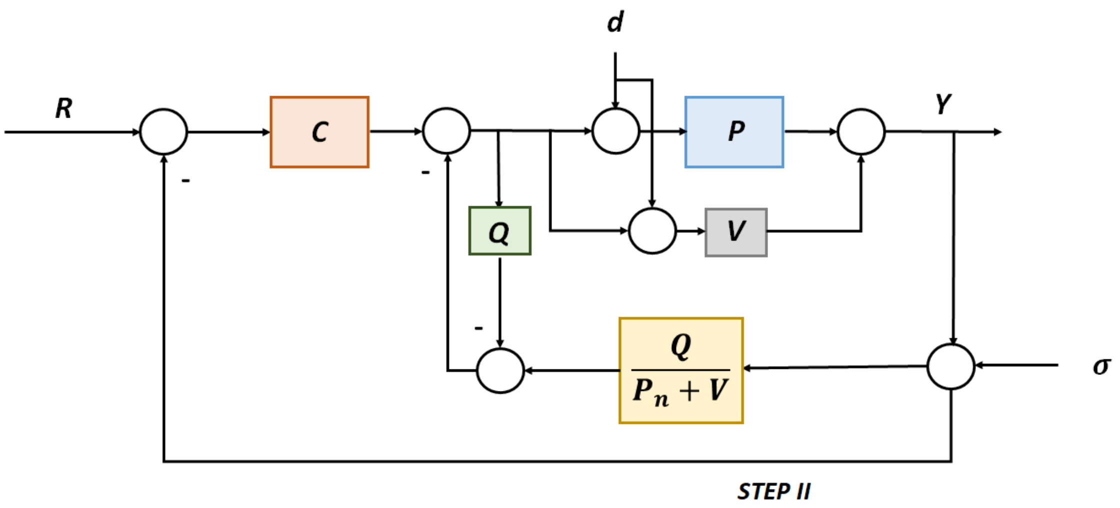

Figure 1.5. Proposed control design with parallel filter and DOB**.**

Although this type of method eliminates the limitation of DOB for NMP systems by providing a filter parallel to the real system, it has two disadvantages: 1) The parallel filter design required to make the system MP requires deeper robustness analysis [2]. 2) The design is carried out by assuming that the disturbance affecting the actual system also affects the input of the parallel filter at the same time. However, at runtime this disturbance only affects the control signal. Therefore, this situation leads to uncertainty in the high frequency range [9]. In the second type of method, using constrained optimization and system identification methods, MP approaches of NMP systems are calculated and DOB design is carried out through these approaches [2][5]. However, in this type of method, the performance of the DOB design is directly dependent on the performance of the optimization method used, and an approach with a high error rate affects the DOB performance and fidelity of the simulation negatively. Within the scope of the proposed research, an approach has been developed to eliminate the disadvantages of both types of methods. For this purpose, the optimization method which is the second method type and specified in [2] has been used by modifying the cost function. In this way, an offline NMP-DOB design, which is both practical and has a low error rate due to optimization, has been presented to the developers.

In the second part of the proposed research, a new design has been developed in order to eliminate the negative effect of time delay in dynamic systems. Although the SP is a simple and effective method, the need for precise measurement of the delay value creates a disadvantage for the flexibility of the design [10]. Also the CDOB design, which can perform delay elimination without the need for delay value, causes unstable control loops in NMP systems as in the classical DOB structure [11]. For this purpose, a new design has been developed that combines the simplicity of the SP and the flexibility of the CDOB. This novel adaptive SP design performs real-time identification of the delayed system, enabling delay elimination without the need for delay measurement.

In the third and final part of the research, both designs are combined to present a new control structure that provides disturbance and time delay elimination in NMP systems. However, in systems with time delay, the modified NMP - DOB design is used. Therefore, after the constraint optimization method given in [2] is modified and the inverse of the nominal NMP system without delay is found, the new DOB structure shown in Figure 1.6 is used [12].

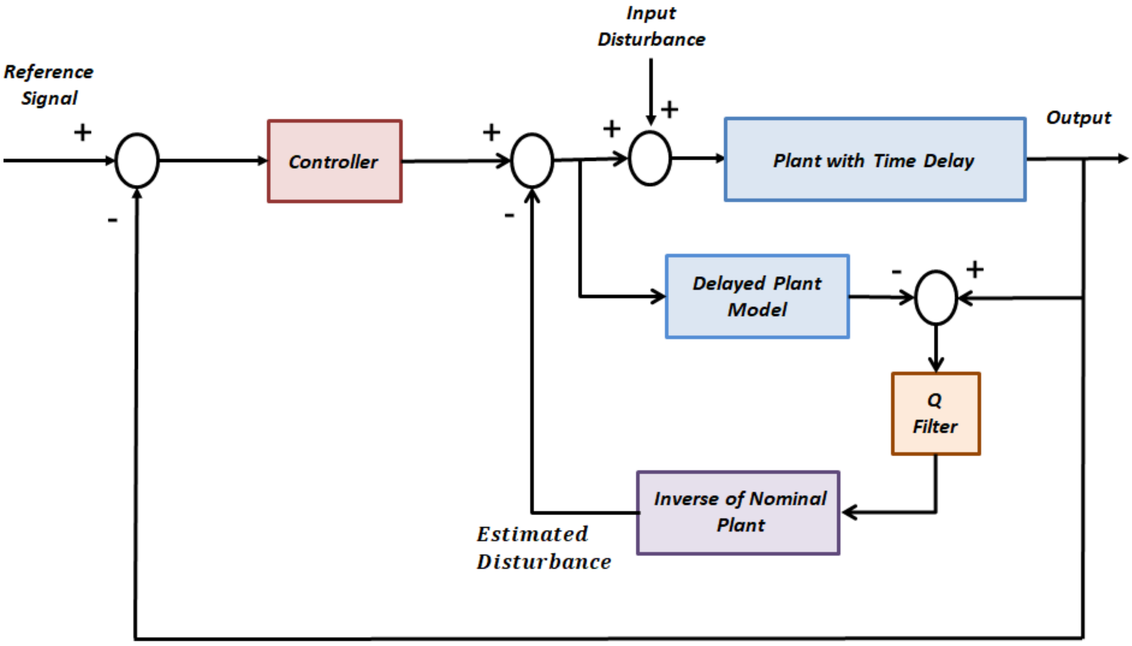

Figure 1.6. DOB structure for the systems with time delay.

As a result, the following features in the presented study are superior to other studies in the literature:

- A novel, simple and reliable DOB design has been created for NMP systems.
- By making the SP design adaptive, time delay elimination is realized without the need for actual time delay measurement. Unlike the CDOB design, it can work for NMP systems without the need for extra design costs.
- NMP-DOB design is modified for delayed systems and can be easily integrated into these systems.
- By combining the new adaptive SP and NMP-DOB design for time delayed systems, both delay and disturbance elimination is provided.
- Both designs can be used both separately and in combination.

1.4 Layout of Thesis

This thesis is organized as follows.

In Chapter 2, the background about types of DOB is provided. It contains literature review of classical DOB, NMP-DOB and CDOB. Then, what problems are best suited to different types of DOB, the differences between them, their advantages and disadvantages are proposed.

In Chapter 3, the important examples of SP in the literature are given. Then SP types and their designs are explained.

In Chapter 4, literature examples and background about types of RLS is provided. Then LS, RLS and RLSWF algorithms are explained.

In Chapter 5, the NMP-DOB design used, its differences from the original solution, the NMP system where the test is carried out and the controller used are explained. Then, the behaviors of the NMP system under different disturbances in both the presence of the controller and the presence of the new NMP-DOB design are shown.

In Chapter 6 how SP design and RLSWF algorithms are combined is explained. Then, the performance of new adaptive SP design under different constant and varying time delays are shown.

In Chapter 7 information about how novel adaptive SP and NMP-DOB designs are combined is provided. Then, the performance of new design under different time delays and disturbances are shown.

Finally in Chapter 8, the results obtained from the research and what will be studied in the future works is explained.

2 BACKGROUND AND LITERATURE REVIEW OF DISTURBANCE OBSERVERS

2.1 Introduction

Disturbances often occur in real systems and this has a negative effect on system stability and performance. In the past, a number of remedies have been proposed to enhance the stability and performance characteristics of feedback control systems.

The classical DOB estimates disturbances acting on the system utilizing a proper inverse model and eliminates the disturbance from the control channel. However, the model inversion for NMP systems leads to unstable control loops, which require a special treatment for the RHP zeros [13]. This undesired situation narrows down both the simplicity and the capabilities of DOB. For this reason, considering that most of the real systems are NMP systems, different methods have been developed to eliminate this constraint of the classical DOBs. In addition to external disturbances, inherent time delays are also inevitable facts observed in dynamic systems, and similar to disturbances, they disrupt the system's stability and deteriorate its operation. CDOB is a different type of classical DOB which provides delay compensation without the need for the actual delay value. In CDOB time delay is treated like disturbance and it is compensated through estimation [6].

Although researchers try to make the system robust by using more complex controllers due to some restrictive effects of DOBs and its types, the designed controllers often achieve one control target, making the system robust against disturbances yet sacrificing other control objectives [8].

This chapter is organized as follows. In Section 2 information about types of DOBs is provided. It contains background and literature review of classical DOB, NMP-DOB and CDOB. In Section 3 what problems are best suited to different types of DOB, the differences between them, their advantages and disadvantages are given. Finally, the chapter is summarized in Section 4.

2.2 Disturbance Observers

Although the origin of DOB dates back to the mid-1960s, the use of DOB-based robust controllers gained popularity in the 1990s, drawing the attention of control designers. In 1991, Komada et al. [14] presented a method of acceleration-dependent force control and utilized a DOB design that works in conjunction with acceleration control to improve the performance of the proposed method. In 1993, Murakami et al. [15] introduced sensorless torque control in a multidegree-of-freedom manipulator, increasing the robustness of the manipulator with the estimated disturbance feedback provided by the DOB. In 1994, Kawamura et al. [16] combined the DOB and SMC designs to create a robust controller with less chattering. In 1996, Lee and Tomizuka [17] used DOB in velocity control of a motion control system and compared this new control design with two different digital tracking controllers. In 1998, Tomita et al. [18] presented sensorless position and velocity control for brushless DC motors using the DOB design and demonstrated the effectiveness of DOB. In the same year, Eom et al. [19] used DOB to estimate the force without a force sensor and show that robust force control can be achieved without sensor. In 1999, Kempf and Kobayashi [20] used the discrete-time DOB and removed low frequency disturbances impacting a discrete time tracking controller.

In the 2000s, the stability and performance of the DOB were improved and it was used in different control areas such as adaptive control and nonlinear observers. In 2000, Chen et al. [21] demonstrated the change of system stability depending on design parameters by using nonlinear DOBs in robot manipulators. In 2004, Chen [22]introduced a more flexible design procedure, separating the nonlinear DOB design phase from controller design. In 2013, Chen and Ge [23] presented a direct adaptive neural control design for nonlinear systems that are subject to time varying disturbance and uncertainty, and benefited from DOB in this design. In 2014, Park and Sul [24] developed a frequency-based adaptive DOB design to obtain higher precision rotor angle estimation in permanent magnet synchronous motor systems. In 2015, Li et al. [25] presented state and output feedback controllers combining fuzzy approximation and DOB and performed performance tests under external disturbances.

In addition to the above studies, DOB design is widely used in NMP and time delayed systems. In the following sections, studies in these areas will be explained in more detail.

2.2.1 Classical Disturbance Observers

The structure of classical DOB is shown in Figure 2.1, where $P(s)$ is the real system, $P_n(s)$ is the nominal model of the system, $C(s)$ is the system controller and $Q(s)$ is a low pass filter. The performance and stability of a closed loop system with a DOB depends tightly on the design of Q filter and inversion of the plant. In [26], a design procedure, which always guarantees the closed loop stability of the Q filter, is proposed. However, the use of inverse system dynamics in the design of DOB also requires some special considerations for NMP systems as the inverse of the nominal plant is unstable.

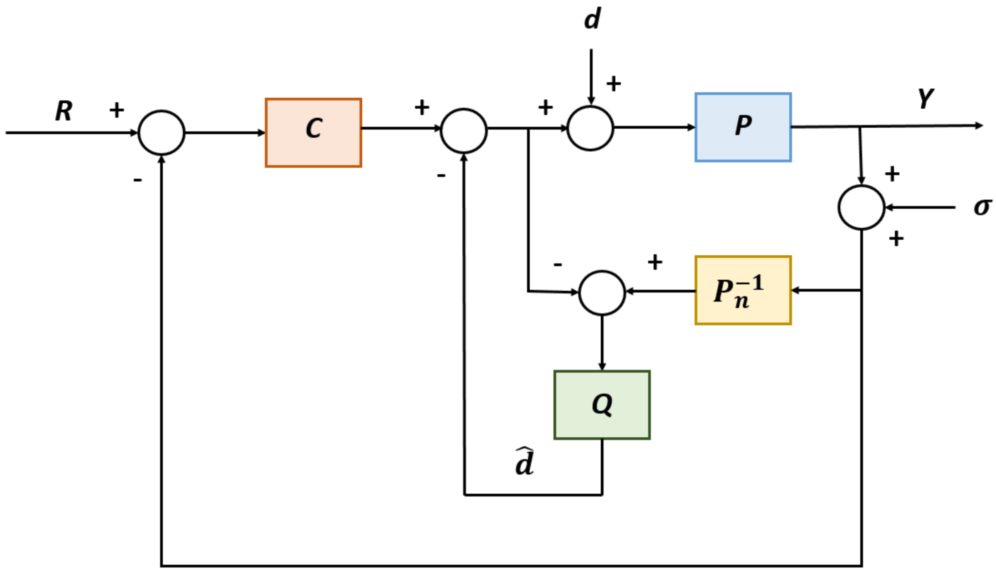

Figure 2.1. Classical DOB structure.

If the stability condition is examined for the inner loop in which the classical DOB is located (See Figure 2.1), we have the following transfer functions from r to y in (2-1) and from d to y in (2-2). The measurement noise is denoted by σ and the transfer function from σ to y is given in (2-3).

$$P_{ry}(s) = \frac{P(s)P_n(s)}{P_n(s)+(P(s)-P_n(s))Q(s)} \tag{2-1}$$

$$P_{dy}(s) = \frac{P(s)P_n(s)(1-Q(s))}{P_n(s)+(P(s)-P_n(s))Q(s)} \tag{2-2}$$

$$P_{\sigma y}(s) = \frac{P(s)Q(s)}{P_n(s)+(P(s)-P_n(s))Q(s)} \tag{2-3}$$

If $P = P_n(1+\Delta)$, i.e. the uncertainty model is multiplicative, the characteristic equation of the closed loop system is as given in (2-4).

$$\begin{gathered} P_n(s)+\big(P(s)-P_n(s)\big)Q(s) = 0 \\ P_n(s)\big(1+\Delta(s)Q(s)\big) = 0 \end{gathered} \tag{2-4}$$

If (2-3) and (2-4) are combined, below transfer function is obtained.

$$P_{\sigma y}(s) = \frac{(P_n(s)+(1+\Delta(s)))Q(s)}{P_n(s)(1+\Delta(s)Q(s))} \tag{2-5}$$

In (2-5) P, Q and Δ are can be expressed as the ratio of polynomials such that $P_n = N_{P_n}/D_{P_n}$, $Q = N_Q/D_Q$ and $\Delta = N_\Delta/D_\Delta$. Rearranging (2-5) with these variables yields

$$P_{\sigma y}(s) = \frac{(P_n(s)+(1+\Delta(s)))Q(s)}{P_n(s)(1+\Delta(s)Q(s))} \tag{2-6}$$

In order to fulfill the internal loop stability condition, the denominator polynomial $N_{P_n}(D_\Delta D_Q + N_\Delta N_Q)$ specified in (2-6) must be Hurwitz. In this case, the nominal system must be MP because N_{P_n} stands for the numerator of the nominal system.

2.2.2 Non Minimum Phase Disturbance Observers

Although it provides ease of use and effective disturbance compensation, the fact that classical DOBs only provide the stability condition for MP systems has forced control engineers to develop DOB designs that can also compatible with NMP systems. In 2004, Chen, Zhai and Fukuda [27] used the LS method to find the MP approximation of the NMP system and incorporated it to the design of the classical DOB. In 2007, Son et al. [7] showed that for a NMP system, a parallel filter which made the system MP can be designed using the transfer function of the controller. In 2008 Shim et al. [8] introduced a parallel Q-filter design method using the H_∞ control design which makes the classical DOB applicable for NMP systems. In 2010, using the same technique, they [9] included a robust controller to the closed loop system and showed that without the proposed DOB design, the controller can only achieve one design goal under disturbance. In 2013, Sarıyıldız and Ohnishi [2] estimated the MP equivalents by running an optimization method for the RHP zero(s) in the system and presented a study on which constraints should be considered when designing Q-filter for such systems. In 2019, Lee and Jung [5] combined RLS and APF, enabling real-time inversion of NMP systems, thereby introducing an adaptive DOB design method.

When the studies mentioned above are examined, it is seen that generally two types of design methods and their variants are used. In the first type of method, it is ensured that the system shows MP behavior by designing a parallel filter to the NMP system [7][8][9]. For example, the parallel filter design steps specified in [8] are shown in Figure 2.2 and Figure 2.3, respectively. In the figures, C is the system controller, P is the actual system, P_n is the nominal system, Q is the low-pass filter, R is the reference signal, Y is the output signal, d is the input disturbance, σ is measurement noise and V is the parallel filter. Classical DOB design is constructed by assuming that the plant is $P + V$. The difficulty of this method is due to the design of the V filter. Assuming $\vartheta = 1 / V$ in the presented NMP-DOB design, the equations for the new method are obtained as in (2-7), (2-8), (2-9) and (2-10).

$$Y(s) = P_{ry}(s)R(s) + P_{dy}(s)d(s) - P_{\sigma y}(s)\sigma(s) \tag{2-7}$$

$$P_{ry}(s) = \frac{(P_n(s)\vartheta(s) + 1)P(s)C(s)}{1 + P(s)C(s) + (1 + P_n(s)C(s))P(s)\vartheta(s)} \tag{2-8}$$

$$P_{dy}(s) = \frac{P(s)}{1 + P(s)C(s) + (1 + P_n(s)C(s))P(s)\vartheta(s)} \tag{2-9}$$

$$P_{\sigma y}(s) = \frac{P(s)C(s) + (1 + P_n(s)C(s))P(s)\vartheta(s)}{1 + P(s)C(s) + (1 + P_n(s)C(s))P(s)\vartheta(s)} \tag{2-10}$$

The aim here is to reduce the negative effect of disturbance on the system by keeping the $P_{dy}(s)$ value small. Also, the measurement noise in the low frequency range is considered to be close to zero. Based on these assumptions, it is desired to obtain ϑ that satisfies the conditions given in (2-11), (2-12) and (2-13).

$$P_{ry}(s) \approx \frac{P_n(s)C(s)}{1 + P_n(s)C(s)} \tag{2-11}$$

$$P_{dy}(s) \approx 0 \tag{2-12}$$

$$P_{\sigma y}(s) \approx 1 \tag{2-13}$$

Using the H_∞ design method, the problem is modified as follows: If L, S and T are defined as $P_n(s)\vartheta(s)$, $(1/1 + P_n(s)\vartheta(s))$ and $(P_n(s)\vartheta(s) / 1 + P_n(s)\vartheta(s))$, (2-14) and (2-15) are obtained. They are called performance recovery condition and robust stability condition, respectively. By solving these equations, $\vartheta(s)$ which achieves conditions given in (2-11), (2-12) and (2-13), is calculated.

$$\left\| \frac{W_1}{1+L} \right\|_\infty < 1 \tag{2-14}$$

$$\| |W_2 S| + |W_3 T| \|_\infty < 1 \tag{2-15}$$

Although this design provides the applicability of the classic DOB design for NMP systems, it has two drawbacks: 1) the input disturbance affecting the system is not injected the input of the *V* filter at runtime. For this reason, this situation leads to a small uncertainty in the design [8]. 2) In order to calculate the V filter, a deep robust stability analysis is required [2].

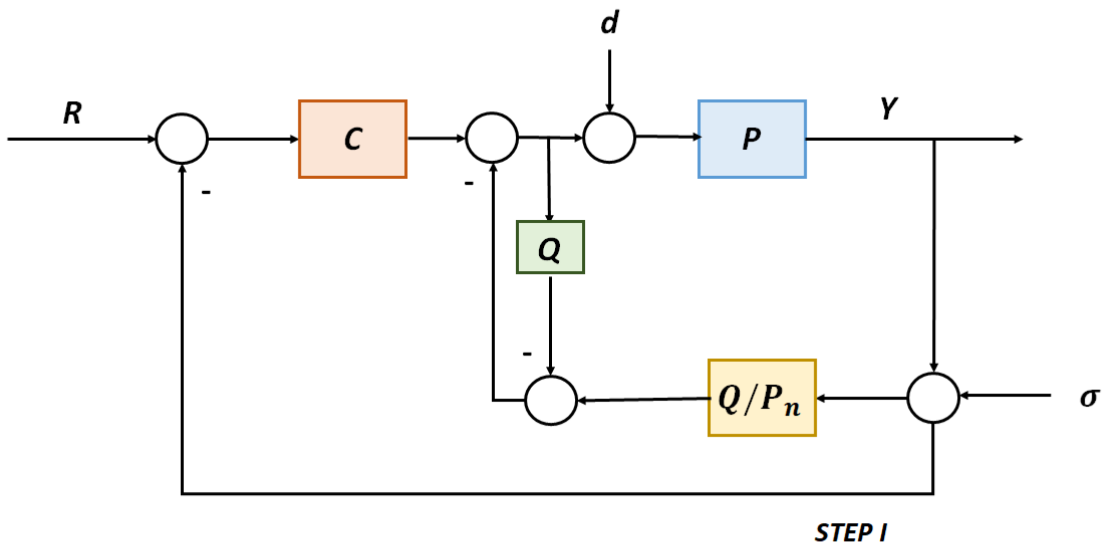

Figure 2.2. Classical DOB design in closed loop system.

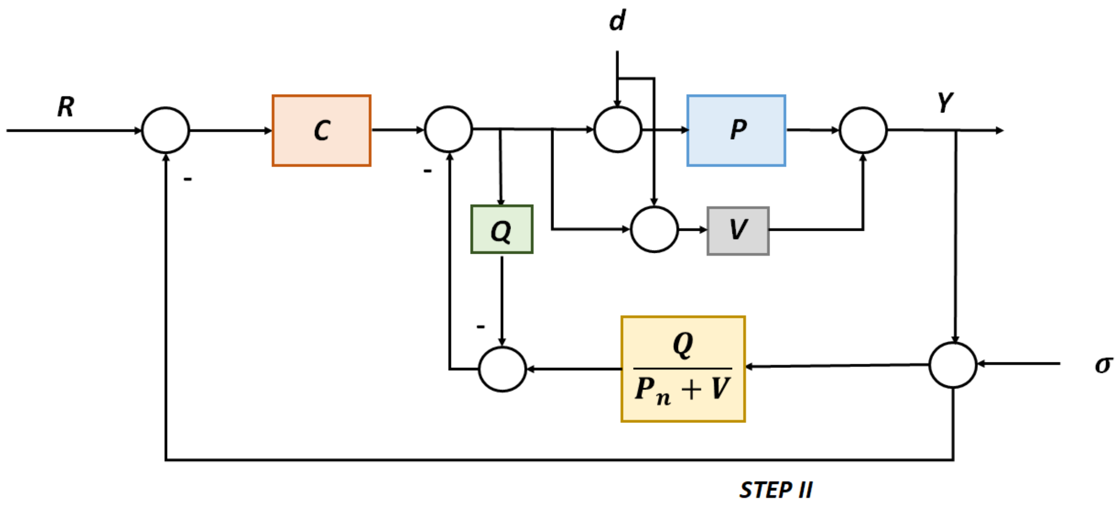

Figure 2.3. Proposed control design with parallel filter and DOB**.**

In the second type of method, the MP approximation of the NMP system is estimated by using the MP conditions, with the help of the constrained optimization technique [2][5]. For example in [2], in order to invert the transfer function of the NMP system, MP equivalents of the RHP zeros in the numerator of the nominal system are found for a certain frequency range. Suppose that the NMP causal system which we want to invert contains RHP zeros and N_P represents the polynomial consists of only RHP zeros. Also the non-causal, MP transfer function that we calculated as the equivalent of N_P at the end of optimization is N_{approx} / D_{approx}. In this case, the error polynomial can be defined as in (2-16).

$$e := N_P - \frac{N_{approx}}{D_{approx}} \tag{2-16}$$

With this definition, the optimization problem can be cast as

$$\textit{minimize}$$

$$\mathrm{E} = x_{amp}|e(jw)|^2 + x_{phase}\big(arg\big(e(jw)\big)\big)^2$$

$$\textit{subject to:}$$

$$E1:\ N_{approx} \text{ and } D_{approx} \text{ are Hurwitz polynomials.}$$

$$E2:\ 0 \leq w \leq min(Re(z_{RHP})) \tag{2-17}$$

x_{amp} and x_{phase} represent magnitude and phase weights. In the minimization of the problem specified in (2-17), numerical solution can be implemented by using any optimization technique. The solution is realized for frequency points up to the smallest of the RHP zeros.

2.2.3 Communication Disturbance Observers

With the spread of network-based control systems and other network-based applications, developers designed methods to overcome the negative effects of time delay on the system. Although simple but effective control methods (e.g. SP) are developed to provide time delay compensation the need for precise measurement of time delay in these designs reduces the effectiveness of the methods. As an updated DOB type, CDOB is designed to perform delay compensation without the exact measurement of time delay.

In 2006, Kato et al. [12] presented a method that can compensate the time delay in motion control systems without the need for a delay value by combining SP and DOB. In 2008, Natori and Ohnishi [28] carried out stability analysis using ND and CDOB for systems with constant delay and derived the design conditions through the relationship between the poles of CDOB and ND. In the same year, Natori et al. [29] performed a practical stability analysis based on design parameters using the Nyquist diagrams for the delay compensation design created using CDOB. Then, they performed tests for 1DOF inertial system and 2DOF manipulator and showed that the design works efficiently. In 2010, Natori et al. [30] combined ND and CDOB concepts for time-varying delays, performed delay compensation and compared it with SP. According to the experimental results, they showed that CDOB design works more effectively than SP for time-varying delays. Although the CDOB design does not require an actual delay model, the observer's model uncertainties negatively affect the robustness of the control system and this situation leads to the need for a delay model. For this reason, in 2010, Rahman and Ohnishi [31] used the delayed input signal in the delay estimation to eliminate the erroneous delay estimation caused by the model uncertainty. In 2012, Natori [32] estimated the approximate polar values of the system using Pade approximation and implemented the CDOB design based on these values.

In CDOB, delay compensation is done by handling the time delay as disturbance. A system with time delay in input and output signals is shown in Figure 2.4. In the figure, τ_i and τ_o represent the time delay values in the input and output of the system, respectively. Therefore, the total time delay value affecting the system is calculated as $\tau = \tau_i + \tau_o$. In this case, the relationship between the system's input and output signals is as follows:

$$\frac{Y(s)}{R(s)} = e^{-\tau_i} P(s) e^{-\tau_o} = P(s) e^{-\tau s} \tag{2-18}$$

In Figure 2.5, the time delay model is connected in series with the nominal system. Considering the relationship between input and output signals, the time delay can be given to the system as disturbance affecting only the input signal, without loss generality. In this case, ND is obtained as follows:

$$\text{ND} = U(s) - U(s) e^{-\tau s} \tag{2-19}$$

CDOB provides time delay compensation by estimating ND. Figure 2.6 shows delay compensation using CDOB for a system with time delay in input and output signals. In the ideal case where the Q-filter value is considered infinite, CDOB ensures that the negative effect of the delay is completely removed from the system.

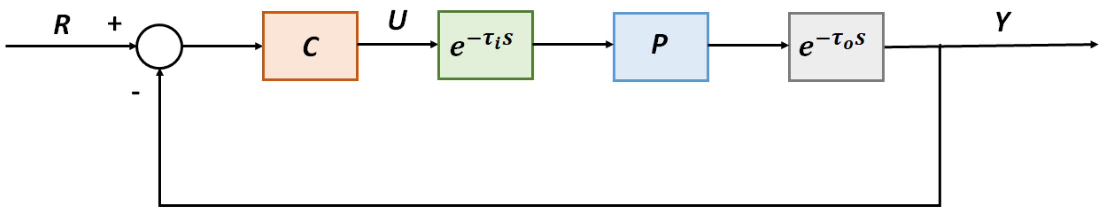

Figure 2.4. Closed loop system with time delay.

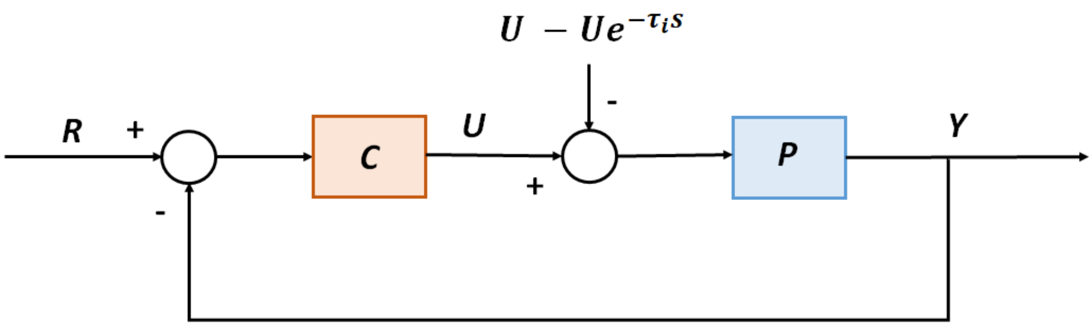

Figure 2.5. Closed loop system with ND.

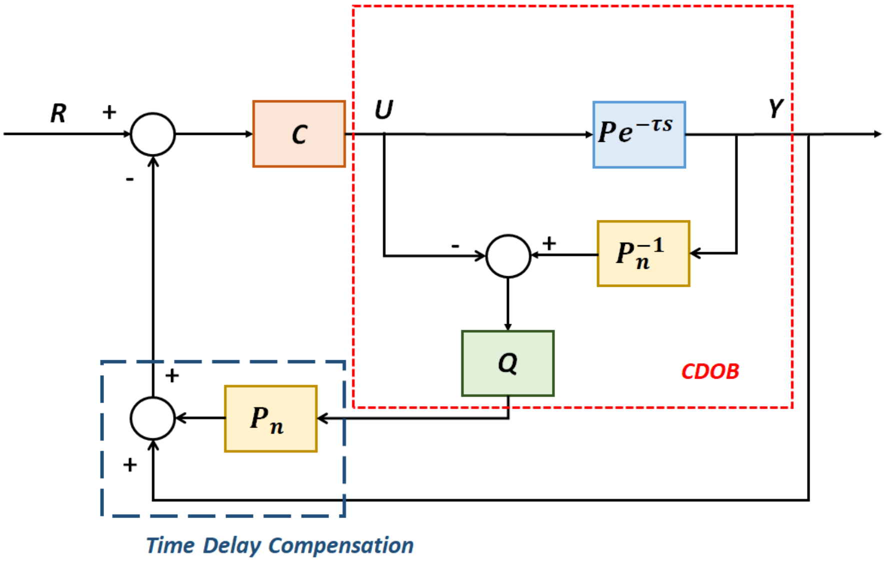

Figure 2.6. Time delay compensation using CDOB.

Although the CDOB provides delay elimination without the need for actual delay measurement, the constraints of the classical DOB design also apply to the CDOB. Therefore, it is not possible to use the classical CDOB design directly in NMP systems.

2.3 Summary

Although DOB is an effective and simple method, it also has important limitations. In particular, the fact that it cannot be used directly for NMP systems draws the attention of developers and leads to the creation of different DOB designs. However, these DOB designs developed for NMP systems also have some deficiencies.

CDOB, which is an updated version of the DOB design, is used for time delay elimination. However, although it provides delay compensation without relying on measurement of actual time delay, it cannot be used directly in NMP systems, as in the classical DOB design.

3 BACKGROUND AND LITERATURE REVIEW OF SMITH PREDICTORS

3.1 Introduction

SP is a simple yet effective design that ensures a stable response from a closed loop system when time delay is available in the loop. In this design, the accurately known delay term of the system is removed perfectly from the system's characteristic equation and the negative effect of the delay on the response is eliminated. Although it provides ease of design and eliminates the negative effect of time delay, the need for exact time delay value and minimum model uncertainty limits the use of the method. Therefore, the designers try to eliminate these limitations of SP or use designs which this restriction is already eliminated [33].

This chapter is organized as follows. In the Section 2, the important examples of SP in the literature are given. In the same section, SP types, their structures and literature examples are explained. In Section 3, different types of SP are compared. Finally, the chapter is summarized in Section 4.

3.2 Smith Predictors

After SP was developed by Otto J. M. Smith [34] in 1957, it has been used in many different areas to eliminate time delay problems. In 1977, Donoghue [35] compared SP with optimal control design for time delay systems, demonstrating that SP is more successful in the presence of external disturbance. In 1983, Bahill [36] developed an adaptive controller and combined it with SP to overcome the differences between the model and the plant. In 1994, Astrom et al. [37] proposed a new SP design that can work for systems with integral mode by separating the set point and load responses. SP studies conducted in recent years are generally on reducing model uncertainties or making more precise time delay measurements. In 2007, Xiaojun and Fengdeng [38] used fast converging genetic algorithm in modeling of nominal system to reduce uncertainty and make SP adaptive. . In 2008, Lai et al. [39] proposed an adaptive SP design that can perform effective time delay compensation for systems that have time-varying delay by making real-time delay measurement. In 2010, Zheng and Fan [40] developed the MRA-SP, minimizing model uncertainties and improving the performance of the control system.

When the examples given above are examined, it is seen that the performance of SP has been tried to be improved by using system identification methods. Because performance of SP is directly dependent on the uncertainty of the system model and a high-fidelity model improves the performance of SP as well. Adaptive system identification methods are also capable of reducing this uncertainty by detecting changes on the system in real time.

3.2.1 Classical Smith Predictors

Classical SP structure is illustrated in Figure 3.1. As shown in the figure, the delay that adversely affects the closed loop system is compensated using the predictor transfer function $P\,(1\text{-}\ e^{-\tau s})$.

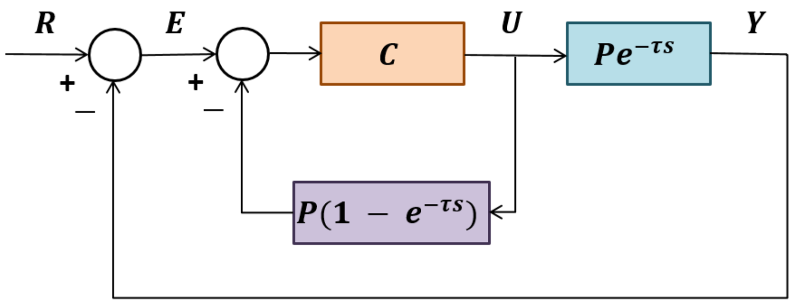

Figure 3.1. Classical SP structure.

If the system structure is expressed using the following equations, then

$$\frac{U}{E} = \frac{C}{1+PC(1-e^{-\tau s})} \tag{3-1}$$

$$\frac{Y}{R} = \frac{\frac{U}{E}\frac{Y}{U}}{1+\frac{U}{E}\frac{Y}{U}} = \frac{\frac{PCe^{-\tau s}}{1+PC(1-e^{-\tau s})}}{1+\frac{PCe^{-\tau s}}{1+PC(1-e^{-\tau s})}} = \frac{PCe^{-\tau s}}{1+PC}$$

(3-2)

are obtained. Equation (3-2) expresses the ideal design expected in the presence of controller and SP. However, in real systems, SP efficiency depends tightly on the exact measurement of delay and correct modeling of the real system. These are rather restrictive conditions for a successful application of SP.

3.2.2 Smith Predictors by Modeling System Parameters

In Figure 3.2, the delayed real system $P(s)\, e^{-\tau s}$ is modeled and $P_{ref}(s)\, e^{-\tau_{ref} s}$ is obtained. Then the SP design is studied on this new block structure. The transfer function of the new SP design is obtained as follows:

$$\frac{Y}{R}=\frac{\dfrac{PCe^{-\tau s}}{1+P_{ref}C(1-e^{-\tau_{ref}s})}}{1+\dfrac{PCe^{-\tau s}}{1+P_{ref}C(1-e^{-\tau_{ref}s})}} \tag{3-3}$$

$$\frac{Y}{R}=\frac{PCe^{-\tau s}}{1+P_{ref}C+C(Pe^{-\tau s}-P_{ref}e^{-\tau_{ref}s})} \tag{3-4}$$

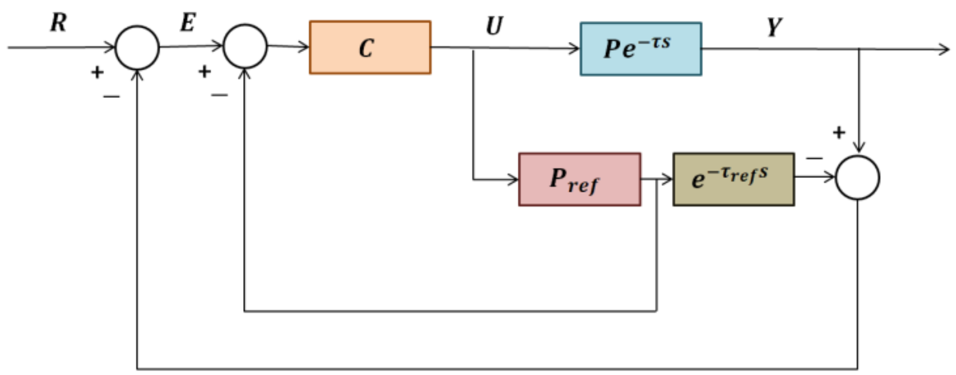

Figure 3.2. SP structure by modeling real system and delay.

As can be understood from (3-4), if the modeling error of the real system with delay is minimized and a sufficient level of fidelity is achieved, the ideal SP design expressed in (3-2) is obtained by assuming $\left(Pe^{-\tau s}-P_{ref}e^{-\tau_{ref}s}\right)\approx 0$.

3.2.3 Adaptive Smith Predictors

As can be seen from (3-4), the efficiency of SP depends on the exact measurement of the time delay value and the uncertainty of model. Therefore, the performance of SP decreases when the time delay or the system is time-varying. Developers make adaptive SP designs to maintain SP performance by tracking these changes in system or time delay. Generally three types of adaptive SP designs are used [41].

The two design types of SP are shown in Figure 3.3 and Figure 3.4, respectively. In the first design type, the plant is modeled in real time in order to follow the parameter changes. In the second design type the delay model is obtained in real time and the changes in the delay are tracked instantaneously. In the last design type, both models are estimated in real time in order to follow the changes in both time delay and system parameters. This design type of SP is shown in Figure 3.5.

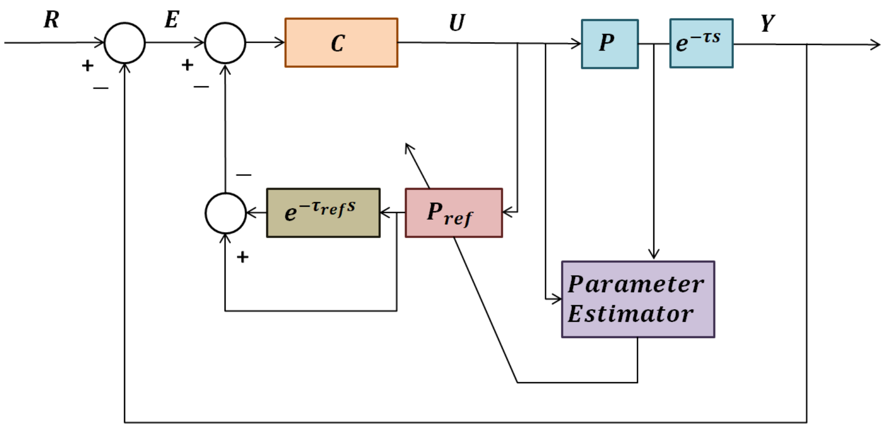

Figure 3.3. Adaptive SP using online parameter estimator.

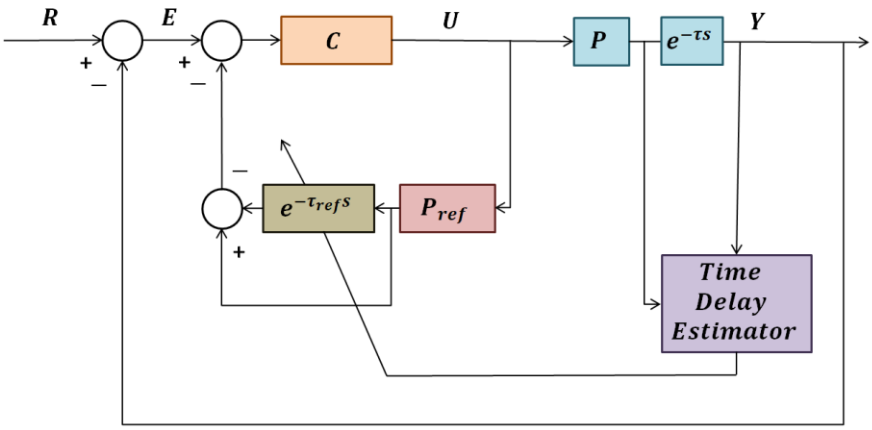

Figure 3.4. Adaptive SP using online time delay estimator.

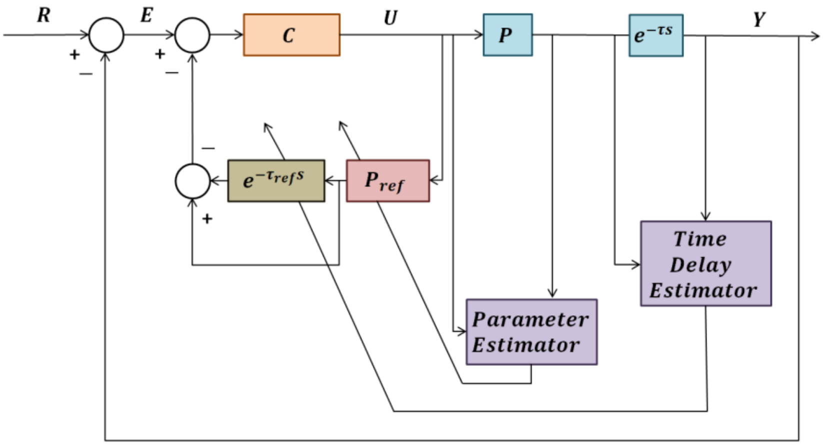

Figure 3.5. Adaptive SP using both parameter and time delay estimator.

The performance of adaptive SP design is directly dependent on the performance of the estimator. For this reason, the estimator to be used should be the identification algorithm that has a low error rate and can track changes quickly.

3.3 Summary

In this section, by giving information about SP, which has important usages in the literature, how to create different SP types and their advantages are explained.

4 BACKGROUND AND LITERATURE REVIEW OF ONLINE TIME-DOMAIN IDENTIFICATION TECHNIQUE: RECURSIVE LEAST SQUARES

4.1 Introduction

RLS algorithm is an iterative implementation of LS regression algorithm. The method allows the LS algorithm to be dynamically applied to time series obtained in real time. Algorithm is a member of KF family and exhibits an adaptive mechanism in terms of execution method. In addition, it is adjustable according to time-varying input data and it has a fast convergence rate. In this respect, it clearly shows a better performance than the LS algorithm [42].

This chapter is organized as follows. In Section 2, important examples about RLS in the literature are given. In Section 3; LS, RLS and RLSWF algorithms, their advantages and disadvantages are explained. Finally, the chapter is summarized in Section 4.

4.2 Literature Review

Due to its efficient performance in online system identification, RLS and its variants is used in many different fields in the literature. In 2010, Underwood and Husain [43] developed adaptive current and torque controllers for permanent-magnet synchronous machines by performing online parameter estimation with RLS. In 2012, Rajami et al. [44] used RLS to estimate the slip-slope used in the measurement of friction coefficient in vehicles and showed that estimation can be done with high accuracy. In 2014, Alonge et al. [45] estimated the speed in the motion control system by using RLS and calculated the rotor flow using 4th order KF instead of using 6th order EKF. In 2015, Badoni et al. [46] presented the control algorithm that predicts the the power components of the load current with RLSWVF for more efficient operation of the distributed static compensator. In 2016, Reichbach and Kuperman [47] used RLS for online estimation of supercapacitor parameters. In 2018, Shen et al. [48] estimated the capacity and maximum power of lithium-ion batteries used in electric vehicles with RLS and increased the accuracy of state estimation using EKF. In 2019, Song et al. [49] used the

RLSWVF to calculate the remaining electrical energy in lithium-ion batteries and they showed that the method is more robust than RLSWF. In the same year, Feng et al. [50] used the RLSWF algorithm to identify the electro-hydraulic proportional system model with high accuracy and speed.

When the studies in the literature are examined, it is seen that three different variants of the RLS algorithm are frequently used: RLS, RLSWF and RLSWVF. Although the basic operating principles of these algorithms are similar, their convergence rate and tracking capabilities differ. In the following sections; RLS, RLSWF algorithms and differences between them are explained.

4.3 Background

4.3.1 Least Squares Estimation

The basis of the LS algorithm is the identification of the linear model with unknown parameter values by minimizing the square of the difference between the real and estimated system outputs. This situation can be defined as optimizing the cost function specified in (4-1). In this equation, T is the sampling time, y is real system output, x is identification input and w is the vector of linear system parameters we want to obtain at the end of the identification.

$$\epsilon(w)=\frac{1}{2}\sum_{i=1}^{m}(x^T(iT)w-y(iT))^2 \tag{4-1}$$

If closed form solution is developed, then

$$\frac{d\epsilon}{dw}(w)=\sum_{i=1}^{m}x(iT)(x^T(iT)w-y(iT)) = 0 \tag{4-2}$$

$$\sum_{i=1}^{m}\left(x(iT)x^T(iT)w-x(iT)y(iT)\right) = 0 \tag{4-3}$$

$$w\sum_{i=1}^{m}\left(x(iT)x^T(iT)\right)-\sum_{i=1}^{m}\left(x(iT)y(iT)\right) = 0 \tag{4-4}$$

$$w = \sum_{i=1}^{m}\left(x(iT)x^{T}(iT)\right)^{-1}\sum_{i=1}^{m}\left(x(iT)y(iT)\right) \quad (4\text{-}5)$$

is obtained.

4.3.2 Recursive Least Squares Estimation

In the RLS algorithm, it is aimed to recursively update the equation given in (4-5) as the real-time data are obtained. If $A(mT)=\sum_{i=1}^{m}(x(iT)x^{T}(iT))$ and $B(mT) = \sum_{i=1}^{m}(x(iT)y(iT))$, then

$$w(mT) = A^{-1}(mT)B(mT) \quad (4\text{-}6)$$

is obtained. The aim is to calculate the value of $w(mT)$ using the data we have obtained at time $(m\text{-}1)T$. In this case, the value of $w((m\text{-}1)T)$ is obtained as

$$w((m\text{-}1)T) = A^{-1}((m\text{-}1)T)B((m\text{-}1)T) \quad (4\text{-}7)$$

If the values of $A(mT)$ and $B(mT)$ are also calculated using $A((m\text{-}1)T)$ and $B((m\text{-}1)T)$, then

$$A(mT) = A((m\text{-}1)T)+x(mT)x^{T}(mT) \quad (4\text{-}8)$$

$$B(mT) = B((m\text{-}1)T)+x(mT)y(mT) \quad (4\text{-}9)$$

are obtained. However, as specified in (4-6), $A^{-1}(mT)$ is needed to obtain the $w(mT)$ value. From the matrix inversion formula,

$$A^{-1}(mT)=A^{-1}((m\text{-}1)T)-\frac{A^{-1}\left((m\text{-}1)T\right)x(mT)x^{T}(mT)A^{-1}((m\text{-}1)T)}{1+x^{T}(mT)A^{-1}((m\text{-}1)T)x(mT)} \quad (4\text{-}10)$$

is obtained. If the covariance matrix $P(mT)$ and Kalman gain $L(mT)$ are shown as $A^{-1}(mT)$ and $P((m\text{-}1)T)x(mT)\left(1+x^{T}(mT)P((m\text{-}1)T)x(mT)\right)^{-1}$ respectively, $P(mT)$ can also be expressed as

$$P(mT)=(I\text{-}L(mT)x^{T}(mT))P((m\text{-}1)T) \quad (4\text{-}11)$$

In this case, to find the value of $w(mT)$ recursively, the following equations are used:

$$w(mT)=P(mT)B(mT)$$

$$=P(mT)\left(A\left((m\text{-}1)T\right)w((m\text{-}1)T)+x(mT)y(mT)\right)$$

$$=P(mT)\left(\left(A(mT)\text{-}x(mT)x^T(mT)\right)w((m\text{-}1)T)+x(mT)y(mT)\right)$$

$$=w((m\text{-}1)T)\text{-}P(mT)x(mT)x^T(mT)w((m\text{-}1)T)+P(mT)x(mT)y(mT)$$

$$=w((m\text{-}1)T)+L(mT)(y(mT)\text{-}x^T(mT)w((m\text{-}1)T)) \tag{4-12}$$

The algorithm structure used for RLS is similar to the one used in many recursive estimation algorithms. Differences between algorithms are mostly achieved by changing the Kalman gain.

4.3.3 Recursive Least Squares Estimation with Forgetting Factor

In cases where the linear system parameters are time-varying, the RLS algorithm alone may not be sufficient. In this case, the forgetting factor, which is a more effective and heuristic approach, is used with RLS. This method allows more focus on recently observed data by reducing the weighting of old data points used during identification. In this case, the cost function used in the RLS algorithm, the covariance matrix P and the Kalman gain L are updated in the RLSWF algorithm respectively as follows [51]:

$$\epsilon(w) = \frac{1}{2}\sum_{i=1}^{m} \lambda^{m-i}(x^T(iT)w\text{-}y(iT))^2 \tag{4-13}$$

$$P(mT) = (\frac{1}{\lambda})\left(I\text{-}L(mT)x^T(mT)\right)P((m\text{-}1)T) \tag{4-14}$$

$$L(mT) = P((m\text{-}1)T)x(m\mathrm{T})\left(\lambda+x^T(mT)P((m\text{-}1)T)x(mT)\right)^{-1} \tag{4-15}$$

The forgetting factor (λ) value varies in between 0 and 1, and this value provides a compromise between the stability and tracking performances of the algorithm. As this value approaches 0, the tracking capability of the algorithm is improved, but negatively affects stability.

4.4 Summary

The RLS algorithm has a fast convergence rate. For this reason, it is a very commonly used method in online system identification. Different variants such as RLSWF, RLSWVF have been developed in order to improve the algorithm and increase its tracking capability. In these variants, using the forgetting factor coefficient, it can be adjusted how the algorithm will follow the changes in the system.

In this section, these algorithms and their basic working principles are explained.

5 DISTURBANCE OBSERVER DESIGN FOR NON MINIMUM PHASE UNMANNED AERIAL VEHICLE

5.1 Introduction

Linear dynamical systems are separated into two classes: MP and NMP systems. Systems with all zeros in the LHP are called MP systems. MP systems and their inverses are causal and stable. On the other hand, systems which have zero(s) in the RHP are called as NMP systems. Although these systems are causal and stable, their inverses are unstable. In addition, the presence of a time delay in the system also leads the system to be NMP [52].

In classical DOB design, the inverse of system dynamics is needed to construct the DOB. Therefore, the fact that the actual system is NMP causes instability in DOB design. Different system inversion methods are presented to eliminate this restrictive effect in classical DOB design. Two types of design methods are frequently used in studies in the literature. In the first design type, a filter parallel to the actual system is designed and the NMP system is transformed into a MP system. Then, DOB design is carried out over this MP system [7][8][9]. In the second design type, constrained optimization methods are used considering the conditions of being MP and the closest MP equivalent of the NMP system is found. These methods can be used offline or online depending on the cost of the algorithm [2][5]. Details of the instability of traditional DOB designs on NMP systems and DOB designs developed for NMP systems can be found in Chapter II.

This chapter is organized as follows. In Section 2 the NMP-DOB design used, its differences from the original solution, the NMP system where the test is carried out and the controller used are explained. In Section 3, the behaviors of the NMP system under different disturbances in both the presence of the controller and the presence of the new NMP-DOB design are shown. Finally, the chapter is summarized in Section 4.

5.2 Experiment Setup

5.2.1 Plant Model

The Tower Trainer 60 autopilot design problem [53] is used to test the new NMP-DOB design. The nominal transfer function of the system takes the elevator angle as input and provides altitude control. This transfer function’s denominator degree is 5 and it has 3 zeros in total. One of these zeros is in the RHP and its value is approximately 12.449088. The transfer function coefficients are shown in (5-1).

$$P_n(s) = \frac{h(s)}{\delta_e(s)} = \frac{-34.16s^3 - 144.4s^2 + 7047s + 557.2}{s^5 + 13.18s^4 + 95.93s^3 + 14.61s^2 + 31.94s} \tag{5-1}$$

5.2.2 Controller

H_∞ synthesis technique is used in the design of system controller. In this controller design type, a closed loop weighted transfer function is obtained by using the system's sensitivity and complementary sensitivity. Then, the optimal transfer function minimizing the H_∞ norm of this weighted transfer function is used as system controller. When the closed loop system indicated in the Figure 5.1 is examined, the sensitivity S and complementary sensitivity T of the system are obtained as in (5-2) and (5-3), respectively.

$$R \rightarrow E:\ S = (\mathrm{I} + PC)^{-1} \tag{5-2}$$

$$R \rightarrow Y:\ T = (\mathrm{I} + PC)^{-1} PC \tag{5-3}$$

$$S + T = \mathrm{I} \tag{5-4}$$

S and T functions of the closed loop system are shaped using weights. The weight of the S function, W_S, determines the system performance, and it should be chosen large for better tracking performance inside the control bandwidth. Similarly, the W_T weight shapes the T function, and for more robust performance, a larger value should be chosen outside the control bandwidth [54]. These weights are used to create an augmented plant which is specified in Figure 5.2. In this way, the problem turns into finding the controller that ensures that the H_∞ norm of $P_{zw} = \begin{bmatrix} W_S S \\ W_T T \end{bmatrix}$ is less than 1.

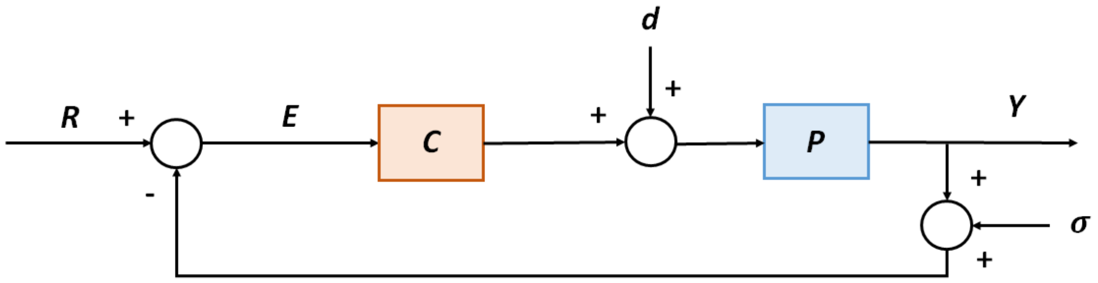

Figure 5.1. Closed loop system.

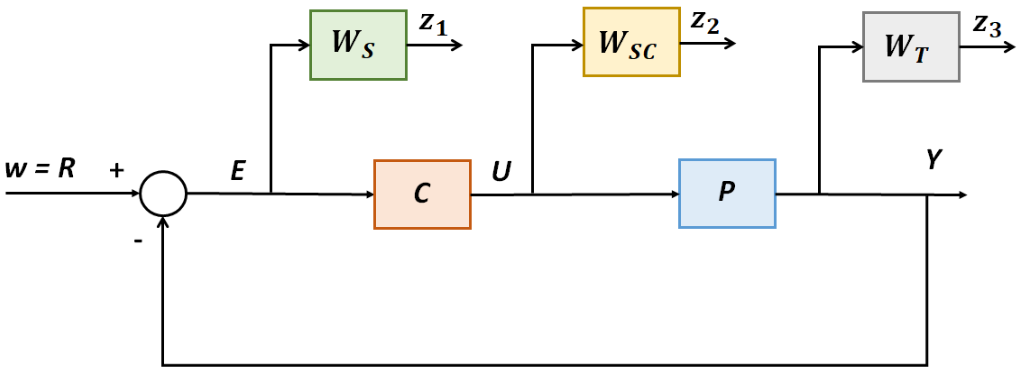

Figure 5.2. Augmented plant.

As mentioned before, the H_∞ design method was used when designing the controller for the unmanned aerial vehicle model which used as a plant. For this purpose, the weighting method given in [9] is used in the control design. Values of weights are given in (5-5).

$$W_S(s) = \frac{s^2+1.84s+0.846}{0.001s^3+1.002s^2+1.84s+1.84e\text{-}06}$$

$$W_T(s) = \frac{s}{5} * \frac{s}{s - 0.001} \tag{5-5}$$

The Nyquist diagram of the nominal system is shown in Figure 5.3. The gain and phase margins of the system are calculated as 38.5 dB and 76.1 deg, respectively. Then 100 MC runs are executed with 10% uncertainty and the Nyquist diagrams are obtained as seen in Figure 5.4.

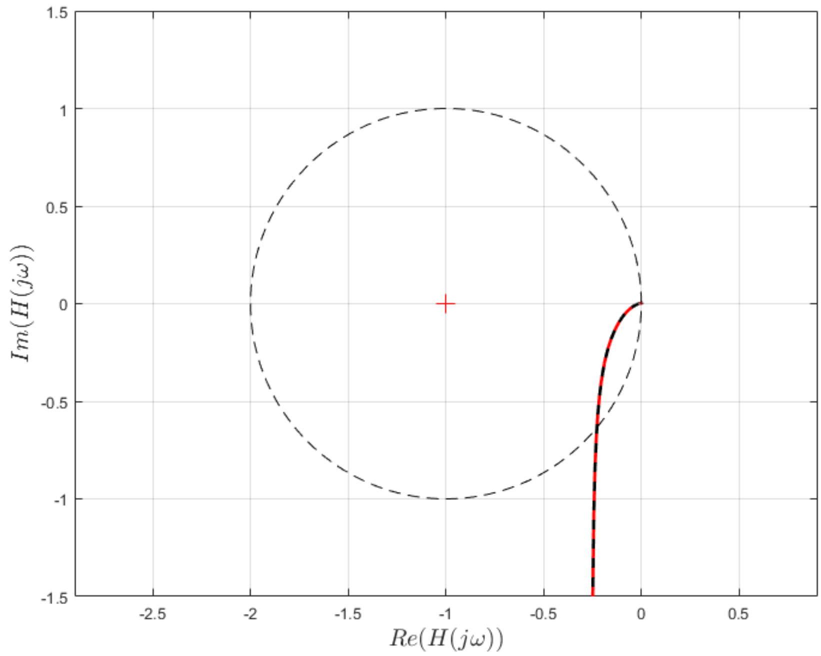

Figure 5.3. The Nyquist diagram of the nominal system.

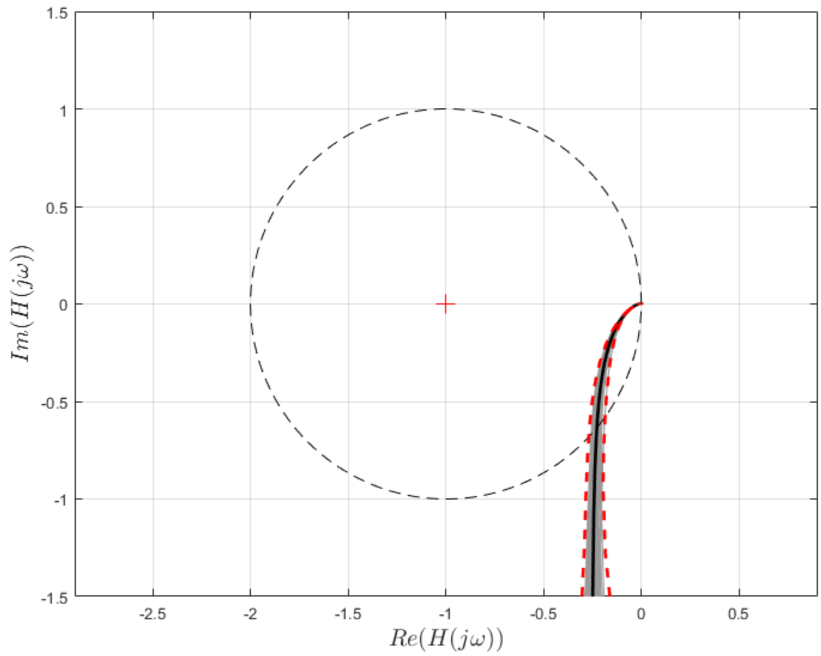

Figure 5.4. The Nyquist diagrams of MC runs with 10% uncertainty.

5.3 Inverse Approximation of Unmanned Aerial Vehicle

The optimization method given in [2] has been used in the NMP-DOB design with some modifications in the cost function. In this method, it is aimed to find the MP approximation of RHP zeros for a certain frequency range. For this reason, the cost function specified in (5-6) is minimized under the specified constraints in the original solution. Detailed information about this solution can be found in Chapter II.

$$\text{minimize}$$

$$E = x_{amp}|e(jw)|^2 + x_{phase}\big(arg\big(e(jw)\big)\big)^2$$

$$\text{subject to:}$$

$$E1:\ N_{approx} \text{ and } D_{approx} \text{ are Hurwitz polynomials.}$$

$$E2:\ 0 \le w \le min(Re(z_{RHP})) \tag{5-6}$$

Unlike the original cost function given in (5-6), the magnitude and phase coefficients x_{amp} and x_{phase} are defined frequency-dependent in the modified cost function which is given in (5-7). Using this new cost function for the second order NMP system used in the test of the original solution, the MP system approximation was found and the inverse of the obtained MP system was taken. During the tests, it was observed that the use of frequency-dependent coefficients is more effective in finding the MP system approximation. For this reason, this new cost function has also been used for different NMP systems where tests are carried out. The results regarding the effectiveness of the new cost function are presented in Section 3.

$$\text{minimize}$$

$$E = \boldsymbol{x_{amp}}(\boldsymbol{w})|e(jw)|^2 + \boldsymbol{x_{phase}}(\boldsymbol{w})\big(arg\big(e(jw)\big)\big)^2$$

$$\text{subject to:}$$

$$E1:\ N_{approx} \text{ and } D_{approx} \text{ are Hurwitz polynomials.}$$

$$E2:\ 0 \le w \le min(Re(z_{RHP})) \tag{5-7}$$

In the minimization of the problem specified in (5-7), numerical solution is implemented by using the off-the-shelf interior point method. Details on optimization methods can be found in [55].

After the controller design of the closed loop system, the design of NMP-DOB is started and the optimization method given at the beginning of the section is used to reverse the NMP system. For this purpose, the following error polynomial is defined:

$$e(s) = (s - 12.449088) - \frac{N_{approx}}{D_{approx}} \tag{5-8}$$

Solving the optimization problem in (5-7) with the error polynomial specified in (5-8), the MP approximation of the NMP zeros of the transfer function is estimated. $x_{amp}(w)$ and $x_{phase}(w)$ are chosen as $exp(-10 * w)$ and 10, respectively. The estimation is realized non-causal by selecting the numerator degree 2 and denominator degree 1 of the MP transfer function. In order to obtain more accurate results, minimization can be carried out for different numerator and denominator degrees by providing the condition of being non-causal. Equation (5-9) shows the MP and non-causal transfer function obtained as a result of minimization.

$$\frac{N_{approx}}{D_{approx}} = \frac{-0.183s^2 - 5.486s - 72.63}{s + 6.963} \tag{5-9}$$

In Figure 5.5, the RHP zero polynomial (s - 12.449088), MP approximation and symmetric zero polynomial (-s - 12.449088) is compared in Bode diagrams. In this figure, Bode diagrams display acceptable similarity up to the RHP zero frequency, which is used as the maximum frequency point in MP approximation. This figure also shows us that the new DOB design has a bandwidth of 12 rad/sec and system responses are acceptable at frequencies below this value [2].

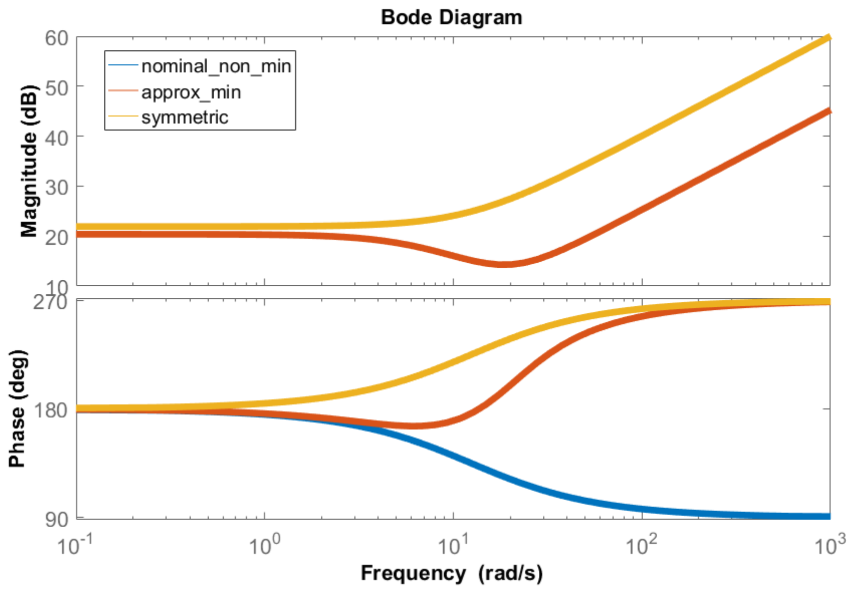

Figure 5.5. Bode diagrams of NMP, approximate MP and symmetric polynomials. Blue, red and orange curves indicate NMP, approximate MP and symmetric polynomials, respectively.

In the presence of new NMP-DOB, the robustness of the closed loop system is investigated.

As can be seen from the Figure 5.6, the classical DOB structure contains inner and outer feedback loops. While the inner loop eliminates the disturbances affecting the system, the outer loop fulfills the performance requirements. Open-loop transfer function formulas for inner and outer loop are given in (5-10) and (5-11) where P is the real system, P_n is the nominal model of the system, C is the system controller and Q is a low pass filter [2].

$$L_{inner} = \frac{PQ}{P_n(1\text{-}Q)} \tag{5-10}$$

$$L_{outer} = \frac{CPP_n}{P_n(1\text{-}Q)+PQ} \tag{5-11}$$

By using the inner loop equation in (5-10), the Nyquist diagram for the DOB with the nominal system is examined and the diagram in Figure 5.7 is obtained. The gain and phase margins of the system are calculated as infinite and 90 deg, respectively

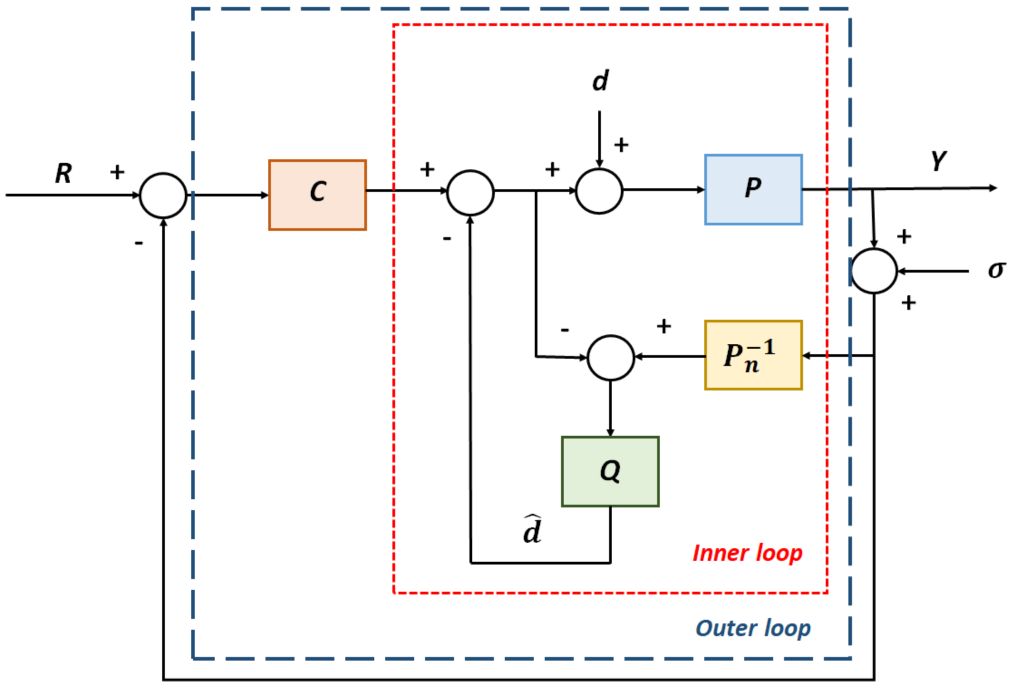

Figure 5.6. Inner and outer loops of classical DOB structure.

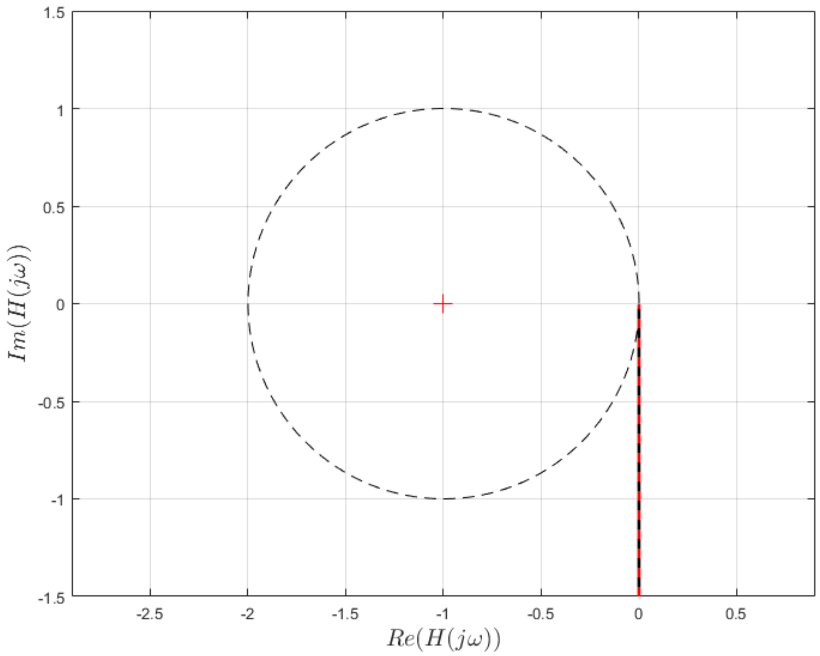

Figure 5.7. The Nyquist diagram of the NMP-DOB.

Then 100 MC runs are executed with 10% uncertainty and the Nyquist diagrams are obtained as shown in Figure 5.8.

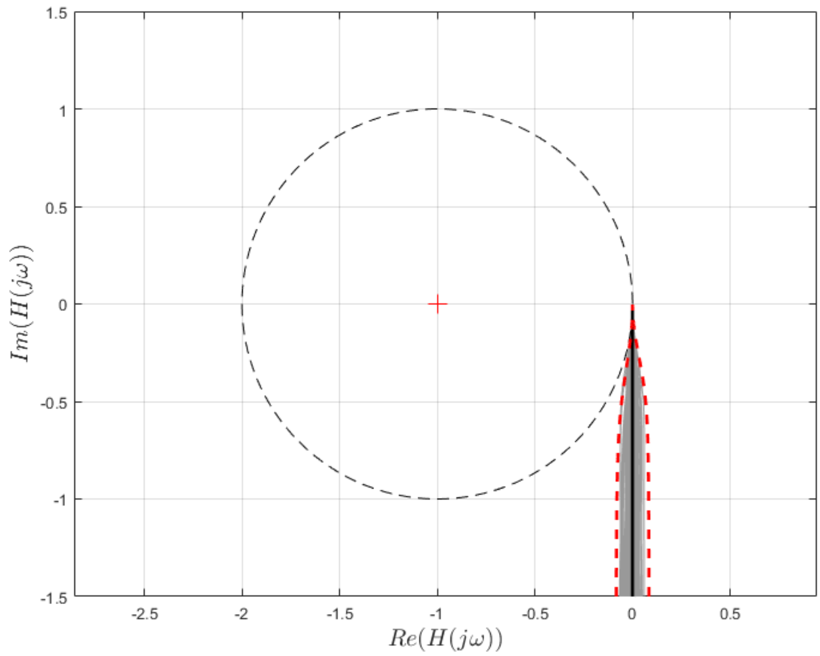

Figure 5.8. The Nyquist diagrams of MC runs with 10% uncertainty.

5.4 Simulation Results

During the tests the reference signal, input disturbances and output disturbances are defined as $r(t) = step(t)$, $d(t) = \sin(t)$ and $\sigma(t)$ is the output measurement noise, which has uniform distribution in between ±1e-3, respectively.

In Figure 5.9 the system response obtained in the absence of DOB when input and output disturbances affect the closed loop system is shown. As can be seen from the figure, when disturbances are active, the controller becomes incapable of alleviating it and this causes oscillations in the system response. In Figure 5.10 the system response obtained in the presence of controller and DOB is compared with the system responses obtained only in the presence of a controller. As can be seen from the figure, the proposed DOB design used with the controller makes the system more robust against disturbances and provides a response close to the nominal system's response.

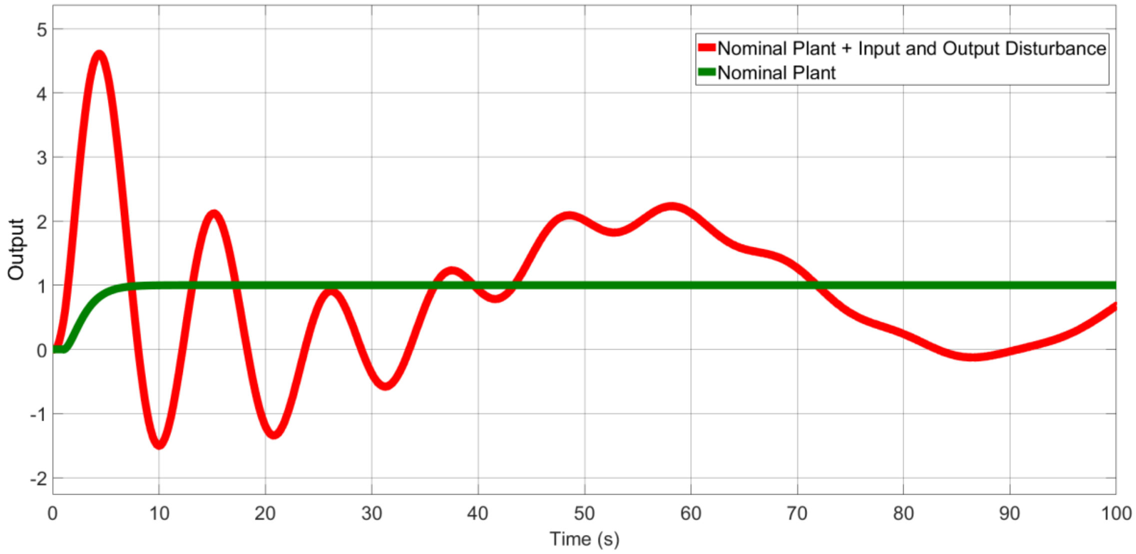

Figure 5.9. Closed loop responses of the system. Red and green curves show system responses in the presence and absence of both input and output disturbances, respectively.

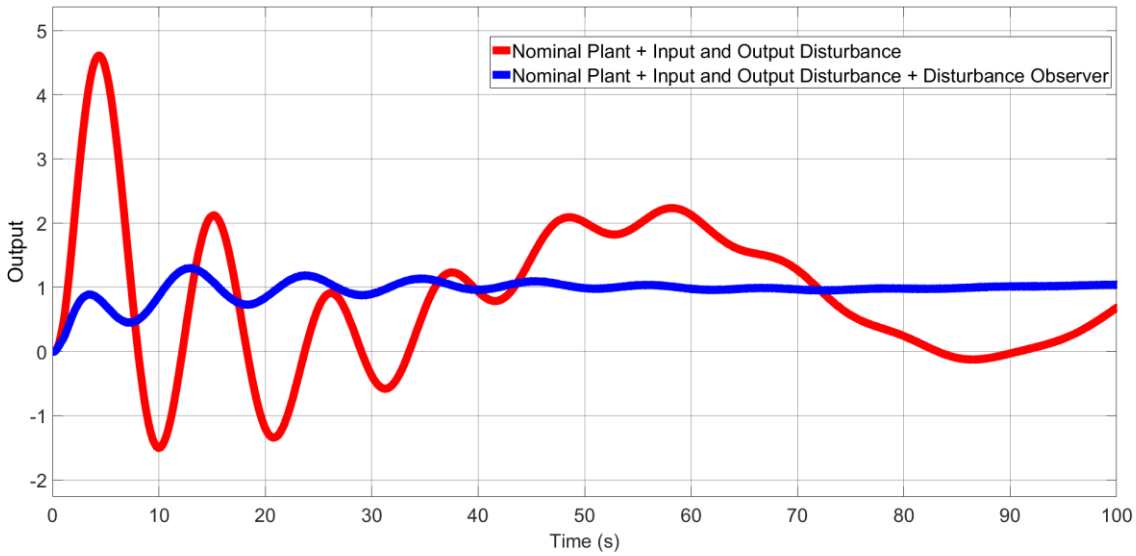

Figure 5.10. Closed loop responses of the system. Red and blue curves show system responses against input and output disturbances in the absence and presence of DOB, respectively.

In Figure 5.11, for the problem in [2] , the results of the original solution given in (5-6) and the results of the modified solution given in (5-7) are compared.

The NMP system used for testing in the original solution is given in (5-12). It is stated in paper that by using the cost function given in (5-6), the MP approximation of NMP system is calculated as in (5-13).

$$\frac{N}{D} = \frac{-s+25}{s^2+15s+50} \tag{5-12}$$

$$(s - 25) \approx -0.2940 \frac{s^2 + 100s + 10}{s+1} \tag{5-13}$$

In the tests performed by using the modified cost function given in (5-7), the MP approximation for the same NMP system is calculated as in (5-14). Then, using the MP approximations given in (5-13) and (5-14), the inverse models of the NMP system are calculated. As shown in Figure 5.11, when the modified cost function given in (5-7) is used, the response of the inverse system is closer to the reference signal. However, this improvement depends not only on the cost function but also on the optimization method. Since it is not specified which optimization method is used in [2], a comparison could not be made over these methods.

$$(s - 25) \approx \frac{-2.764\, s^2 - 24.98\, s - 0.4944}{s + 0.01978} \tag{5-14}$$

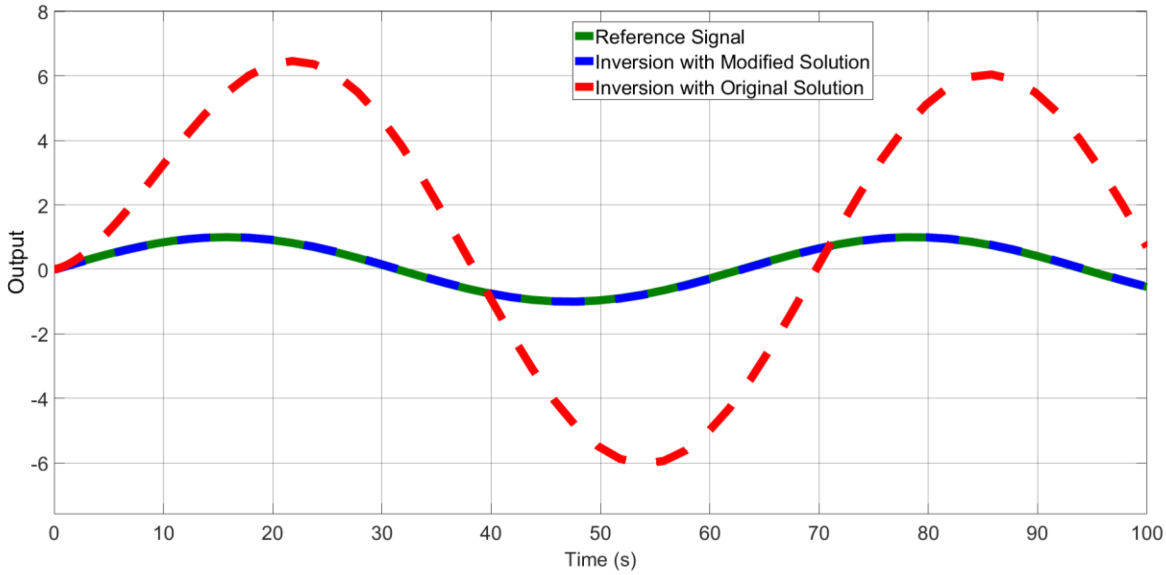

Figure 5.11. Comparison of original and modified methods of NMP-DOB. Red and blue curves show system responses using original and modified solutions, respectively.

5.5 Summary

In this section, the NMP-DOB design for the unmanned aerial vehicle was developed and performance tests were carried out under artificial disturbances. According to the results, the restriction of DOB for NMP systems was removed and the negative effect of the disturbance on the system response was eliminated.

6 ADAPTIVE SMITH PREDICTOR DESIGN USING RECURSIVE LEAST SQUARES FOR NON MINIMUM PHASE UNMANNED AERIAL VEHICLE

6.1 Introduction

Time delay in dynamic systems affects the operation of the system negatively. For this reason, the developers proposed different methods to protect system performance and eliminate the negative effects of time delay. SP is a simple and effective method designed to eliminate the time delay in the system. However, although it provides ease of design and effective delay compensation, the need for high-accuracy modeling of the actual system and precise measurement of the time delay makes the use of the SP design difficult. Details on the SP design can be found in Chapter III.

Unlike SP, CDOB design provides delay compensation without the need for the measurement of actual time delay. However, the need for the inverse of the actual system makes it difficult to apply the CDOB to NMP systems. Considering that most of the dynamic systems are NMP, special inversion methods are required to apply the CDOB design to such systems. Details on NMP inversion methods and CDOB design can be found in Chapter II.

For this reason, a design that combines both the flexibility of the SP and the independence of the CDOB from the precise time delay measurement was developed. This design combines the classical SP with the RLSWF algorithm, allowing delay compensation without the need for actual time delay measurement. In addition, by using the simple and flexible design structure of the classical SP, it can work for NMP systems without any extra design cost. In this respect, the new design provides superiority to CDOB.

This chapter is organized as follows. In Section 2 how SP and RLSWF are combined is explained. In Section 3, the performance of new design under different constant time delays and varying time delays are shown. Finally, the chapter is summarized in Section 4.

6.2 Combination of Smith Predictor Solution and Recursive Least Squares with Forgetting Factor

In the new adaptive SP design, the classical SP structure is combined with the RLSWF algorithm, aiming to eliminate the adverse effect of delay without entailing precise delay measurement. The new adaptive SP design steps are given in between Figure 6.1 and Figure 6.5. Unlike the classical SP shown in Figure 6.1, it is assumed that the nominal model of the system is known and only the delayed system is modeled using RLSWF. In addition, it is aimed to model only the delayed system by eliminating the necessity of modeling the time delay separately.

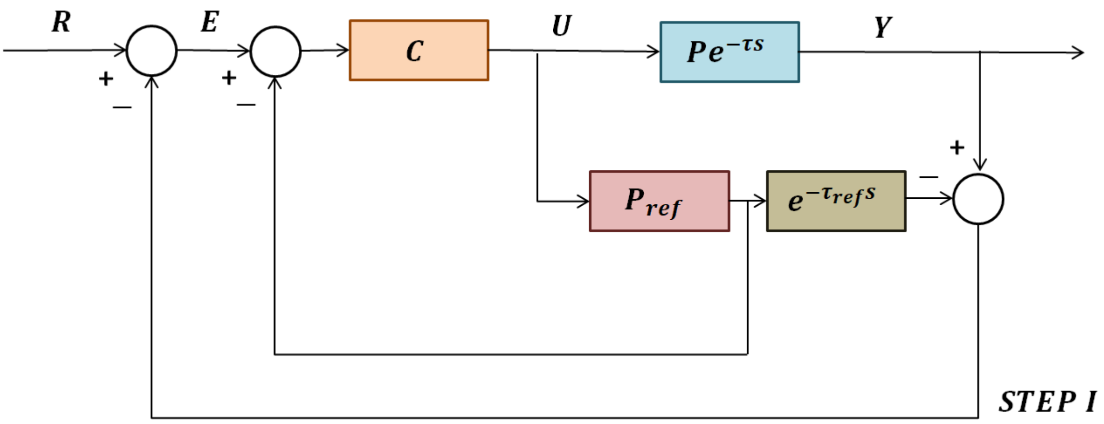

Figure 6.1. Classical SP structure.

The modified SP structure is shown in Figure 6.2. The SP design shown in this figure is exactly the same as the classical SP structure in Figure 6.1 and is arranged to explain the future design steps more easily. The reference model and the delayed reference model in the SP structure in Figure 6.3 are divided into different internal loops. In this way, it is ensured that the time delay and the reference model are identified together. Figure 6.4 shows that the delayed actual system can be modeled with the help of any online model estimation. In this structure, model estimation algorithm uses the inputs and outputs of the delayed system for identification and yields the error value between the real and the estimated system as output. This value is then subtracted from the reference signal.

Similarly, the difference between the error signal and the nominal system output is given to the system controller as input.

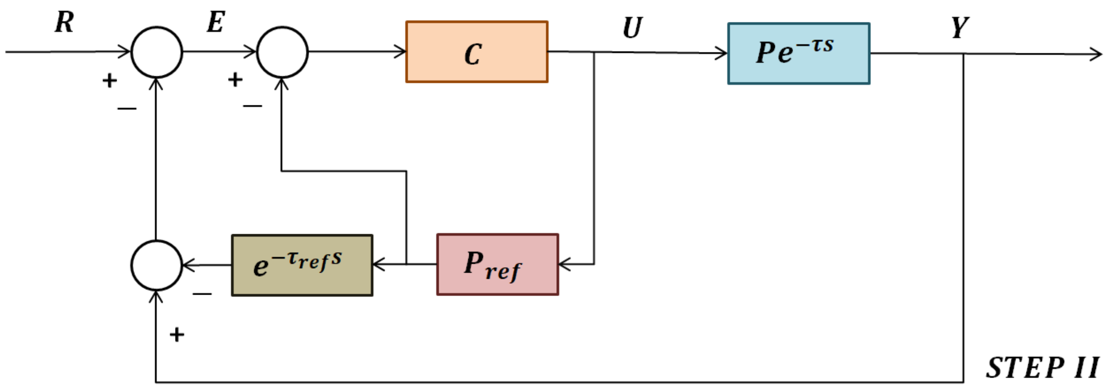

Figure 6.2. Modified SP structure.

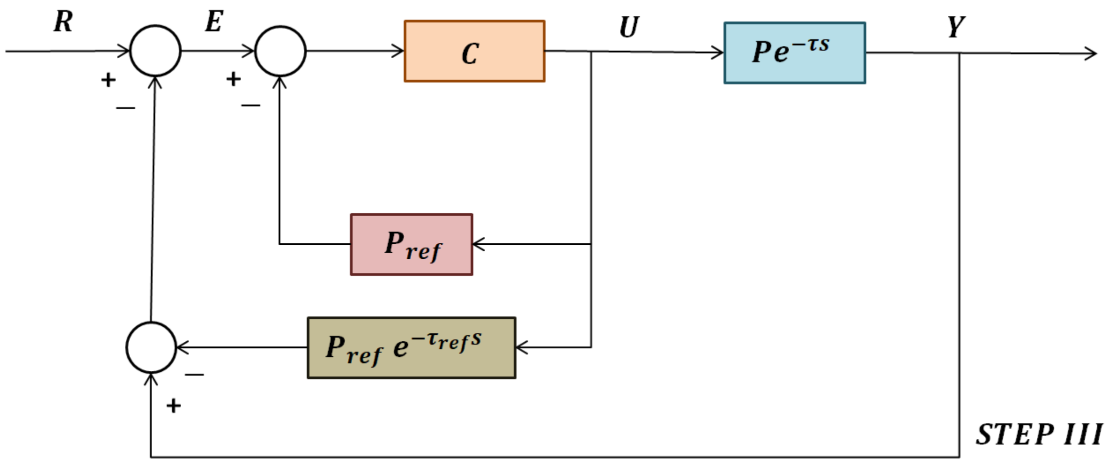

Figure 6.3. SP structure which reference model and delayed reference model are separated.

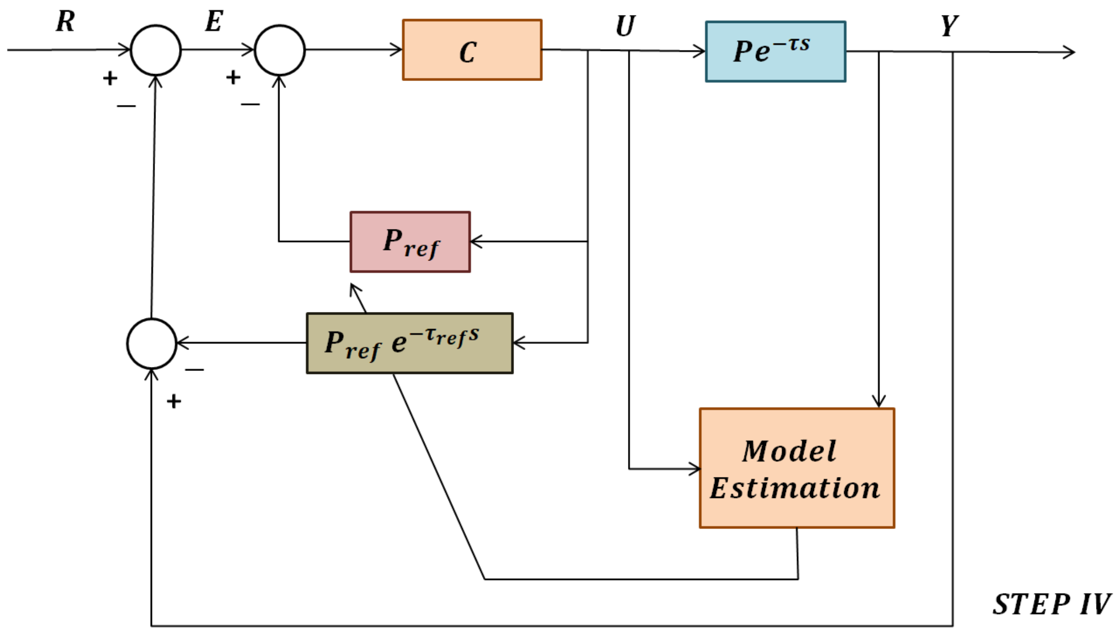

Figure 6.4. Adaptive SP structure using model estimation.

In Figure 6.5, online identification of the actual delayed system is performed using the RLSWF algorithm. The execution performance of this new solution is directly dependent on the performance of the RLSWF algorithm. As specified in (3-4), if the modeling of the delayed system is done with a sufficient level of fidelity and $\left(Pe^{-\tau s}-P_{ref}e^{-\tau_{ref}s}\right) \approx 0$ is obtained, the ideal SP design is achieved. Therefore, if the RLSWF algorithm also performs high-fidelity identification and obtains the error value between the real and the identified delayed systems close to zero, more acceptable delay compensation is achieved by approaching the ideal SP design. Details on the RLSWF algorithm can be found in Chapter IV.

6.3 Simulation and Results

In order to compare the new adaptive SP design with the classical SP, the autopilot of the Tower Trainer 60 unmanned aerial vehicle is used, in which the DOB design presented in the previous section, is also tested. Details about the experiment setup can be found in Chapter V.

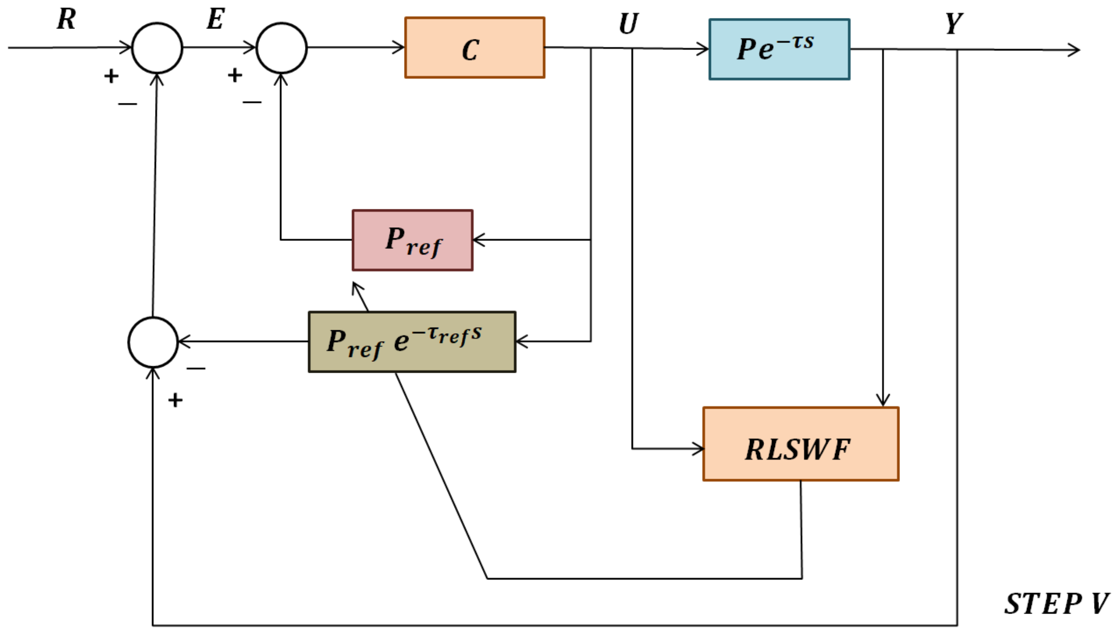

Figure 6.5. Adaptive SP structure using RLSWF algorithm for model estimation.

In Figure 6.6 and Figure 6.7, it is observed how robust the system is against delays in the presence of the controller designed using the H_∞ synthesis method. Time delay values are chosen as τ = 0.1 s and 1 s, respectively. The reference input is a step signal.

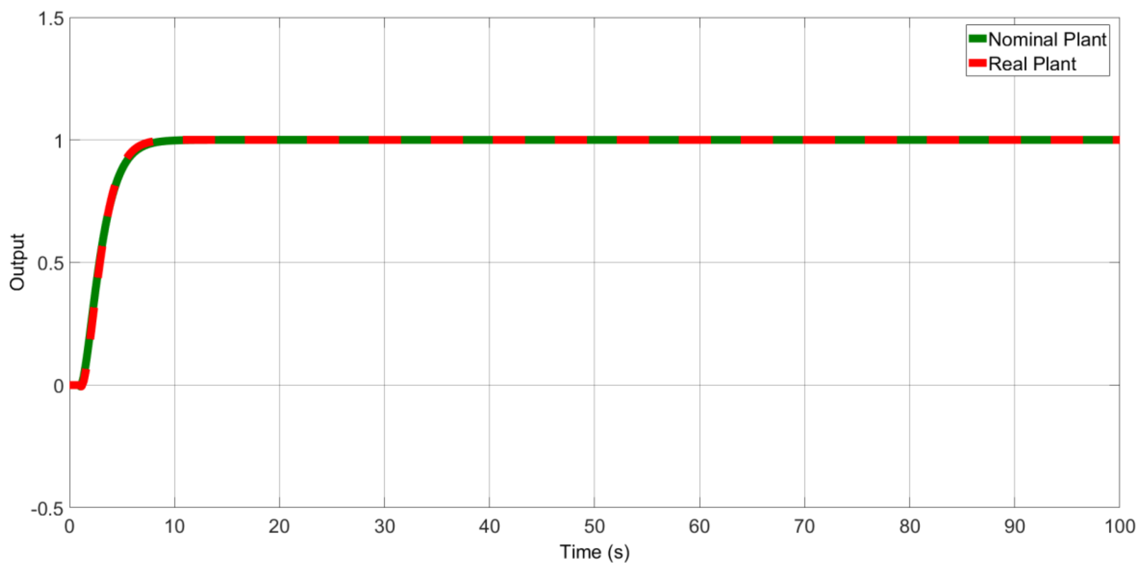

Figure 6.6. Closed loop responses of the system. Red and green curves show system responses in the presence and absence of $\boldsymbol{\tau = 0.1\ s}$, respectively.

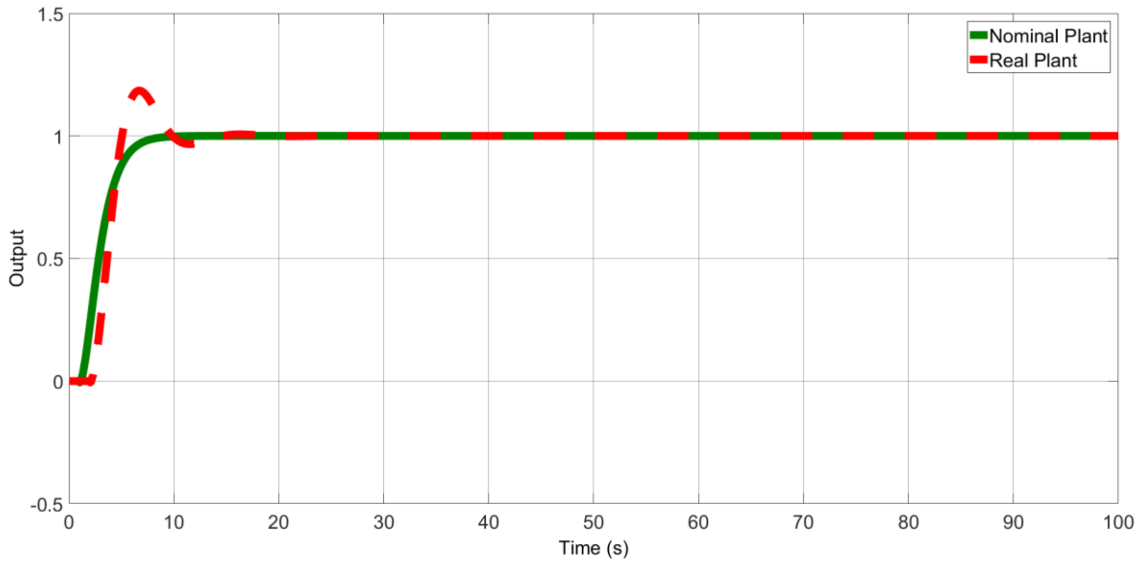

Figure 6.7. Closed loop responses of the system. Red and green curves show system responses in the presence and absence of $\boldsymbol{\tau = 1\ s}$, respectively.

In Figure 6.8 the responses of nominal and delayed real systems are compared by choosing τ = 10 s. As can be seen from the figure, the system response loses its stability at high delay values and the controller cannot perform the satisfactory performance. For this reason, the adaptive SP design approach created using the RLSWF algorithm is added to the closed loop system and responses are examined.

In Figure 6.9, the response of the closed loop system in which this design is used and the response of the system obtained in the presence of the controller only are compared. As can be seen from the figure, the new adaptive SP design ensures a stable response from the system by eliminating the deteriorating effect of the delay without the need for the actual delay information, even at high delay values.

After the tests with constant time delay, the new adaptive SP design was tested by using varying time delays. For this purpose, the varying artificial delay shown in Figure 6.10 is used. In Figure 6.11, the response of the closed loop system in which this design is used and the response of the system obtained in the presence of the controller only are compared. As can be seen from the figure, the new design eliminates the negative effect of the varying time delay.

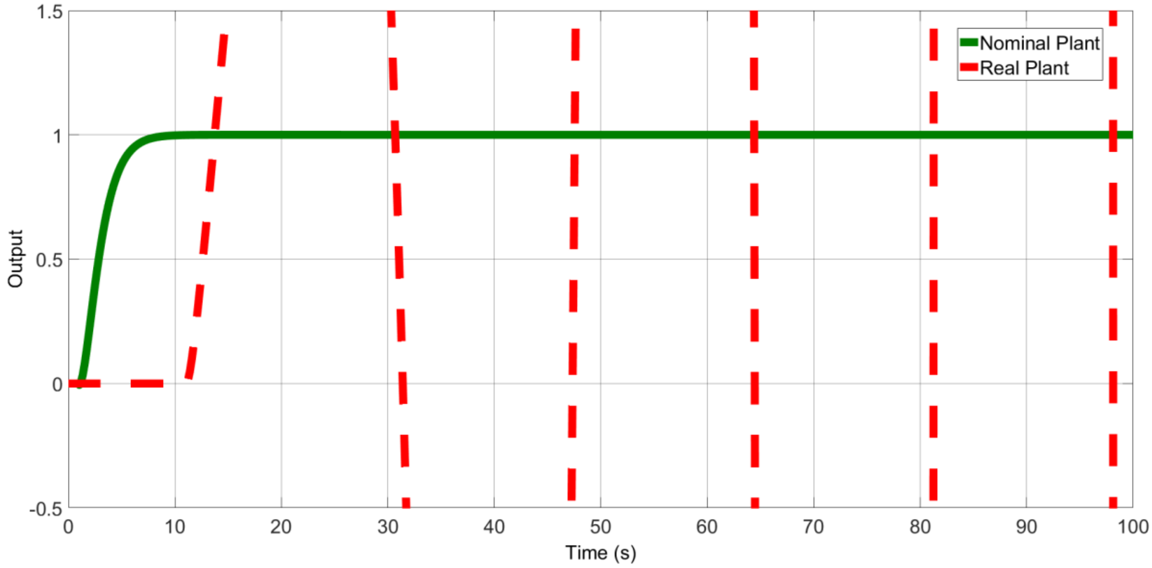

Figure 6.8. Closed loop responses of the system. Red and green curves show system responses in the presence and absence of $\tau = 10\ s$, respectively.

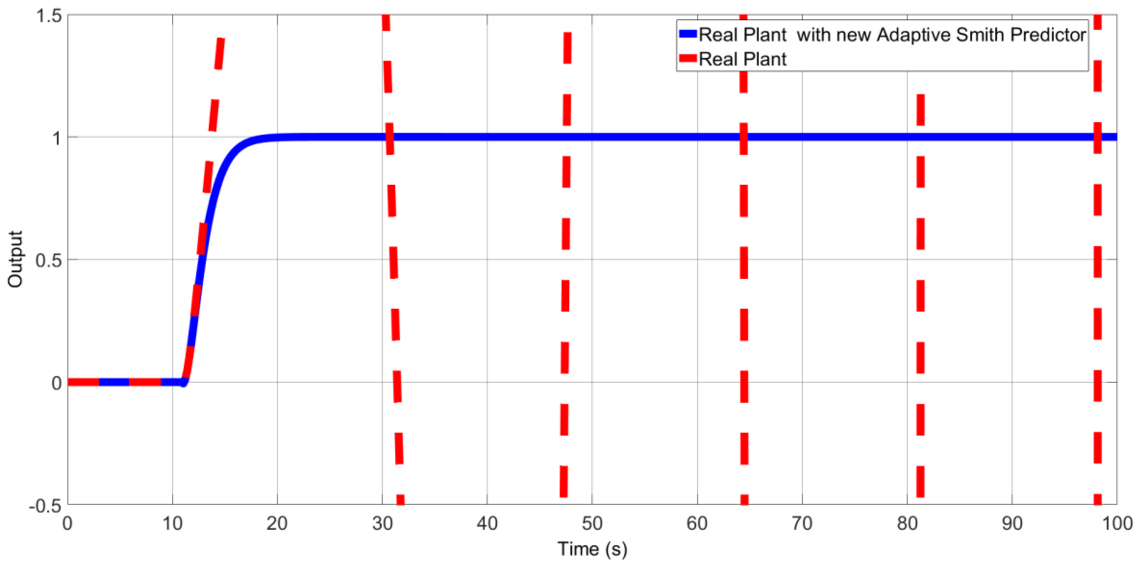

Figure 6.9. Closed loop responses of the system. Red and blue curves show system responses when $\tau = 10\ s$. The loop in the presence (blue) and absence (red) of new SP approach produces radically different responses.

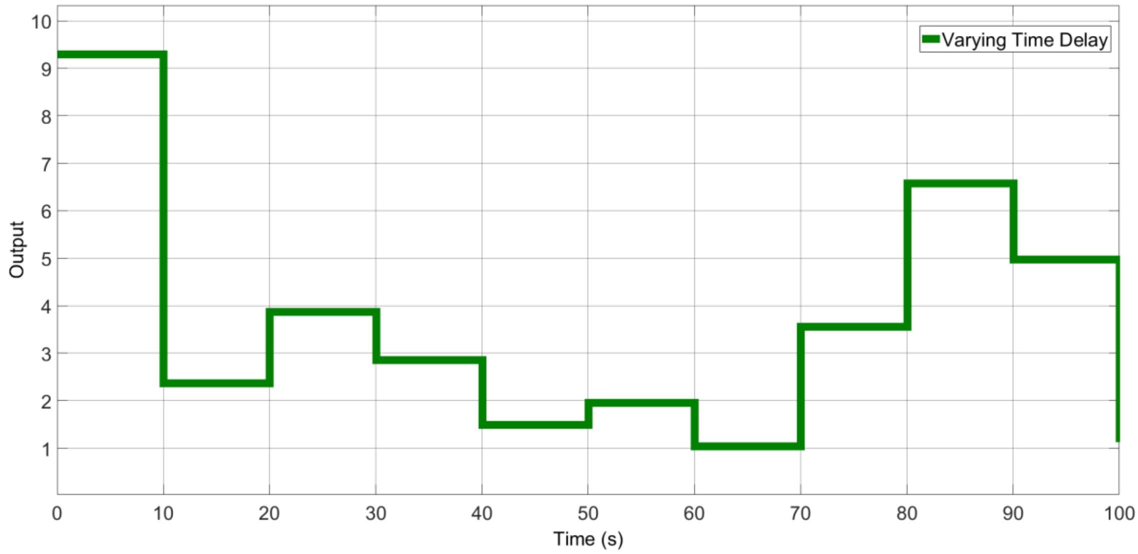

Figure 6.10. Artificial varying time delay.

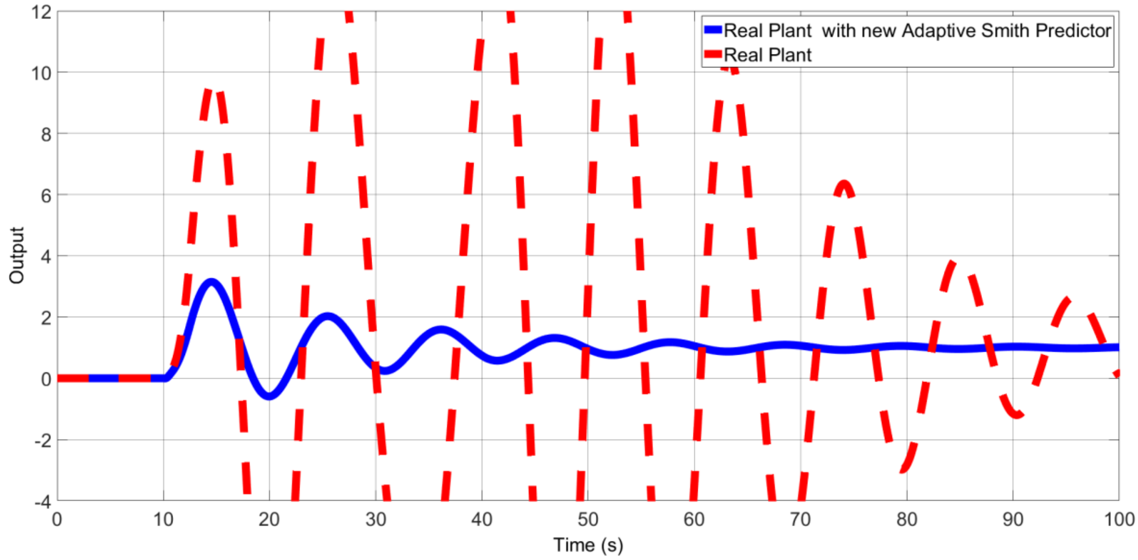

Figure 6.11. Closed loop responses of the system. Red and blue curves show system responses under artificial varying time delay. The loop in the presence (blue) and absence (red) of new SP approach produces radically different responses.

6.4 Summary

This chapter explains the new adaptive SP design developed by combining RLSWF and SP. This design eliminates the need for the classical SP design for precise delay measurement, eliminating the negative effect of time delay on system response. The results show that the new SP design performs well for both constant and varying time delays.

7 ONLINE DISTURBANCE AND TIME DELAY COMPENSATION DESIGN FOR NON MINIMUM PHASE UNMANNED AERIAL VEHICLE

7.1 Introduction

The time delay problem in dynamic systems negatively affects the system stability and response. SP is used in order to eliminate time delay in dynamic systems. Although this design is simple and effective, the need for precise measurement of the actual time delay value makes it difficult to use the design. Details on SP structure and the different types of SP can be found in Chapter III.

Unlike SP, CDOB provides delay elimination without the need for the actual measurement of the time delay. However, the need for the inverse of the real system in CDOB creates a constraint for NMP systems as in other DOB designs. Therefore, a new SP design was developed by combining the simplicity of the classical SP and the flexibility of the CDOB. In this new adaptive SP design, delay elimination is provided without the need for actual delay measurement by using the RLSWF algorithm. In addition, the fact that it is easily applicable for NMP systems provides superiority to CDOB. Details on this new adaptive SP design can be found in Chapter VI.

Although classical SP can eliminate the time delay in the system, disturbances negatively affect the operation of the SP. In 2008, Lee et al. [56] proposed the design that could eliminate the negative effect of disturbance and time delay by combining classical SP and DOB. Similarly, in 2010, Kim and Son [57] combined NMP-DOB and classical SP, and tested the design using time-varying disturbances. Finally, in 2016, Ahmadi and Nikravesh [58] made the classical SP design robust against parameter variations using the modified DOB.

In the proposed study, the novel DOB designed for NMP systems and the new adaptive SP which is implemented without relying on the actual delay measurement are combined to create a new controller design against both time delays and disturbances. Unlike other studies in the literature, not needing actual delay measurement by using adaptive SP design gives this new design an advantage.

This chapter is organized as follows. In Section 2, how novel adaptive SP and NMP-DOB designs are combined is explained. In Section 3, the performance of new design under artificial time delays and disturbances are shown. Finally, the chapter is summarized in Section 4.

7.2 Combination of Adaptive Smith Predictor Solution and Non Minimum Phase Disturbance Observer Design

In combining NMP-DOB and adaptive SP designs, the technique specified in [12] is used. The structure of this technique is shown in the Figure 7.1. In this structure, the classical DOB design is modified for time delayed systems and combined with the classical SP structure.

In the new controller design, the NMP-DOB design given in Chapter V and the adaptive SP design given in Chapter VI are combined. However, the NMP-DOB design is used in a modified form for time delayed systems as shown in Figure 7.1.

The design steps of new control structure are shown in Figure 7.2, Figure 7.3 and Figure 7.4, respectively. Figure 7.2 shows the closed loop system with the NMP plant (P_{nmp}). As can be seen from the figure, there is both external disturbance (d) and time delay (τ) in the system. In Figure 7.3, NMP-DOB design is added to the closed loop in order to eliminate external disturbance affecting the system. In this DOB design customized for NMP systems, it is provided to find MP approximation of RHP zeros in the plant in a certain frequency range. The process of finding the MP approximation is achieved by optimization under certain conditions. Details on this novel NMP-DOB design can be found in Chapter V. Although this external disturbance affecting the system can be eliminated with the NMP-DOB design, an additional design is required for the time delay in the system. For this reason, novel adaptive SP design is added to the closed loop system. By utilizing the RLSWF algorithm in this novel SP design, the need for actual delay measurement of the classical SP design is eliminated. Details on the design can be found in Chapter VI. The system structure formed when two designs are combined can be seen in the Figure 7.4. Both designs can be developed and used independently, or they can be combined as shown in the figure.

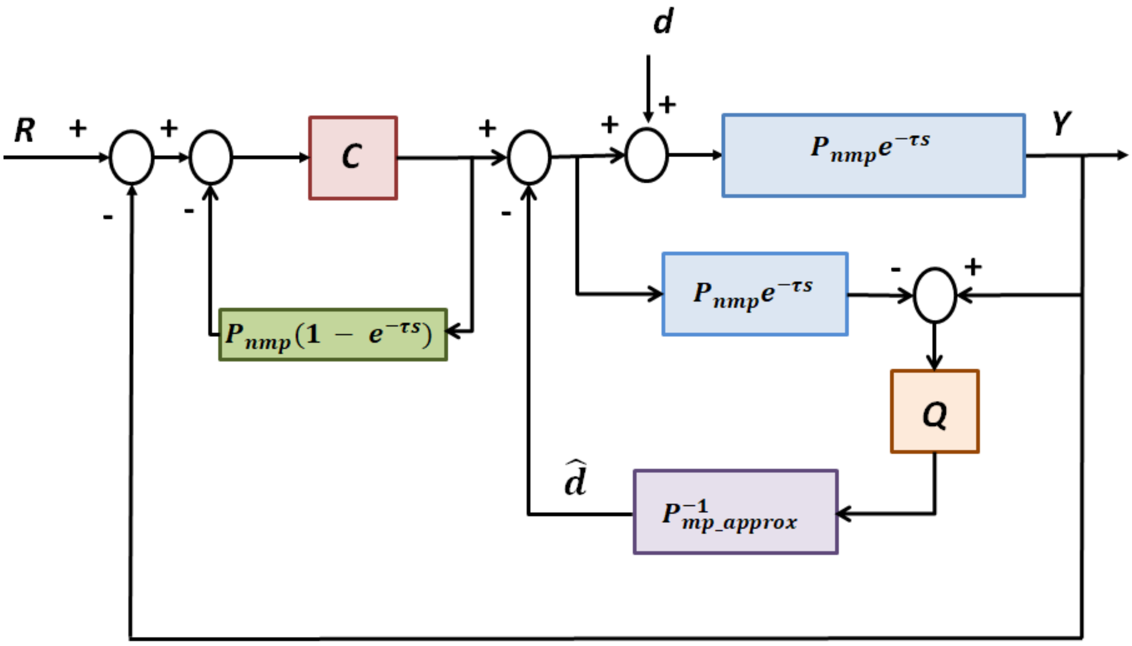

Figure 7.1. Modified DOB structure and classical SP design for time delayed systems.

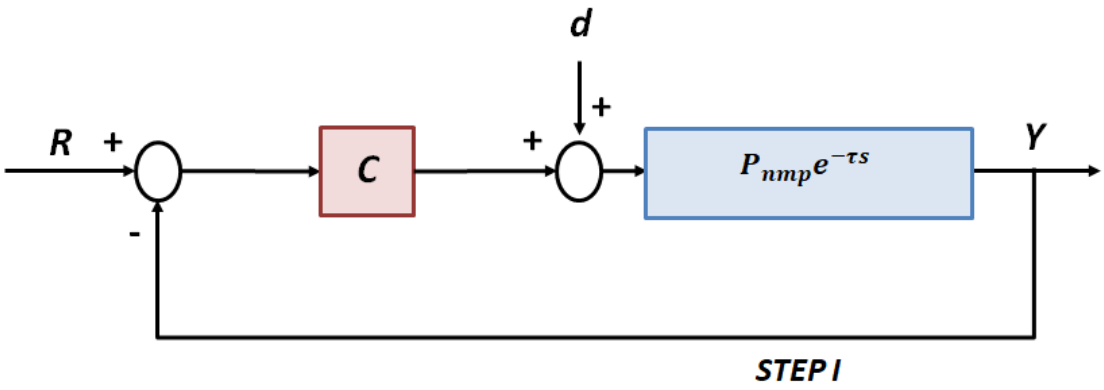

Figure 7.2. Closed loop system.

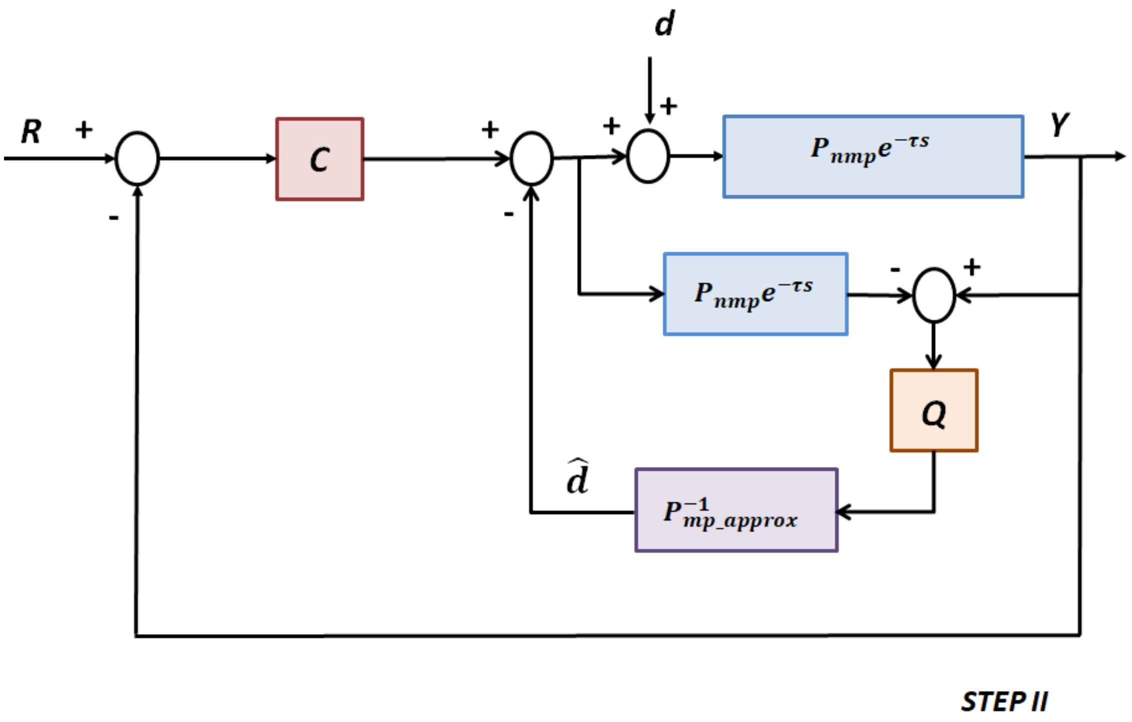

Figure 7.3. Closed loop system with the modified NMP-DOB design.

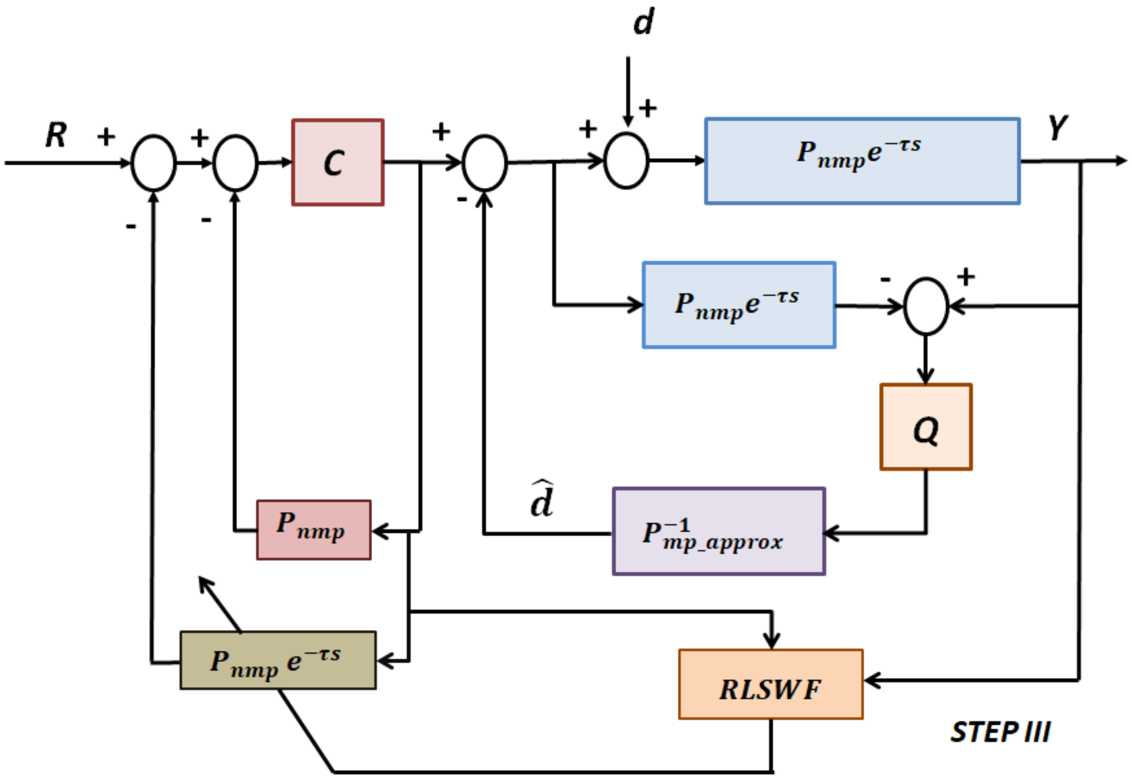

Figure 7.4. Proposed control structure.

7.3 Simulation and Results

The Tower Trainer 60 model used in Chapters V and VI is also used to show that the new controller structure provides disturbance and time delay compensation. This system takes an elevator angle as an input and provides altitude control. The H_∞ synthesis technique is used in the design of the system controller. Details about the plant and controller can be found in Chapter V.

By applying the disturbances to the system with time delay, system response in the presence of a controller, system response in the presence of adaptive SP design and system responses when NMP DOB and adaptive SP are used together are compared. $R(t) = step\,(t)$ is given to the system as a reference input. Artificial input disturbance is chosen as $d = \sin(t)$.

Figure 7.5 shows the case where the time delay is $\tau = 10\ s$ and the input disturbance is injected to the control signal of the system. As can be seen from the figure, the efficiency of the adaptive SP is tested design under time delay and disturbance. Similarly, Figure 7.6 shows system response with the same time delay and disturbance value with the presence of new controller structure. As can be seen from the system responses, when both designs are used in combination, the system exhibits better tracking performance with the presence of time delay and disturbance.

7.4 Summary

In this chapter, NMP-DOB design is modified for time delayed systems and combined with adaptive SP design. Both designs can be used together or they can be used separately according to system requirements. The results show that in the presence of disturbance and time delay, adaptive SP design alone is not sufficient, but effective time delay and disturbance elimination can be achieved when NMP-DOB design is combined with adaptive SP.

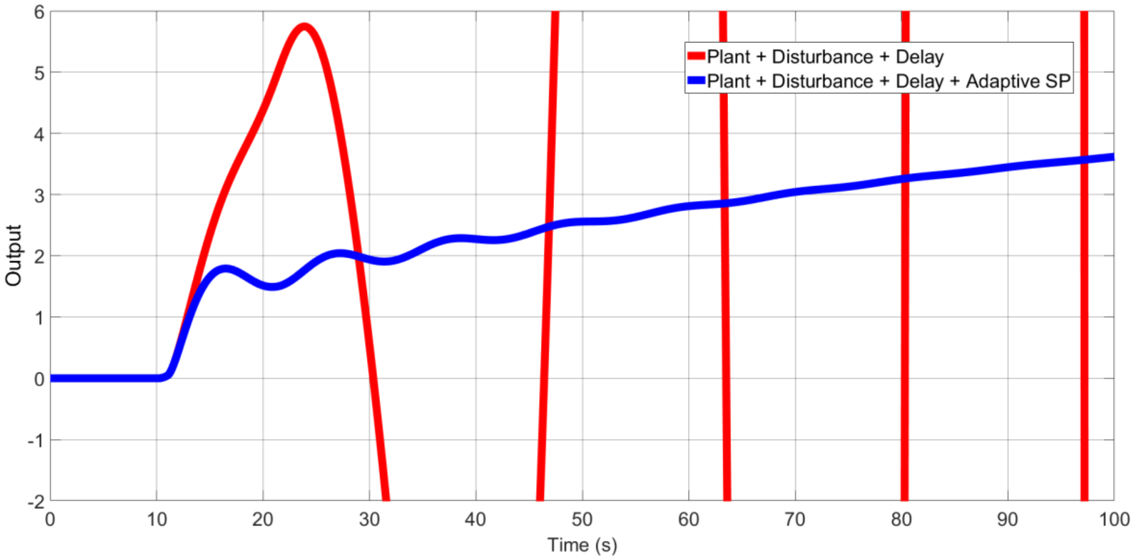

Figure 7.5. Closed loop responses of the system. Blue and red curves show system responses in the presence and absence of new adaptive SP design, respectively.

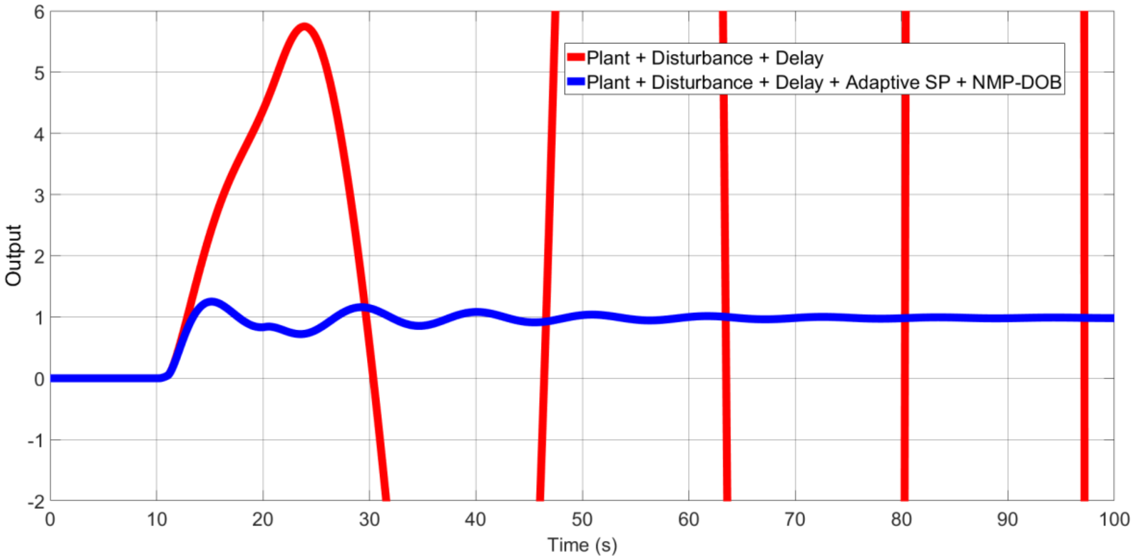

Figure 7.6. Closed loop responses of the system. Blue and red curves show system responses in the presence and absence of new control structure, respectively.

8 CONCLUSION AND FUTURE WORK

8.1 Conclusion

In the proposed research study, the novel control design that can compensate both disturbance and time delay in linear dynamical systems has been developed. However, there already exist designs with these abilities in the literature. Therefore, the constraints of these designs were eliminated and a new design was presented to the developers.

In the first part of the research, disturbance compensation in linear dynamic systems has been examined. The classical DOB design improves the closed loop system response by providing disturbance compensation when the system controller is not sufficient. Although it is a simple and effective design, it is a constraint for NMP systems that the DOB structure requires the inverse of the actual system. In order to eliminate this constraint, the MP approximation of the NMP system was calculated with the constrained optimization method and the DOB design was developed over this MP approximation. In the second part of the research, time delay compensation in linear dynamic systems has been examined. Although the classical SP design is a frequently used method for time delay compensation, the need for precise time delay measurement makes the usage of design difficult. For this purpose, by using system identification methods, the need for actual time delay measurement of SP design has been eliminated. Finally, both designs were combined to create the novel control design that can compensate both disturbance and time delay. These two new designs can be used both separately and in combination according to the system requirements.

The performance of all three designs has been compared with the performance of the system controller. According to the results, in cases where the robust controller designed with the H_∞ synthesis technique does not provide sufficient disturbance and / or time delay compensation, all three designs improve system response.

8.2 Future Work

In the proposed research, although constraint optimization techniques are used to make the classical DOB design available for NMP systems, this process is carried out offline. Therefore, for time varying dynamical systems, the inverse of the system cannot be obtained in real time. This situation can cause the NMP-DOB design to perform less efficiently for time varying systems. In future studies, the inverse of the system will be obtained in real time and NMP DOB design will be provided to work more efficiently for time varying systems.

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