NON-MINIMUM PHASE SYSTEMS

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DOI: 10.17973/MMSJ.2023_12_2023133

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The aim of this paper is to create a mathematical model of a manipulator of a dynamic system with a non-minimum phase. The first introductory part of the paper deals with the actual problem of manipulator control. The second part deals with the control of dynamic systems and the formulation of the control problem. The third and last section deals with the construction of the mathematical model of the manipulator.

KEYWORDS

Manipulator, minimum phase, non-minimum phase, mathematical model, control of dynamic system

2 INTRODUCTION

Nowadays, many scientific publications and research works are devoted to the problem of manipulator control, where various dynamic models are used to describe the manipulator instead of the real manipulator. Manipulator is a device that is used for handling work, performing technological tasks in order to facilitate heavy physical work. This system must be designed as a whole, thus combining mechanics, electronics and computer science into a unified mechatronic system. The problem of robotic manipulators involves solving the position and orientation of the manipulator segments [Astrom 2010, Dyadyura 2021, Gmiterko 2010 & 2013, Hroncova 2022a,b, Kelemenova 2021, Milovanovic 2016, Sincak 2021, Trojanova 2021, Vagas 2023, Virgala 2014 & 2020, Wu 2015].

The control of actuators in mechatronic devices and instruments is a very important problem in industrial applications. Handling devices such as cranes are widely used for transporting heavy and hazardous materials in factories, tall buildings, or ports. Based on their configuration, they are divided into two categories namely mobile and rotating cranes. Overhead cranes known as gantry cranes are mainly used in factories for the purpose of transporting loads in the shortest possible time without any large sway in the final position. In these applications, crane systems are affected by unfavorable factors such as parametric uncertainties consisting of unknown frictional force, trolley weight, payload weight which is secured by wire rope or chain. The biggest problem and challenge are the control of such systems, where the control is affected by less available control inputs as well as degrees of freedom. Control using proportional-integral-derivative controller (PID) is used as a control technique for industrial processes and electrical drives, as well as to maintain stable operation of linear and nonlinear systems. In this well-known problem, a new intelligent hybrid structure is used in online tuning of PID controllers. The structure is based on two adaptive neural networks that are used to approximate the control signals and handle system deviations. The developed structure and its experimental testing allow us to analyze and monitor the deviation signals in order to significantly minimize the deviation of the signals compared to other controllers. In this form of solution, it is recommended to use a highly nonlinear system that operates in the presence of unwanted disturbances [Bozek 2013 & 2014 & 2021, Galajdova 2018, Kelemen 2014 & 2021, Lestach 2022, Mikova 2013 & 2014 & 2016 & 2022, Nikitin 2020 & 2022, Sapietova 2018, Vagas 2011 & 2022].

3 CONTROL OF DYNAMIC SYSTEMS

Dynamic systems can be classified according to continuity, linearity, number of inputs and outputs, and time dependence. These divisions are further subdivided into subgroups [Bratan 2023, Dodok 2017, Kosinar 2011, Kuric 2016 & 2020, Peterka 2020, Ramesh 2010, Saga 2018 & 2020, Sagova 2022, Segota 2021, Shakhatreh 2012, Tlach 2019, Virgala 2022, Wiecek 2019].

SISO is characterized as the simplest type of single-input, single-output system. The simplicity of this system is exploited in the control design by using the Bode diagram, the Nyquist stability criterion and by using frequency analysis. The controller design can be done using polynomial expressions, which have the advantage of being easy to solve [Blatnicky 2020, Saga 2019].

3.1 Minimum phase system

A transfer function G(s) is minimum phase if G(s) and 1/G(s) are causal and stable. That is, the system has neither zeros nor poles in the right half-plane and, moreover, has no delay. For a system with minimum phase, Bode discovered that the phase can be uniquely derived from the magnitude slope. Minimum phase systems can be divided into:

- Stable - in stable minimum-phase regulated systems of 1st and 2nd order, the gain of the controller is not bounded from above. To control a stable regulated system with 1st and 2nd order minimum phase, the magnitude of the controller gain can be set without any constraints, where the following applies:

$$0 < K < \infty \tag{1}$$

  For stable regulated systems with a minimum phase higher than 2nd order, the gain of the controller K is bounded from above.
- Unstable - in unstable minimum-phase controlled systems, one or more poles occur in the right half-plane, while the other poles and all zeros are located in the left half-plane of the root plane "s". For unstable minimum-phase regulated systems, the gain of the controller is bounded both from above and below. For these systems, faster controller responses are required compared to the stable regulated system.

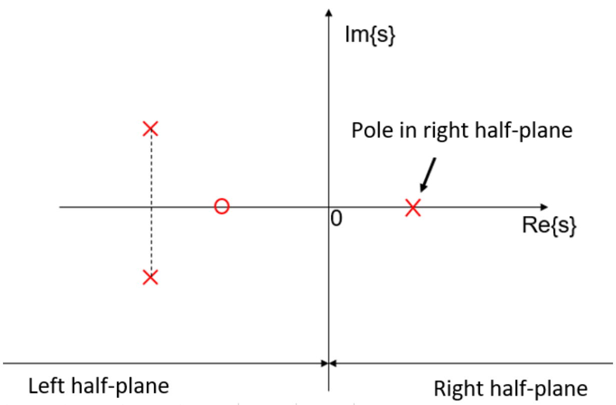


Figure 1. An unstable dynamic system with minimum phase

As an example, we can consider a regulated unstable system with minimum phase with transmission:

$$P(s) = \frac{1}{(s-1)(s+2)(s+3)} \tag{2}$$

The Hurwitz rule is used to investigate the effect of controller gain. The control transmission of the control circuit is equal to:

$$\frac{Y(s)}{W(s)}=\frac{\frac{K}{(s-1)(s+2)(s+3)}}{1+\frac{K}{(s-1)(s+2)(s+3)}}=\frac{K}{s^3+4s^2+s-6+K} \quad (3)$$

The characteristic equation and the main Hurwitz determinant are:

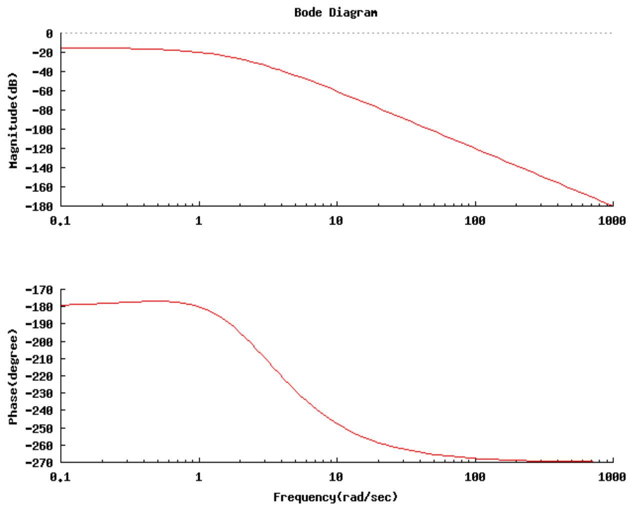
$$s^3+4s^2+s-6+K=0 \quad (4)$$

$$H_3=\begin{vmatrix}4 & -6+K & 0\\ 1 & 1 & 0\\ 1 & 4 & -6+K\end{vmatrix} \quad (5)$$

$$H_3=(-6+K)(10-K)>0 \quad (6)$$

The stability condition is:

$$6<K<10 \quad (7)$$



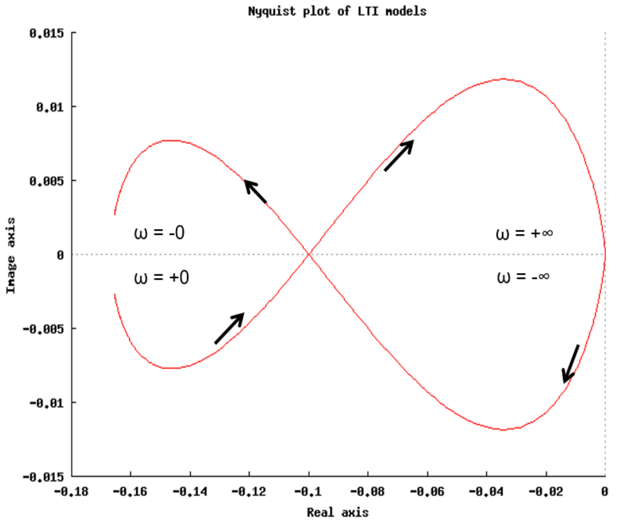


Figure 2. Delay of a non-minimum phase system

A minimum phase system has a minimum phase change among all transfer functions that have a graph of the same size.

3.2 Non-minimum phase system

The non-minimum phase system consists of two transfer functions.

$$G_1(s)=1, G_2(s)=\frac{1-s}{1+s} \quad (8)$$

$G_1(s)$ is the minimum phase until it contains no unstable zeros and poles. The magnitude of the transfer function $G_1(s)$ is 0 dB, and the phase is 0°. The magnitude of the transfer function with non-minimum phase $G_2(1)=0$.

It can be verified that $1/\,G_2(s)=\frac{1+s}{1-s}$ is unstable.

$$G_2(j\omega)=\frac{\sqrt{1+\omega^2}}{\sqrt{1+\omega^2}}=1 \quad (9)$$

$$G_2(j\omega)=\frac{\sqrt{1+\omega^2}}{\sqrt{1+\omega^2}}=1, \angle G_2(j\omega)=-tan^{-1}\omega-tan^{-1}\omega=-2tan^{-1}\omega \quad (10)$$

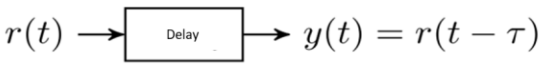


Figure 3. Delay of a non-minimum phase system

Time-delay systems do not have minimum phase behaviour. The transfer function G_3 (s)=exp(-τs), where τ is the delay. Time-delay systems do not have minimum phase behavior. The transfer function G_3 (s)=exp(-τs), where τ is the delay.

$$G_3(j\omega)=\exp(-j\omega\tau)=1\angle-\omega\tau\times\frac{180°}{\pi} \quad (11)$$

Non-minimal phase systems can be divided into:

Stable - a regulated system with a non-minimal phase has all poles located in the left half-plane "s", where some zeros may be located in the right half-plane "s". As an example, we can consider a stable regulated system with a non-minimum phase with transfer function:

$$P(s)=\frac{(s-4)}{(s+1)(s+3)} \quad (12)$$

The transfer function of the control loop is:

$$\frac{Y(s)}{W(s)}=\frac{\frac{K(s-4)}{(s+1)(s+3)}}{1+\frac{K(s-4)}{(s+1)(s+3)}}=\frac{K(s-4)}{s^2+(4+K)s+3-4K} \quad (13)$$

The characteristic equation is:

$$s^2+(4+K)s+3-4K=0 \quad (14)$$

Using the Hurwitz criterion assessing the stability of the system, we can determine the controller gain to determine the stability of the control system.

$$-4<K<\frac{3}{4} \quad (15)$$

In a stable regulated system with a non-minimum phase, there is a zero in the transmission of the regulated system in the right half-plane "s", so there is a limitation in the gain of the controller.

Unstable - a regulated system with a non-minimum phase is characterized by some poles and zeros being located in the right half-plane of the "s" plane.

We can consider a regulated system with transfer function:

$$P(s)=\frac{(s-4)}{(s-1)(s+3)} \quad (16)$$

Where transfer function of control loop is:

$$\frac{Y(s)}{W(s)}=\frac{\frac{K(s-4)}{(s-1)(s+3)}}{1+\frac{K(s-4)}{(s-1)(s+3)}}=\frac{K(s-4)}{s^2+(2+K)s-3-4K} \quad (17)$$

The characteristic equation is:

$$s^2 + (2 + K)s - 3 - 4K = 0 \tag{18}$$

Applying the Hurwitz criterion, we obtain conditions for stability:

$$-2 < K < -\frac{3}{4} \tag{19}$$

If a pole from the right half-plane of the roots "s" is in the transmission of the regulated system, the gain of the regulator is bounded from below. In the case of 1st and 2nd order systems, the constant K is not bounded from above. Thus, the consequence of the non-minimal phase looks as follows:

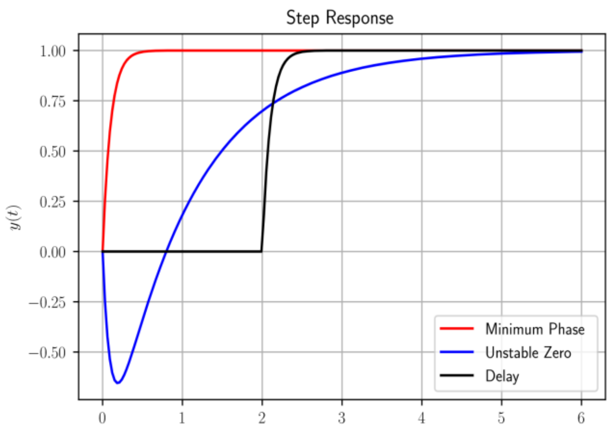


Figure 4. Bode amplitude-frequency diagram for a non-minimum phase dynamic system

Non-minimum phase systems are more complex to control than minimum phase systems. Their use in practice is quite common.

3.3 *Formulation of the control problem*

the aim is to find a feedback controller that generates the control variable:

$$u(t) = A[w(t) - y(t)] \tag{20}$$

based on the measurement of the controlled variable y(t) in such a way that the control objectives are achieved. This concerns the determination of the operator A, which represents the controller as a dynamical system. If the dynamic system is controlled linearly, then operator A is represented by a transfer function. In the search for the controller, the controller is joined to the controlled and together they form the controlled system.

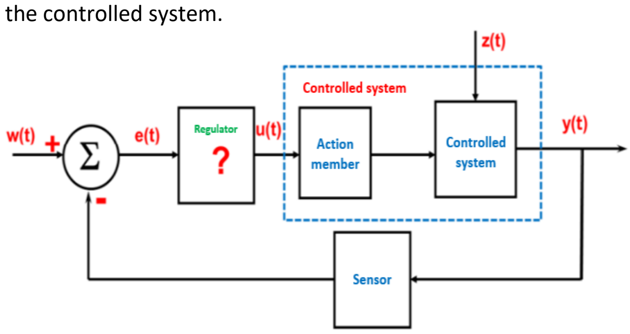


Figure 5. Structure of deviation control

4 CREATION OF A MATHEMATICAL MODEL

Figure 6 shows a system that is considered to be elastic. It is assumed that a flexible beam is attached to the trolley, when the trolley moves the beam deflects.

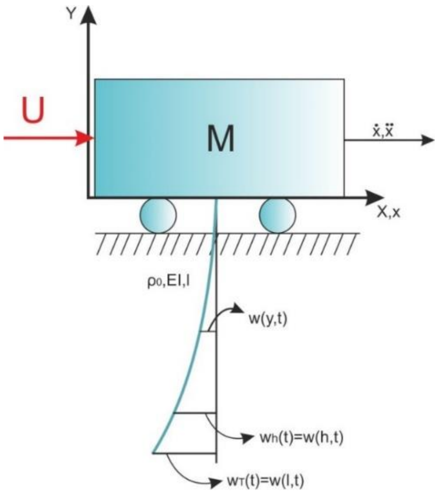


Figure 6. Flexible dynamic system

Under the Euler-Bernoulli assumption, the equations of motion are derived from Hamilton's principle:

$$M\ddot{x}(t) + \int_l^0 \rho \left(\ddot{x}(t) + \frac{\partial^2 w(y,t)}{\partial t^2} \right) dy = u(t) \tag{21}$$

$$MEI \frac{\partial^4 w(y,t)}{\partial y^4} + \rho \left(\ddot{x}(t) + \frac{\partial^2 w(y,t)}{\partial t^2} \right) = 0 \tag{22}$$

where M is the mass of the trolley, l is the length of the flexible beam, ρ is the specific gravity of the flexible beam, EI is the bending stiffness of the beam, y is the position of the trolley and w (y, t) is the deflection of the beam.
The boundary conditions can then be written as:

$$w(0,t) = \frac{\partial w(0,t)}{\partial t} = \frac{\partial^2 w(l,t)}{\partial t^2} = \frac{\partial^3 w(l,t)}{\partial t^3} = 0 \tag{23}$$

As is well known, a moving elastic beam represents a system with a non-minimum phase. For simplicity, only the first eigenmode, i.e. *n* = 1, is considered. First, the transfer function between the end position of the beam (y_2) and the input U(t) must be determined. The position of the beam end is given by the relation:

$$x_2(t) = \alpha(t) + \Psi_1(l) q_1(t) \tag{24}$$

Laplace transforming the transfer function is of the form:

$$\frac{X_2(s)}{U(s)} = \frac{k_1 \left(\frac{1}{\omega_1^2} \left(1 - \frac{\Psi_1(l)\mu_1}{m_1} \right) s^2 + 1 \right)}{M_s s^2 (m_1 s^2 + k_1)} \tag{25}$$

The value of the non-minimum phase of the system can be determined from the following criterion:

$$B(r) = 1 - \frac{\Psi_1(l)\mu_1}{m_1} \tag{26}$$

5 CONCLUSION

If B(r) is negative, the system is with non-minimum phase If B(r) is positive, the system is with minimum phase.
The aim of the paper was to develop a mathematical model of a manipulator of a dynamic system with a non-minimum phase. In the first part, current manipulator control solutions and basic concepts related to the problem are described. In the second part, it was necessary to understand the control theory based on the different characteristics of the dynamic system with minimum and non-minimum phase, where based on the theory, the development of the mathematical model was started. For the selected dynamic system model, an elastic

dynamic system of a trolley to which an elastic beam is attached was chosen where deflection occurs during motion. According to the Euler-Bernolli assumption, the equations of motion are derived from Hamilton's principle based on which the boundary conditions were determined. This moving elastic beam represents a system with a non-minimal phase where only the first eigenmode is considered. Based on the mathematical operations, the transfer function of the dynamic system was determined, where the value of the non-minimum phase of the system is determined using the B(r) criterion.

ACKNOWLEDGMENTS

The authors would like to thank the Slovak Grant Agency - project VEGA 1/0201/21 and project KEGA 027TUKE-4/2022.

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