



Study of Angular Velocity Control of Double Motor Propeller Shaft System

التحكم بالسرعة الدورانية لداسر محور الحركة لسفينة ذات محركين

by

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DECLARATION

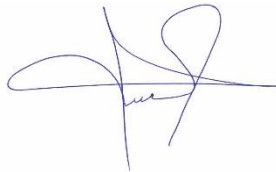
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Abstract

An investigation into multivariable control of propeller shaft system of marine vessels is introduced in this study. Two motors drive the shaft with two input voltages to produce torques which overcome the inertia of the load as well as the inertia of internal components of propeller shaft system in order to generate a rotational movement with two different angular speeds. In order to find the best response, best performance and the lowest power consumption by the controller of propeller shaft system, two approaches of control theory is presented; H-infinity control as well as Looping shaping. This paper shows how to reduce energy consumption, hence reduce tear of system's internal component, the noise generated by system and maintenance cost. This research provides a comparison between the two control strategies in order to determine the pros and cons of each method and find the suitable controller based on application may be targeted later.

خلاصة البحث

دراسة تم القيام بها لتقديم بحث مفصل في كيفية التحكم في نظام متعدد المتغيرات لداسر محور حركة لسفينة ذات محركين. يتم استخدام محركين كهربائيين يتم تزويدها بمصدري طاقة كهربائية مختلفين "فولتية" و ذلك لتوليد عزم دوران يجب أن يتغلب على عزم القصور الذاتي لداسر محور حركة السفينة بالإضافة الى عزم القصور الذاتي للأجزاء الأخرى في النظام و ذلك لتمكينه من توليد حركة دورانية في داسر محور حركة السفينة بسرعتين مختلفتين. للحصول على أفضل استجابة لنظام لداسر محور حركة السفينة؛ أفضل إنجاز و أقل استهلاك للطاقة من قبل المتحكم؛ تم تقديم طريقتين للتحكم في نظام السفينة و هما ال اتش اللانهائية بالإضافة الى طريقة تشكيل الدائرة المغلقة. في هذا البحث تم تقديم كيفية تقليل الاستهلاك في الطاقة المستخدمة من قبل المتحكم و بالتالي تقليل الحرارة للأجزاء الداخلية للنظام و تقليل التآكل, تقليل الضجيج المولد من النظام, زيادة عمر مكونات نظام شافت السفينة و بالتالي تقليل الكلفة التشغيلية. يقدم البحث دراسة مقارنة بين كلتا الطريقتين المستخدمتين للتحكم في نظام داسر محور حركة السفينة ذات المحركين, و يتم الوقوف على الإيجابيات و السلبيات لكل طريقة للوصول الى المتحكم الذي يتناسب مع التطبيق المستخدم له النظام.

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List of definitions and/or Abbreviations

$G(s)$	Transfer function	matrix
$d(s)$	Denominator of $G(s)$	function
$V(s)$	Input voltage signal	scalar
$L(s)$	Inductance	scalar
R	Resistance	scalar
$T(s)$	Torque signal	scalar
$\theta(s)$	Angular deflection	scalar
$\omega(s)$	Angular speed	scalar
K	Stiffness	scalar
J	Inertia	scalar
C	Damping	scalar
$M(t)$	Moment	scalar
Λ	Eigen value matrix	scalar
U	Eigen vector matrix	scalar
$u(t)$	Reference input signal	scalar
$e(t)$	Error signal	scalar
$v(s)$	Input voltage signal	scalar
$g_{ij}(s)$	Elements of $G(s)$,	function

I	Identity matrix	matrix
m	Number of inputs and outputs	scalar
$P(s)$	Pre-compensator	matrix
$W(s)$	Weighting function	matrix
$\mathbf{F}_c(s)$	H-infinity transfer function	matrix
$\mathbf{d}(s)$	Disturbance signal	scalar
$\mathbf{E}(t)$	Energy consumption	scalar
$I(s)$	Finite time delays	matrix
$v(s)$	Disturbances	vector
τ	Time constant	scalar
$y(s)$	Transformed output	vector
$h_j(s)$	Feedback path compensator	function

(1)

Introduction

1.1 Research background:

Without a driven mechanism, Ships would be just floating objects on the water surface; it wouldn't be useful for cargo carrying, passenger's transport, oil transport as tankers, containers trading and many other functions. Movement of all marine ships and vessel on water is accomplished through a mechanism called "propulsion".

In general, Propulsion means creating a force pushing a mass to move. The force is called thrust and it changes the state of a working fluid from static and accelerates it for movement. The amount of thrust depends basically on two factors: the amount of displaced mass and the velocity of the displacement of that mass. Propulsion examples are available everywhere; Airplanes, jet fans and rocket engines which mainly passes gas or steam through nozzles and create a repulsive force. Furthermore, it can be found in some internal systems of cars and trains, and it's an obvious example in birds and insects like bees in figure (1.1).



Figure 1.1: Bee with propulsion system

Based on working material, there are various types of propulsion systems like air, gas, nuclear, fuel, steam, jet water and diesel propulsion which is the most common type used in naval field. In 1897 Charles Algernon Parsons developed the first propulsion system through a steam turbine fueled with coal, and this system was used later in merchant ships and warships.

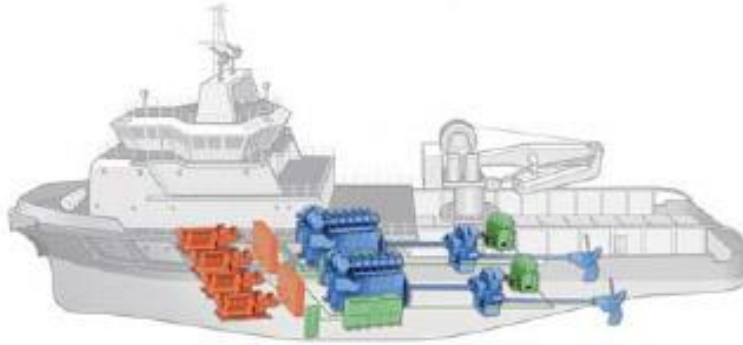


Figure 1.2: Ship propulsion system

Figure (1.3) shows nuclear propulsion system whereas the nuclear reactor is considered as the heart of the system, hence it generates the mechanical force moving the vessel and the heat generated from the reactor is used to generate the electrical power to supply the vessel. Nuclear reactors are more complex and efficient for long distance trips and it is used in specific functions.

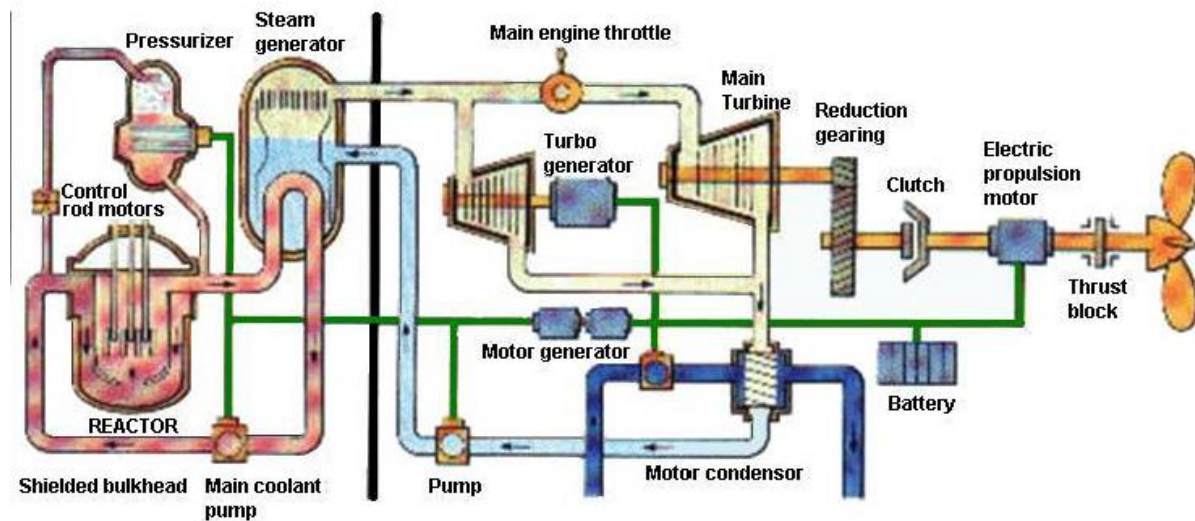


Figure 1.3: Pressurized-water Naval Nuclear Propulsion System

For naval propulsion systems, water is considered as the working fluid, and the action force is the mechanism of propelling the water opposite to the required movement direction, whereas the reaction force is the one pushing the ship forwards through the sea. The propeller is connected to a shaft and the shaft is connected to the motor/engine to produce a rotational movement.

The main components of electrical propulsion system are shown in figure (1.4) as following:

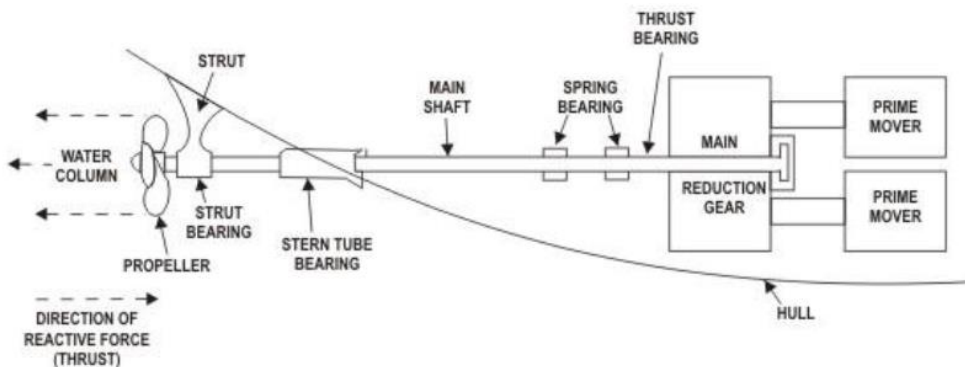


Figure 1.4: Propulsion System Main Components

1. **Battery:** batteries exist in propulsion system to store the required energy and feed it to motors during the whole trip. There are different types of batteries like lead-acid, nickel metal hybrid, lithium ion and fuel cell batteries.
2. **Prime mover “Motor”:** motors convert the input voltage to rotational movement. It is the source of mechanical force connected to the gear box. In general, Motors have two type of supply; AC and DC, whereas there are many types of motors based on power connection methods between stators and rotors.
3. **Reduction gear:** the output rotational speed of the motor/engine is usually high; hence the reduction gear reduces the speed and transmits it to the shaft. The shaft now rotates with low speed and accordingly higher torque.
4. **Shaft:** it’s the interconnection element between the gearbox and the propeller, and it transmits the reduced rotational movement to the propeller. Proper design and manufacturing should be considered for the shaft to withstand the different types of dynamic and static forces that will be applied.
5. **Bearings:** it is the interconnection between loads and shaft and it enables the shaft to move freely. There are different types of bearings, but one of the most commonly used in ships shaft propeller systems stave bearings which is a normal journal bearings.
6. **Propeller:** according to newton’s third law, the rotational movement of this part generates a water column cause the water to be displaced backwards of the movement direction of the ship and generates a force called thrust. The thrust is the action force here and the reaction force moves the ship forward. Propellers are widely used in aircraft systems but propellers in marine system are usually called “screw propellers” since it acts

like screwing the water through the device. Propellers consists of number of discs or helicoidal blades “two or more but usually three to five”; hence a proper design should be done to ensure the best efficiency and to get the maximum propulsion force. Based on the required application; three types of marine propellers are available: controllable pitch propeller, skewback propeller and modular propeller.

1.2 Problem statement:

Investigation of controlling the propeller shaft system for a marine vessel is introduced in this study. The propeller shaft system is a multivariable system having two inputs represented by two motors m_1 and m_2 powered by two input voltages v_1 and v_2 respectively. The motors are the motive forces for the shaft propeller. The outputs are represented by two rotational speeds ω_1 and ω_2 generated from the two motors m_1 and m_2 respectively, in order to get the open loop response of the propeller shaft system. The physical parameters of system like shaft diameter, stiffness, length of shaft, material ultimate strength and etc. are applied, and the system's transfer function is derived. Once a unit step input is applied for the system transfer function; it is found that the output is poor and needs to be enhanced. The overshoot, settling time and steady state error will be considered. Controller will be designed to improve the performance. Since it is not single input single output system SISO, outputs interaction is examined in this study as well, since it has a direct impact on system stability in some cases.

Disturbances are inputs for all systems but the impact is varying from negligible to major causing failure of the system in extreme cases. Noise and heat is a common result of disturbance inputs.

Improper Control of speed leads to high energy consumption, whereas systems get rid of this energy as a heat. Heat reduces the effect of internal components life like bearings, seals, electrical component etc. Sometimes, improper speed control might even cause uncomfortable behavior and in some rare cases shaft failure.

1.3 Study aims and objectives:

The drives in this dissertation review two control theories in order to utilize and improve the propeller shaft system response. H infinity and loop shaping are the two control techniques where will be used in this research.

The performance of the propeller shaft system with both methodologies will be highlighted considering transient and steady state conditions including overshoot, input/output decoupling, settling time and steady state error.

The energy consumption by the controllers will be computed for both techniques and results will be compared. One important property of systems is the disturbance rejection; hence a unit input disturbance signal will be injected into the system in order to consider both controllers ability to eliminate the error signals and consider the performance accordingly.

1.4 Dissertation organization:

The structure of the dissertation is organized in order to provide detailed presentation for the control of techniques used to regulate the speed of the propeller shaft system. The structure is in 7 parts, as following:

Part one gives a general information and background of a propeller shaft system with major components, functions, operations, application and the development of the system. Part one explains as well the purposes of controlling the speed as well as the methodology will be used.

Part two comprises a literature review of the marine propeller system, and the history of the development of control theory through the years. It explains as well the main control concept, terms, mythologies and theories which are available to improve the systems output. Some details about material properties and strength of materials are provided also in this part.

Part three presents the mathematical model of propeller shaft system and derives the transfer function of the propeller shaft system. Selections for the system's parameters are accomplished here and the design is carried out for the diameter of the shaft to insure avoiding system's failure. Moreover, an open loop response simulation is presented based on selected parameters.

Part four present H-infinity control theory used in this paper to improve the system performance, with mathematical derivation of the controller equations. After applying the H-infinity controller, simulation for system response is presented and discussed.

Part five presents loop shaping control theory as well with mathematical derivation of controller equations. Simulation for system response with loop shaping controller is provided.

Part six is a comparison study between the two control methods used in this paper. The comparison based on main system performance parameters, energy consumption a disturbance rejection characteristics.

In the last part, number 8, the conclusions are detailed; references and some appendix are provided.

(2)

Literature Review

2.1 Introduction:

To enable the drive system for any ship to operate normally, a simple control technique is required to drive the vessel forward, backward or stop it. To reverse the movement of the ship, a gear box is utilized to reverse the direction of rotation the whole system, while a simple push bottom is used to switch on/off. To control the direction of a vessel while moving, a flat metal object called a rudder changes its direction to tilt left and right by a steering mechanism.

The power supply for the motors can be controlled through a conventional, common technique which called a pulse-width modulation. This technique is a switching mechanism used to cut the power supplied to the load through different intervals to manage the delivered power. As shown in figure (2.1) the red wave is the input power to the load and the blue wave is the control signal, input voltage. As shown, once the power signal is constant, the input voltage will be zero “hence the input power “. On other direction, once the control signal “wave” changes with time, it switches the input voltage to the load.

Switching should be accomplished at a high frequency to avoid impact on the load “motor” and the whole system.

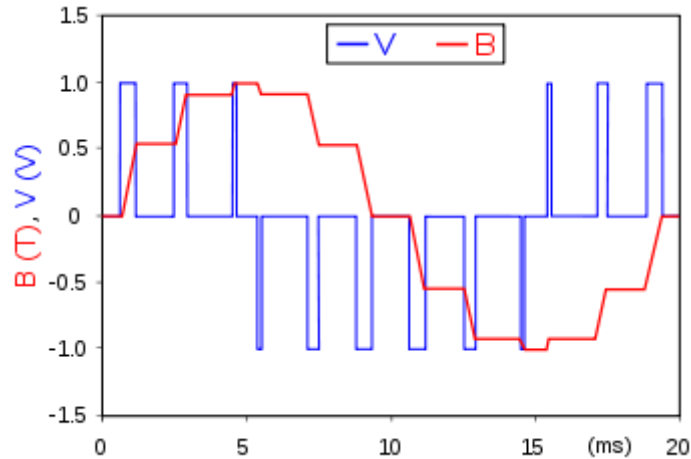


Figure 2.1: Voltage Modulation

The required power supply will be known through feeding back the output signal and compare it with the set value. Two convenient control theories will be applied to the error signal to improve the output signals which are H infinity and the loop shaping method. Comparison will be carried out between both techniques to understand the pros and cons of each mythology.

2.2 Development of control concept overview:

The need to control the output of many processes has existed for several decades. People from Greek, Hellenic, Arabs, and Europeans countries wanted to control the level of water, oil, and movement of objects.

2.2.1 First control idea, control of water and oil level:

The first feedback control system was presented by Greek in 300B.C. when Ktesibois designed a clock working by water shown in figure (2.2). A floating valve was utilized to keep the water level

at the supply container constant all time. Water drops to another container which indicates the time.

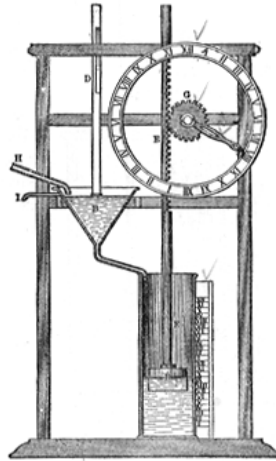


Figure 2.2: Water clock

A Greek engineer and inventor Philo of Byzantium “280B.C - 220B.C” introduced the “oil lamp” which main function is to keep the oil in level the same at all times. The water clock was developed and re-introduced later by an Arab engineer Al Jazari “1136 –1206” who wrote about the control of the liquid level.

2.2.2 Control development during the industrial revolution:

During 16th century Industry got more developed during the Europe industrial revolution and along with those new challenges raised for the need to control functions.

Temperature control was introduced for the first time in Europe by the Holland inventor Cornelis Drebbel “1572 1633”, he presented an oven which can kept the temperature within certain limits through a feedback control mechanism. A few years later, in 1681, Denis Papin innovated the first pressure release valve which was used to keep the pressure in a boiler at certain level. It was

a simple idea of putting a certain object above the boiler orifice. Once the pressure inside boiler overcame the object weight, then the orifice opened and released the steam pressure.

In the eighteenth century, steam engines were developed, to convert heat to evaporate the water and then generate steam force. The steam force was then then converted to rotary motion. Steam engines can't be functional without controlling speed.

In 1769 Speed control was introduced for the first time for an industrial application. The controller for the speed of engine was called "Watt's Flyball Governor". As shown in below figure (2.3), the output rotational velocity is fed back to the governor. Once the speed increases, the distance between the metal sphere increases due to the centrifugal force effect and the connection with boiler valve is released to decrease "or close" the steam valve opening then the engine speed reduce accordingly.

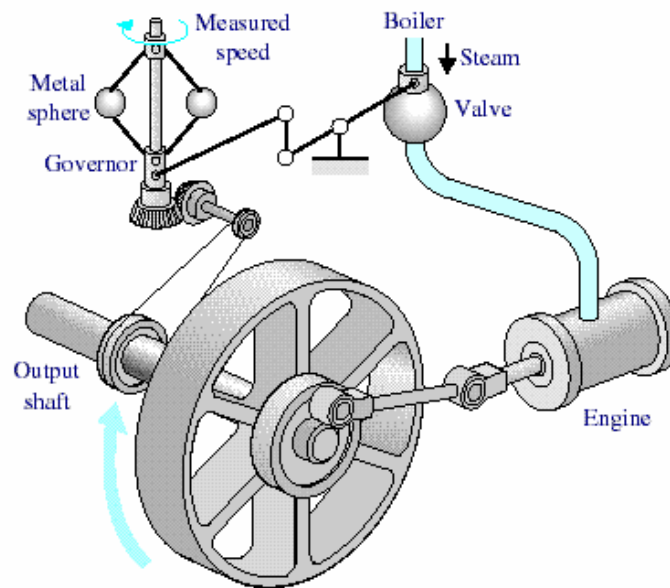


Figure 2.3: Watt's flyball governor

In 1765 a Russian inventor I. Polzunov “1728 –1766” introduced a simple feedback system through the design of a controller for a boiler which keeps the water level within the set limits. A floating object pulls an arm which then covers and closes the water supply orifice.

In 1868 differential equations were used for the first time to represent the physical system and develop a controller by the British scientist and mathematician J.C. Maxwell “1831-1879”. He applied differential equations to control the governor of a steam engine.

2.2.3 Development of Control in the 20th century:

Breakthrough in control theory occurred and took a place in untied state during the World War II, when AT&T Company was working on the improvement of a telecommunication system and enhancement of the performance of a telephone system. Since the signal generated and transmitted though thousands of kilometers; it was a crucial challenge to get the best performance of communication system. In 1932 American physicist Nyquist “1889 - 1976” introduced a new theory of determining the stability of negative feedback systems called the “Nyquist Stability Theorem” which gave control feedback systems during the World War II.

In World War II, David B. Parkinson who was hired by an American company “Bell Telephone laboratories” in United States of America, visualized an airplane with potentiometer and gun. Pointing at other planes the gun hit all perfectly. Parkinson believed its application was good idea and worked to make this dream true. In 1941 and Parkison introduced a feedback control system whereas the potentiometer measures the distance and create a signal which is fed back to be compared with a radar signal. The error signal was he fed to the controller which controls the position of the gun to hit the target.

2.2.4 Modern control system and automation era:

Control theory has a direct impact on our life. Controllers are in touch with our daily life when we use air conditions, cars, lifts, pumps, microwave and etc. on other hand, controller might be more distant like industrial controllers, state space methods and the weapons industry.

Energy consumption is one of the biggest challenges worldwide. Achieving the required output with best energy performance is the aim of all end users and manufacturers; actually it is an international target. Saving in energy reduces the carbon foot print, saves earth's natural resources, lessens greenhouse effects, and protects the future of next generations.

2.3 Basic Control Theory:

2.3.1 Definition of control system:

R.C. Doof & R.H. Bishop described the control system as "A control system is an interconnection of components forming a system configuration that will provide a desired system response". The basic components of any system are:

1. The input which is the physical source entering to system. Inputs may be called set point, or desired output response.
2. The process which is a set of items bounded to each other with relations.
3. The output which is the measured value which results from the whole process. The main purpose of control a system is to make the output has the same value as the input. The mathematical equation describes the relation between input "after it enters the process" and the relation between input and output is called the transfer function.

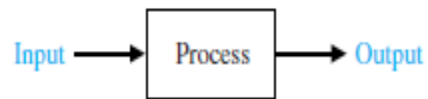


Figure 2.4: System basic components

Dorf and Bishop described the relationship between components as a cause and effect relationship.

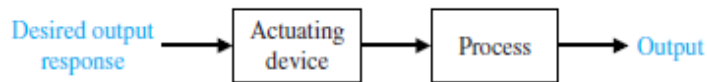


Figure 2.5: Simple control system

The main purpose of controllers is to monitor, adjust and improve the behavior and operation of a certain system (Albertos.P and Sala.A 2004). Since controllers have inputs and outputs, it can be described as a system that controls other systems.

Systems might be single input single output “SISO” or it might have more than one input/output or both (input and output and called MIMO). Practically, systems are not so simple and many items have a direct impact on the process. Hence systems usually have multiple inputs, multiple outputs. On the other side, due to environment or system conditions, unwanted signals fed to systems are called disturbances. The better the control system, the less the disturbance effect on system output and the ideal controller eliminates the disturbance and leads to zero “disturbance rejection”.

2.3.2 Open and closed loop control systems:

Open loop control system means that the input is not affected by the output signal and the control is carried out through pre-set values feeding to the system.

One of most common examples of an open loop system is the washing machine. In this simple system, the washing process continues regardless of the clothes being clean or not, until the set finish time. On other hand the washing will stop also regardless the clothes still being dirty or not.

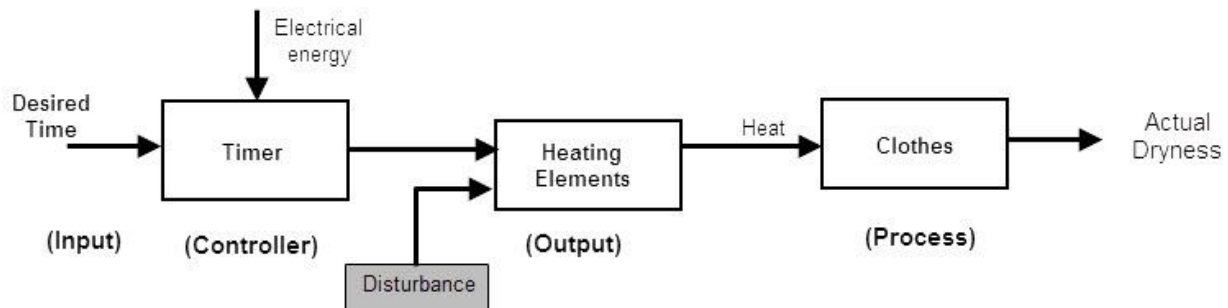


Figure2.6: Block diagram of open loop control system

Advantages of this control system are simplicity in manufacturing and maintenance. Less cost, doesn't need transducers for measuring output and usually is stable. The reliability and accuracy are the main disadvantages.

Closed loop control systems make a comparison between the input signal and output to give information to the controller. This can be done through measuring the output signal and feeding it back to system as shown in figure (2.7).

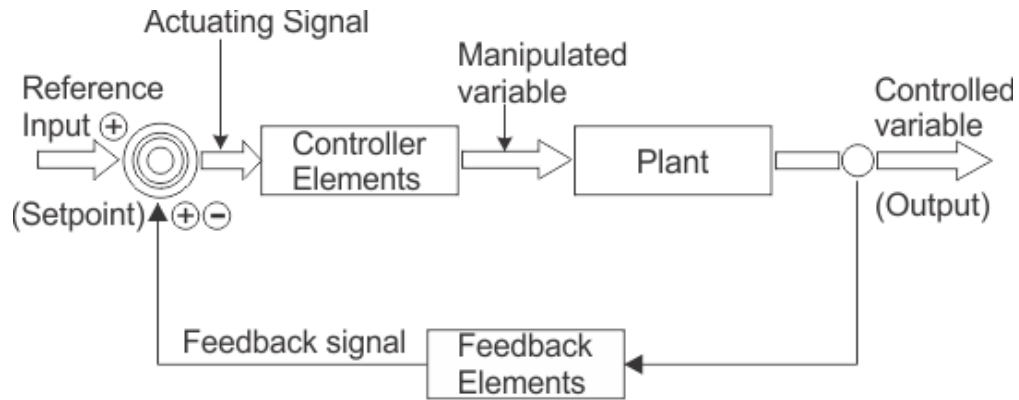


Figure2.7: Block diagram of closed loop control system

Advantages of this system are the accuracy since the system keeps rectifying the error. Another advantage is the noise rejection. The closed loop feedback is complicate to design and construct.

2.3.3 Controllability and Observability:

These control properties was introduced for this first time by R. Kalman in 1960. For a system with inputs $u(s)$ in state space form, if any of state variables $z(s)$ can be changed to a required condition through changing the input signal, then this state is controllable. Whereas if all states in the system are controllable; then the system will be called completely controllable. On other hand, if a state variable can be recognized and measured in the output signal (s) , then that state variable is called to be observable. If all state variables are observable, then the system is called completely observable. Figure (2.8) shows different conditions of observability and controllability of system.

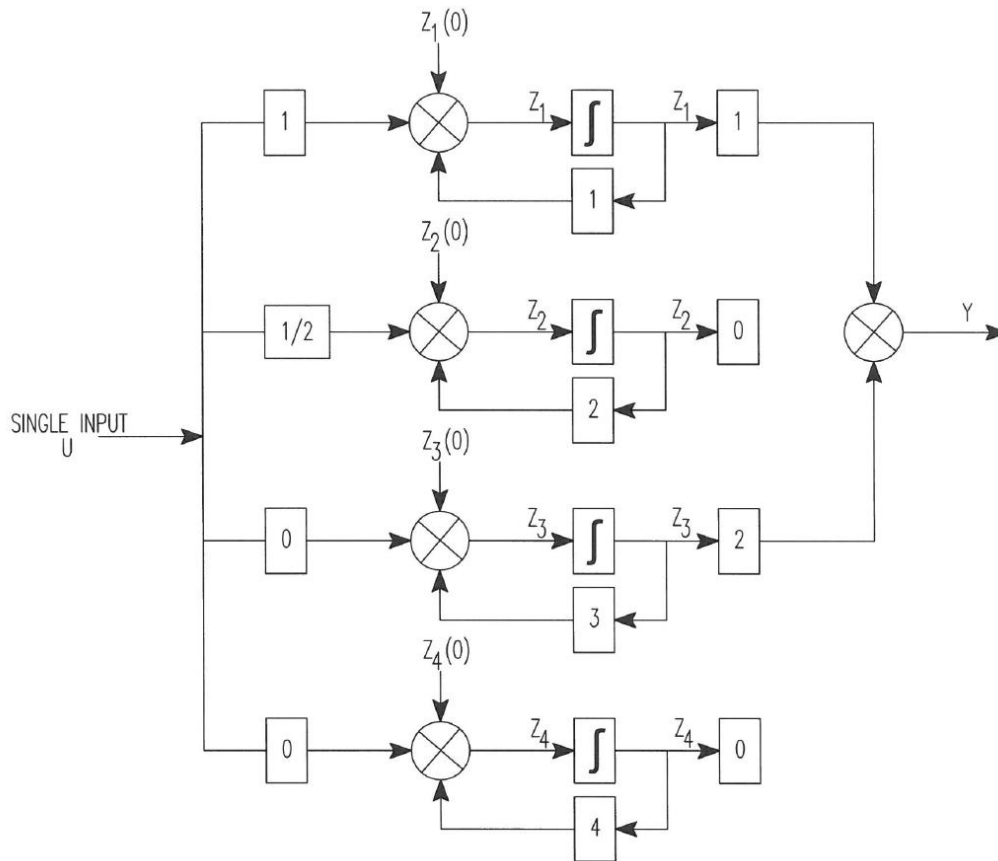


Figure 2.8: Controllability and Observability conditions

Some years later, Chen, C.T. introduced a mathematical check-up procedures through equations and matrices to determine the observability as well as the controllability of a given system.

2.3.4 Stability:

“A stable system is defined as a system with a bounded (limited) system response. That is, if the system is subject to a bounded input or disturbance the response is bounded in magnitude, the system is said to be stable” (modern control system by Richard C. Dorf & Robert H. Bishop- page 357).

Unstable system may cause damage and failure. One of the main purposes of controllers is to the dynamics of the systems.

There are mythologies to examine the stability of system, but one of the most common is root locus criteria. Consider a transfer function $G(s)$ which has poles $P(s)$ and zeros (s), hence If any of those poles in the right side of the S-Plane, the system is unstable. All poles should be in the left hand side of the S-plane. Another condition is that if one or more poles are on the imaginary part axis, then the system would be called marginally stable.

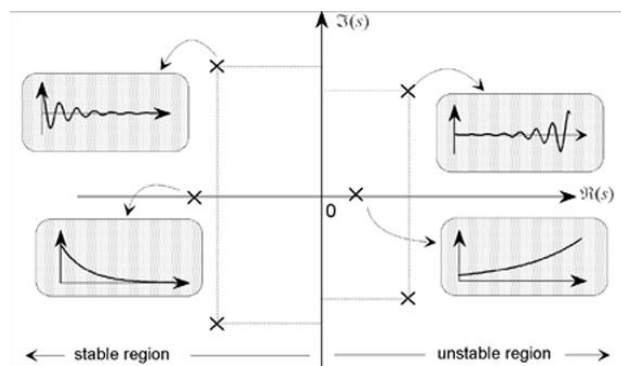


Figure 2.9: Poles location on S-plane and stability

2.3.5 Eigen values and Eigen vectors:

For a square matrix $n \times n$ called "A", there is a scalar " λ " which satisfy the equation:

$$Ax = \lambda x \quad (2.1)$$

There will be a vector "x" which makes the matrix determinant is equal a scalar if both sides are multiplied by the same vector "x". The scalar " λ " is called Eigen value and the vector "x" called the Eigen Vector. From equation (2.1) then

$$(A - \lambda)x = 0$$

Since $x \neq 0$; the equation becomes:

$$\det (A - \lambda I) = 0 \quad (2.2)$$

The scalar λ is called an Eigen value for the matrix “A”, and “I” is an identity matrix with the same rank of matrix “A”. Since there are two Eigen values satisfy equation (2.2) Then Eigen vector can be determined as following:

$$AU = U\Lambda$$

Whereas: $U = [u_1: u_2]$ and $\Lambda = \text{Diag} (\lambda_1, \lambda_2)$.

2.3.6 Robust control

The main purpose of robust concept is to keep the system stable despite disturbances. A robust concept was introduced and developed rapidly after the 1980s, where in this technique it's required utilizing a number of feedbacks as well as forward loops to reduce disturbance impacts. One of the vital purposes of controllers is to make the system “Robust” and the design techniques are mostly developed to achieve this property.

2.4 Classical Control Theory:

2.4.1 PID controller:

In 1930 the concept of PID was introduced for the first time as a trial and error or tuning methodology. PID controller refers to three term “proportional, integral, derivative”, and it is used mainly to get an output with minimum error value, acceptable overshoot and limits time delay.

Basically, PID controllers are based on measuring the output signal of the system and comparing it with a desired set point signal through a simple summation “ $e(t) = r(t) - y(t)$ ”. Since the action of the controller is based on the error signal, hence the transfer function of the PID controller can be given by the following equation:

$$G_c(S) = K_P + K_I \frac{1}{S} + K_D S$$

Accordingly, the output response in time domain can be explained by the equation:

$$u(t) = K_P e(t) + K_I \int e(t) + K_D \dot{e}(t)$$

Figure (2.10) below shows a block diagram of a PID controller, whereas the $r(t)$ is the set point signal, $e(t)$ is the error signal and $y(t)$ is the output measured signal.

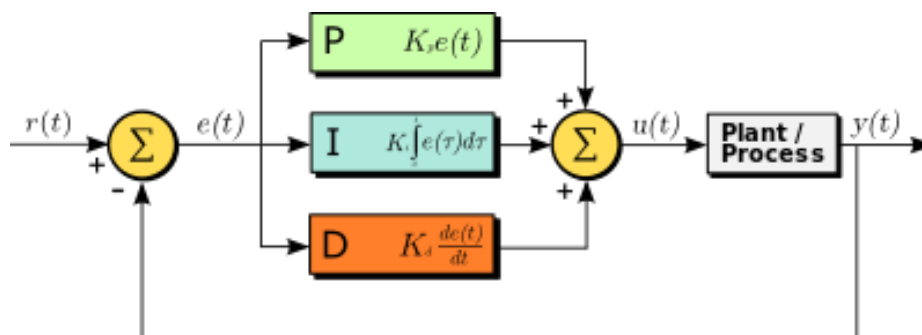


Figure 2.10: Block diagram representing PID controller

A proportional strategy means that the controller output will be in proportion to the error signal; it may be used for speed up or to slow systems and to decrease settling time. If the overshoot is too high of the output signal, from the proportional controller may cause system instability.

An integral strategy means that the controller output will act in proportion to the error signal integral as well as the duration of error signal too. This controller slows down the response of system and reduces the steady state error.

A derivative strategy means that the controller output will act in proportion to the slope of output error value over the time.

The three control strategies may work together as PID, or as PI, PD or individually. Based on the application, the required output is specified and the proper controller would be used. The figure below (2.11) shows an example of different impact of the controller on the output signal.

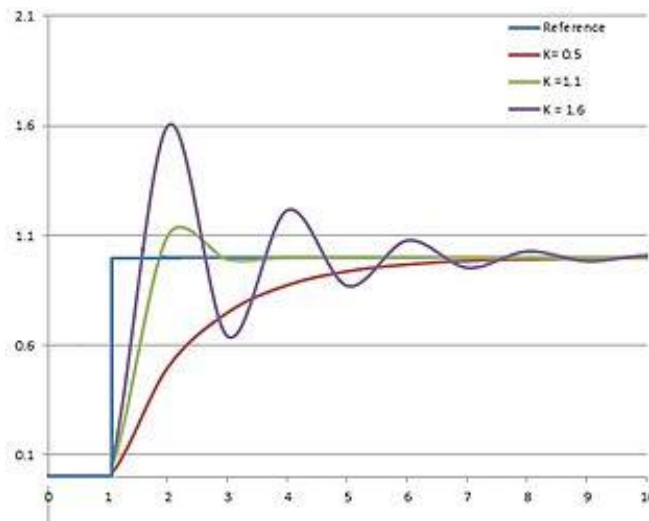


Figure 2.11: PID controller impact on step input

2.4.2 Routh Hurwitz Theory:

This theory was initiated by the British mathematician E. John Routh (1876) and then represented individually by the German scientist Adolf Hurwitz (1895). The theory provides a mathematical check for the stability of a system.

For a linear time invariant system, the Physical systems parameters are represented through a polynomial. Hurwitz suggested arranging the coefficient of polynomial in a matrix, and the determinate of the matrix should not be negative. Routh stated that the system will be stable if the real roots of the characteristic equation should be negative. Hence once allocating the roots on the S-plane, all the roots would be in the left hand side.

2.5 Multi Variable system controller representation by American school:

2.5.1 State Space Representation:

In addition to inputs and outputs, and in order to study as well as understand the behavior of multivariable system, another vector to be considered relates to the internal parameters/variables which have a direct impact on the output of the system, it's called state variables. Before world war II, after the year 1930, Leroy MacColl presented this control approach for the first time, and then it was developed by Kalman.

The equations show the relation between inputs, outputs and state space variables are given by the equations:

$$\dot{X}(t) = A.X(t) + B.U(t) \quad (2.3)$$

$$Y(t) = C.X(t) + D.U(t) \quad (2.4)$$

And if there is no direct mapping between input and output, the D matrix becomes zero, hence equation (2.4) can be written as:

$$Y(t) = C.X(t) \quad (2.5)$$

The input vector is represented by $U(t)$ and its related matrix is B , output vector $Y(t)$ and it's related to matrix is U and the state space vector $X(t)$ and it's related matrix is A . The block diagram of a state space model in the time domain is shown below (figure (2.12)).

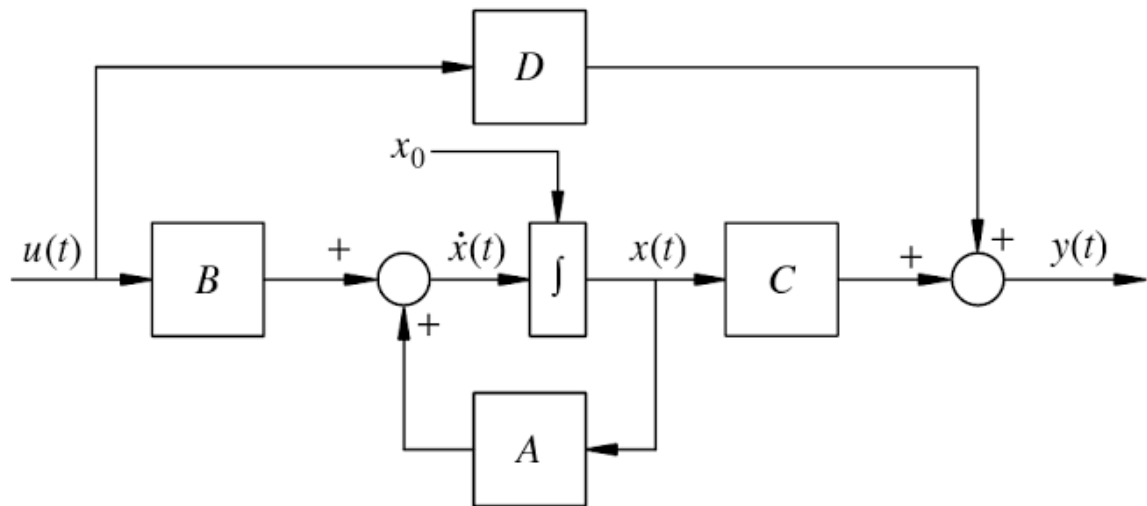


Figure 2.12: Block diagram representing state space modeling

If the above state space equations are converted to Laplace form, the equation below can be derived:

$$S.X(s) = A.X(s) + B.U(s)$$

$$Y(s) = C.X(s) + D.U(s)$$

Accordingly, the transfer function of the system can be written as following:

$$Y(s) = [C.(SI - A)^{-1}.B + D.]U(s)$$

$$G(s) = \frac{Y(s)}{U(s)} = C \cdot (SI - A)^{-1} \cdot B + D$$

If there is a direct mapping between input and output, the transfer function will be given by:

$$G(s) = \frac{Y(s)}{U(s)} = C \cdot (SI - A)^{-1} \cdot B$$

2.5.2 Optimal Controller:

“Optimal Control is the process of determining the state trajectories for a dynamic system over a period of time to minimize the performance index” Victor M. Becerra (2008). Since this design technique is a mathematical approach, a number of mathematicians contributed to the development of this theory over years started from the seventeenth century, until 1950s when R. Bellman introduced the dynamic equations of LTI systems and Lev Pontryagin presented the theory individually.

Optimal controller treats and solves the issues related to systems performance like overshoot as well as settling time. These issues are in direct relation to the energy consumption of the system, and the minimum energy of system reduces the maintenance of internal parts and accordingly the operational cost. The subject controller reduces the quadratic index to be at the minimum to achieve the best system performance. A number of constraints are defined to get the minimum value of the performance index given by the equation:

$$J = \int_0^{\infty} (\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{u}(t)^T \mathbf{R} \mathbf{u}(t)) dt$$

The lowest value of performance index change according to time and state, hence

$$J = s(\mathbf{x}, t)$$

And when applying Hamilton Jacobi equation to the above, the following will be derived:

$$\frac{d}{dt}(s(\mathbf{x}, t)) = \text{Min} \left\{ \frac{\delta s}{\delta t} + \frac{\delta s}{\delta x_0} \dot{x}_0 + \frac{\delta s}{\delta x_1} \dot{x}_1 + \dots + \frac{\delta s}{\delta x_n} \dot{x}_n \right\}$$

$$\dot{x}_1 = f_1(\mathbf{x}, \mathbf{u})$$

$$\dot{x}_2 = f_2(\mathbf{x}, \mathbf{u})$$

:

$$\dot{x}_n = f_n(\mathbf{x}, \mathbf{u})$$

Where:

$$\dot{x}_0 = \mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{u}(t)^T \mathbf{R} \mathbf{u}(t)$$

Since the Hamilton function is given by the equation:

$$H = P_0 f_0 + P_1 f_1 + \dots + P_n f_n$$

And

$$\frac{\partial H}{\partial P_i} = f_i(\mathbf{x}, \mathbf{u}, t)$$

$$\frac{\partial H}{\partial x_i} = P_0 \frac{\partial f_0}{\partial x_0} + P_1 \frac{\partial f_1}{\partial x_1} + \dots + P_n \frac{\partial f_n}{\partial x_n} = \sum_{i=0}^n P_i \frac{\partial f_i}{\partial x_i}$$

$$H(x, u, p, t) = \frac{1}{2} \left(\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{u}(t)^T \mathbf{R} \mathbf{u}(t) \right) + P_1 f_1 + \dots + P_n f_n$$

$$H(x, u, p, t) = \frac{1}{2} \left(\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{u}(t)^T \mathbf{R} \mathbf{u}(t) \right) + \mathbf{P}^T (\mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u})$$

$$\mathbf{P}^T = (P_1, P_2, \dots, P_n)$$

$$\frac{\partial H}{\partial \mathbf{u}} = \frac{1}{2} (2\mathbf{R} \mathbf{u}) + \mathbf{B}^T \mathbf{p} = \mathbf{0}$$

$$\mathbf{u} = -\mathbf{R}^{-1} \mathbf{B}^T \mathbf{p}$$

$$H_{min} = \left(\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{u}(t)^T \mathbf{R} \mathbf{u}(t) \right) + \mathbf{P}^T (\mathbf{A} \mathbf{x} + \mathbf{B} \mathbf{u}) \Big|_{\mathbf{u} = -\mathbf{R}^{-1} \mathbf{B}^T \mathbf{p}}$$

$$H_{min} = \frac{1}{2} \left(\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) + \mathbf{P}^T \mathbf{B} (\mathbf{R}^{-1})^T \mathbf{R} \mathbf{R}^{-1} \mathbf{B}^T \mathbf{p} \right) + \mathbf{P}^T \mathbf{A} \mathbf{x} - \mathbf{P}^T \mathbf{B} \mathbf{R}^{-1} \mathbf{B}^T \mathbf{p}$$

The matrix R is symmetrical, hence $(R^{-1})^T = R^{-1}$, then the above equation (4.2) becomes accordingly:

$$H_{min} = \frac{1}{2} \left(\mathbf{x}(t)^T \mathbf{Q} \mathbf{x}(t) \right) + \mathbf{P}^T \mathbf{A} \mathbf{x} - \frac{1}{2} \mathbf{P}^T \mathbf{B} \mathbf{R}^{-1} \mathbf{B}^T \mathbf{p}$$

Deriving equation (4.3) under the condition that $-\frac{\partial H_{min}}{\partial x_i} = -\mathbf{Q} \mathbf{x} - \mathbf{A}^T \mathbf{P} = \dot{\mathbf{P}}(t)$, the the following

will be concluded:

$$\mathbf{K}_{opt} = -\mathbf{R}^{-1} \mathbf{B}^T \mathbf{P}$$

And the steady state solution of system will be:

$$0 = (Q + A^T P + PA - PBR^{-1}B^T P)x$$

Accordingly, The design of optimal controller starts with selecting the matrices Q and R , and then obtaining the P matrix to calculate the gain of the controller. Figure (2.14) shows the block diagram representation of optimal controller.

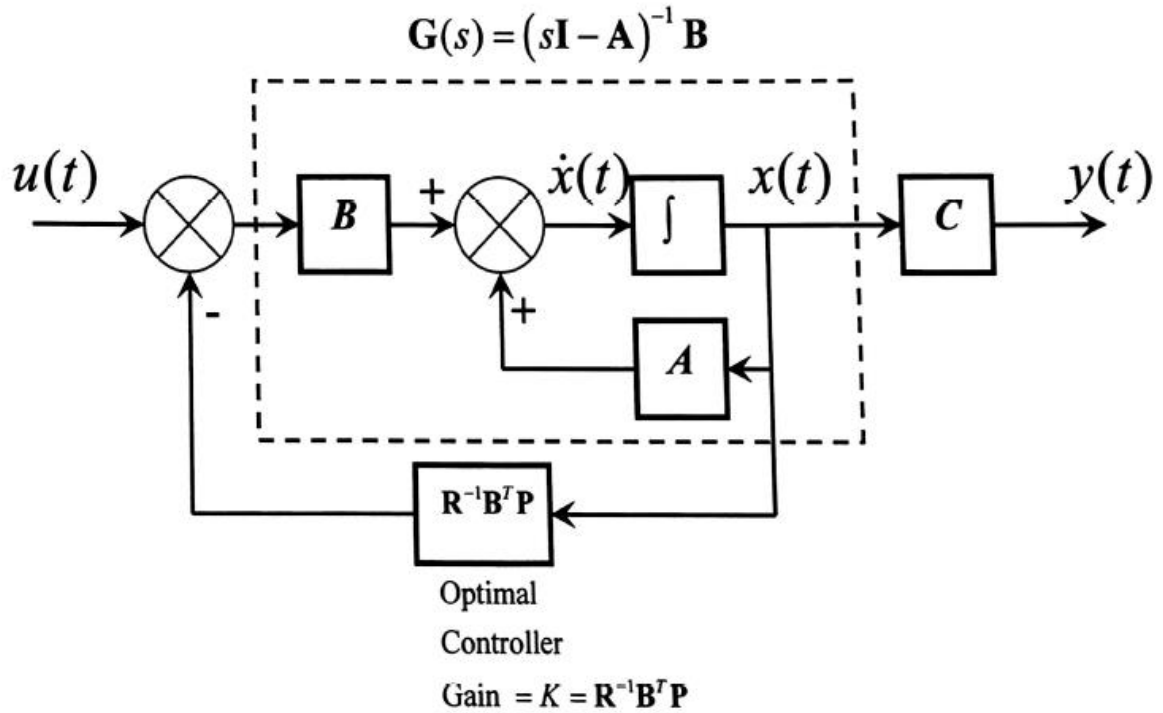


Figure 2.14: diagram of optimal Controller

(Whalley R., "lecture notes", 2015)

2.6 Multi Variable system controller representation British school:

2.6.1 Nyquist Stability theory:

This theory is a stability checking methodology for SISO systems, and it was presented for the first time in 1932 by a Swedish, born American engineer, Harry Nyquist. This approach doesn't need to determine the closed loop poles neither zeros to check the stability of SISO systems.

Nyquist used a plot to determine the stability of SISO systems. If the poles of the open loop system located on the left hand side of the S-plane, the system would be stable while the system called unstable if any of system open loop poles all located on the right hand side of the S-plane. The system is called marginally stable if one "or more" poles are located on the imaginary axes of the S-plane while no poles may be located on the right hand of s-plane.

2.6.2 Inverse Nyquist array theory:

This control theory of the design of multivariable systems controllers was presented in 1969 by the English engineer H. Rosenbrock (16 December 1920 – 21 October 2010), and it is an improvement on Nyquist theory of SISO system. Multivariable system is supposed to be described by a transfer function " $m \times m$ " matrix, whereas $K(s)$ is the controller of the system as shown in figure (2.15). A unity feedback loop is compared with input signal to produce the error signal " e ".

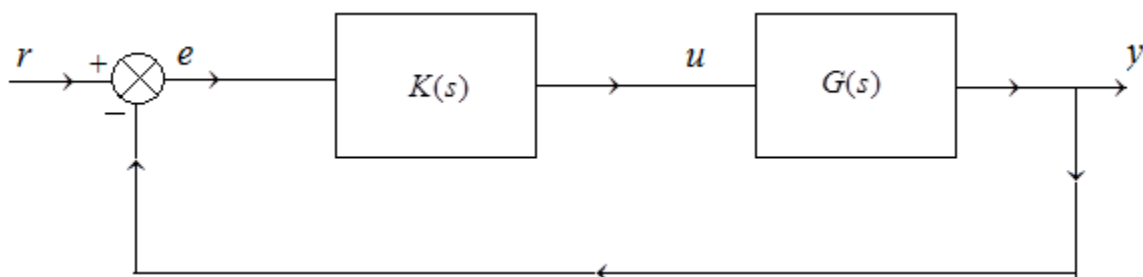


Figure 2.15: General Form of Multivariable Control System

In order to reduce the coupling of the outputs, and turn the open loop transfer function to diagonal dominance, a List of assumption should be considered:

- In s domain, the transfer function as well as controller is considered to be rational polynomial.
- The open loop transfer function is considered to be stable.
- The controller transfer function is considered to be stable, and the zeros are in the left hand side of the S plane as well.
- The matrices represent both systems' transfer function and controller is invertible matrices.

If the coupling between outputs of the system are ignorable; an independent transfer function can describe the relation between each input and output; hence the original transfer function could be replaced with a number of SISO transfer functions. Figure (2.16) shows representation of a multivariable system, and considering no coupling between input and output, there will be a transfer function between U_1 and Y_1 and another between U_2 and Y_2 and so on.

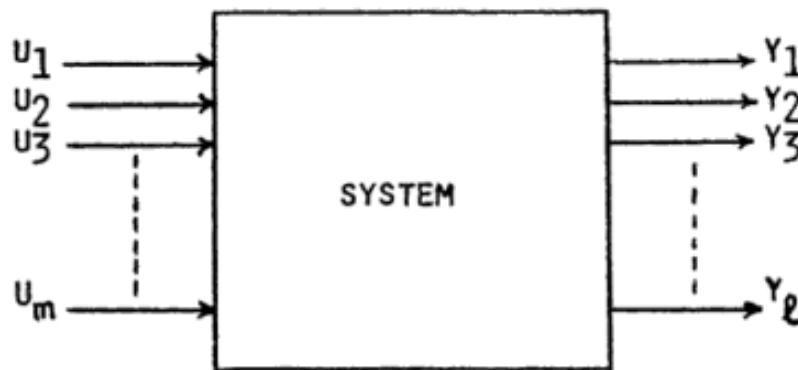


Figure 2.16: Inputs/Outputs representation of a multivariable system

Figure below (2.17) shows a block diagram representation of closed loop multivariable system, whereas $F(s)$ is a diagonal matrix and the closed loop transfer function of the system can be given by:

$$H(s) = (I + G(s)K(s)F) - 1 G(s)K(s)$$

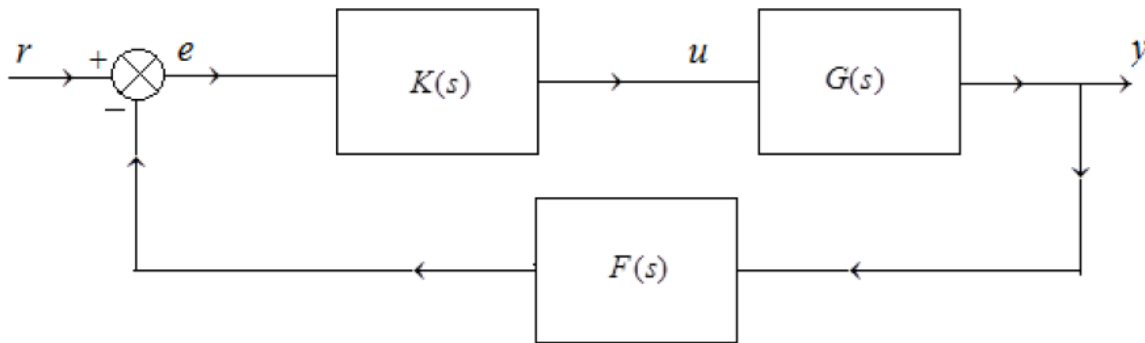


Figure 2.17: closed loop representation of multivariable system

In order to consider the system stable, all the poles of the transfer function $H(s)$ should be in the left side of the S -plane. The system can be considered stable if the transfer function $H(s)$ has all poles located on the left hand side of the s -plane. Gershgorin bands are used to assess the stability of the systems.

2.6.3 Least effort theory:

Least effort method is a new multivariable system regulation technique produced by Robert Whalley and M Ebrahimi in 2006. Base on the minimum effort of controller using the closed loop technique. This technique is a useful tool to reduce the generated heat, wear and system noise making the implementation of the least effort controller easy to be implemented and maintained.

The closed loop technique in least effort relies on calculating the inner and outer loop to obtain the required steady state value with minimum output interaction to achieve the required output.

The equation of the open loop is:

$$\mathbf{y}(s) = \mathbf{G}(s)\mathbf{u}(s) + \boldsymbol{\delta}(s)$$

Ad for the closed loop is:

$$\mathbf{u}(s) = \mathbf{k}(s)[\dot{\mathbf{r}}(s) - \mathbf{h}(s)\mathbf{y}(s)] + \mathbf{P}(\mathbf{r}(s) - \mathbf{F}\mathbf{y}(s))$$

The inputs in the open and closed loop equations are represented by \mathbf{m} where the \mathbf{F} :

$$\mathbf{F} = \mathbf{Diag}(f_1, f_2, \dots, f_m), 0 < f_j < 1, 1 \leq j \leq m$$

The transient part of the output which obtained from the inner loop as per the following equation:

$$\mathbf{k}(s)[\dot{\mathbf{r}}(s) - \mathbf{h}(s)\mathbf{y}(s)]$$

The steady state part of the output obtained from the following:

$$\mathbf{P}(\mathbf{r}(s) - \mathbf{F}\mathbf{y}(s))$$

Then doing the inner loop calculation using the general transfer function equation:

$$\mathbf{G}(s) = \mathbf{L}(s) \frac{\mathbf{A}(s)}{\mathbf{d}(s)} \mathbf{R}(s) \boldsymbol{\Gamma}(s)$$

Where equation elements of $\mathbf{L}(s)$, $\mathbf{A}(s)$, $\mathbf{R}(s)$, $\boldsymbol{\Gamma}(s)$ and $\frac{\mathbf{A}(s)}{\mathbf{d}(s)} \in H_\infty$, $s \in \mathbb{C}$

The following figure (2.18) showing the inner and outer closed system used in least effort controller representation.

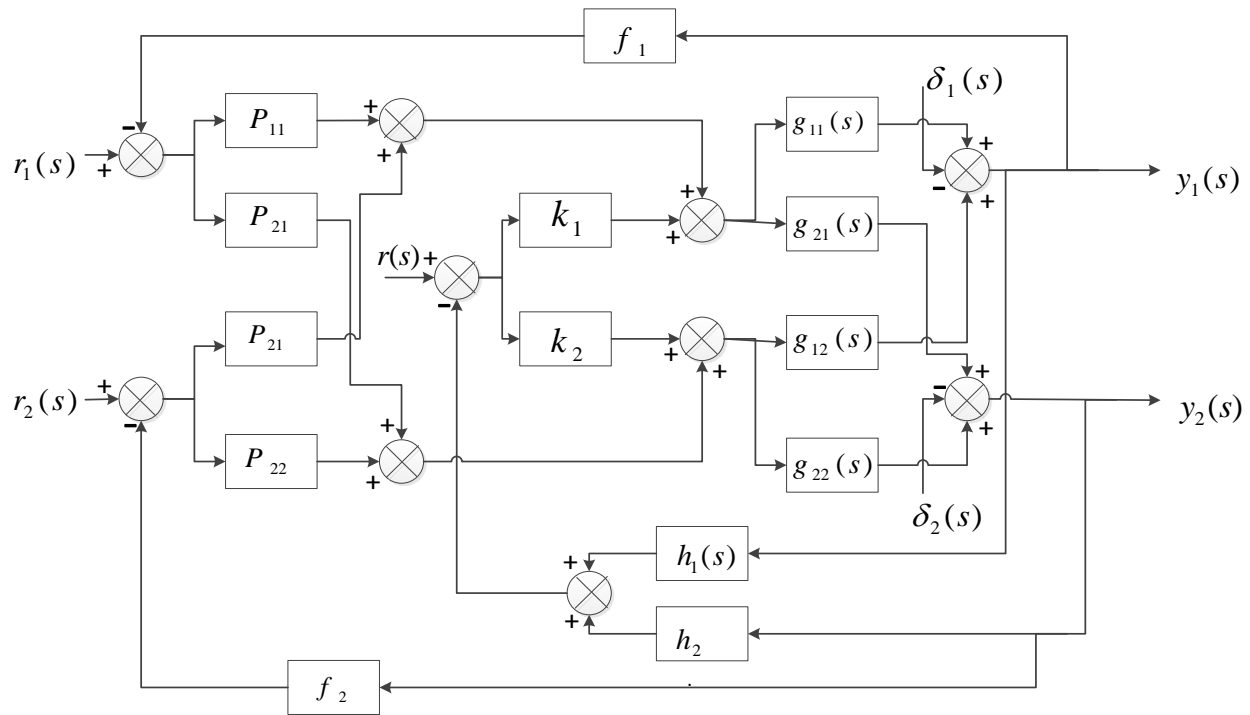


Figure 2.18: closed loop representation of least effort

Using the following controller energy equation:

$$E(t) = \int_{t=0}^{t=1} (u_1(t)^2 + u_2(t)^2) dt$$

To prove that the least effort controller has less consumed energy which will be produced as a heat and noise. Least effort has the lowest controller functions and algorithms orders, simplifying the controller production and implementation.

(3)

Research Methodology

3.1 Modeling of Propeller Shaft System:

Figure (3.1) shows the block diagram representation of propeller shaft system.

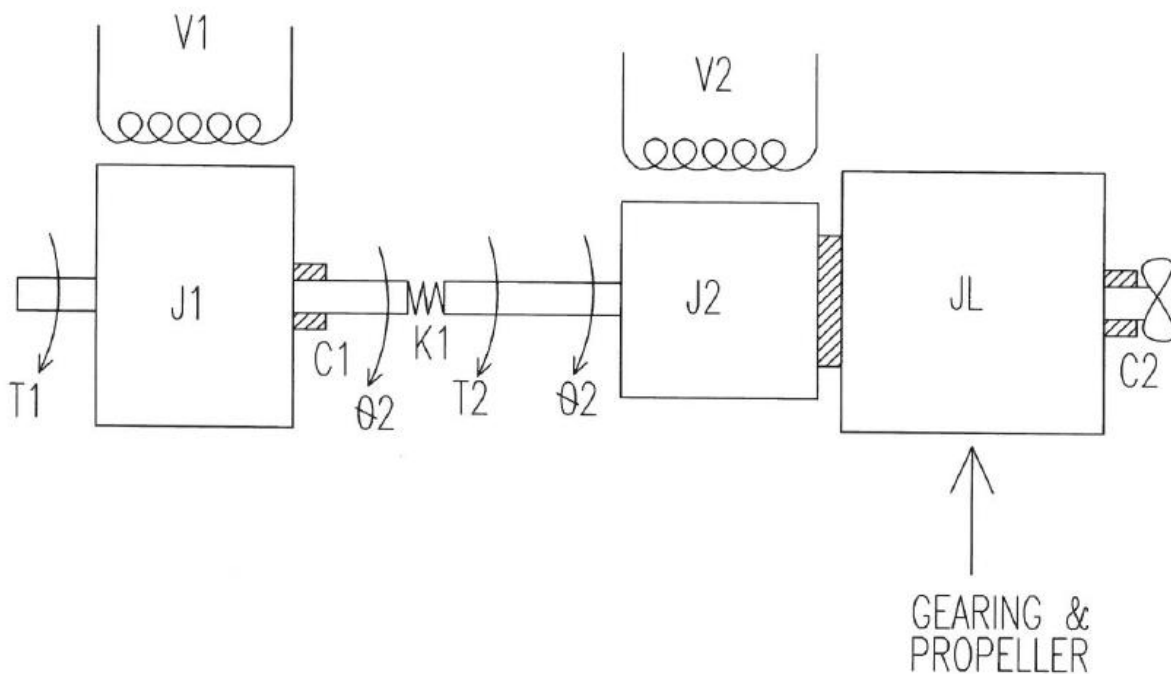


Figure 3.1: Block diagram of propeller shaft system

In order to generate rotational movement; the torque generated by the motor should overcome the inertia of the motor itself, inertia of shaft, damping of motors and propeller, the stiffness of

the elements in propeller system. Accordingly, the following represents the equilibrium equation of forces:

$$T_1 = (J_1 D^2 + C_1 D) \theta_1 + K_1 (\theta_1 - \theta_2)$$

$$\Rightarrow T_1 = (J_1 D^2 + C_1 D + K_1) \theta_1 - K_1 \theta_2 \quad (3.1)$$

$$K_1 (\theta_1 - \theta_2) + T_2 = (J_2 D^2 + C_2 D) \theta_2 + (J_L D^2 + C_2 D) \theta_2$$

$$\Rightarrow T_2 = -K_1 \theta_1 + ((J_2 + J_L) D^2 + (C_2) D + K_1) \theta_2 \quad (3.2)$$

From equations (3.1) and (3.2), a derivation of the equation describes the mathematical relation between input torque and the angular velocity is given by:

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} J_1 D^2 + C_1 D + K_1 & -K_1 \\ -K_1 & J_3 D^2 + C_2 D + K_1 \end{bmatrix} \cdot \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

Whereas $J_3 = J_2 + J_L$. Accordingly, the deflection angle " θ " can be given by the equation:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \frac{\begin{bmatrix} J_3 D^2 + C_2 D + K_1 & K_1 \\ K_1 & J_1 D^2 + C_1 D + K_1 \end{bmatrix}}{J_1 J_3 D^4 + (J_3 C_1 + J_1 C_2) D^3 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D^2 + (K_1 C_1 + K_1 C_2) D + K_1^2 - K_1^2} \cdot \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

In order to derive the equation represents the relation between angular velocity and torque, both sides of equation are derived, and the equation becomes:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} = \frac{\begin{bmatrix} J_3 D^2 + C_2 D + K_1 & K_1 \\ K_1 & J_1 D^2 + C_1 D + K_1 \end{bmatrix}}{J_1 J_3 D^3 + (J_3 C_1 + J_1 C_2) D^2 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D + (K_1 C_1 + K_1 C_2)} \cdot \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} \quad (3.3)$$

The above equation describes the system transfer function between the input torques produced by both of motors and the output angular velocities for the two rotors.

Moreover, the source of force drives the propeller is represented by two motors m_1 and m_2 whereas the inputs for the motors are the applied voltages v_1 and v_2 on the windings of the motors. Applied voltages on motors produce the torques T_1 and T_2 as per the following equations:

$$T_1 = V_1 / (L_1 D + R_1)$$

$$T_2 = V_2 / (L_2 D + R_2)$$

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} \frac{V_1}{L_1 D + R_1} & 0 \\ 0 & \frac{V_2}{L_2 D + R_2} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_1 D + R_1} & 0 \\ 0 & \frac{1}{L_2 D + R_2} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (3.4)$$

Accordingly, from the equation (3.3) and (3.4), the relationship between the input of propeller shaft system “voltage” and the output of the system “angular velocity” can be given by the equation:

$$\begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} = \frac{\begin{bmatrix} J_3 D^2 + C_2 D + K_1 & K_1 \\ K_1 & J_1 D^2 + C_1 D + K_1 \end{bmatrix}}{J_1 J_3 D^3 + (J_3 C_1 + J_1 C_2) D^2 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D + (K_1 C_1 + K_1 C_2)} \times \begin{bmatrix} \frac{1}{L_1 D + R_1} & 0 \\ 0 & \frac{1}{L_2 D + R_2} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

accordingly,

$$\begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} = \frac{\begin{bmatrix} \frac{J_3 D^2 + C_2 D + K_1}{L_1 D + R_1} & \frac{K_1}{L_2 D + R_2} \\ \frac{K_1}{L_1 D + R_1} & \frac{J_1 D^2 + C_1 D + K_1}{L_2 D + R_2} \end{bmatrix}}{J_1 J_3 D^3 + (J_3 C_1 + J_1 C_2) D^2 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D + (K_1 C_1 + K_1 C_2)} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

The transfer function $G(s)$ which describes the relationship between input voltage and output angular speed of propeller shaft system is given by the equation:

$$G(D) = \frac{\begin{bmatrix} \frac{J_3 D^2 + C_2 D + K_1}{L_1 D + R_1} & \frac{K_1}{L_2 D + R_2} \\ \frac{K_1}{L_1 D + R_1} & \frac{J_1 D^2 + C_1 D + K_1}{L_2 D + R_2} \end{bmatrix}}{J_1 J_3 D^3 + (J_3 C_1 + J_1 C_2) D^2 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D + (K_1 C_1 + K_1 C_2)} \quad (3.5)$$

3.2 Propeller Shaft design:

3.2.1 Selected system's parameters:

Figure (3.2) shows the representation of propeller shaft system schematic diagram.

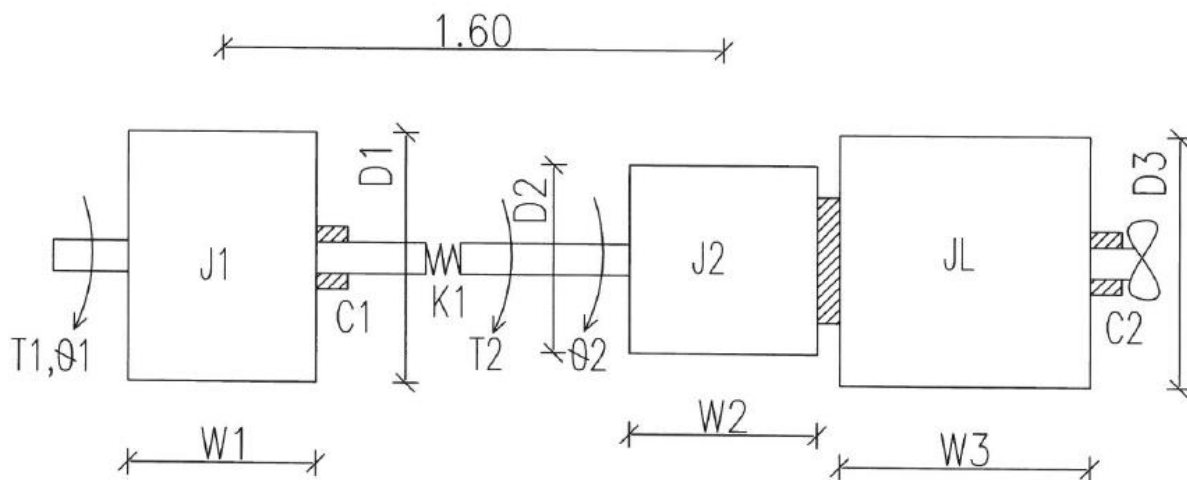


Figure 3.2: Propeller shaft system mass presentation

Accordingly, the following points could be concluded:

- The rotors of the two motors are represented by two discs. The rotor of motor one has disc diameter $D_1 = 0.80 \text{ meter}$ and width $w_1 = 0.60 \text{ meter}$ whereas the rotor of motor two has disc diameter $D_2 = 0.60 \text{ meter}$ and width $w_2 = 0.60 \text{ meter}$. On other hand, the

load is also represented as a disc with diameter $D_3 = 0.80 \text{ meter}$ and width $w_3 = 0.080 \text{ meter}$.

- Shaft diameter considered to be the same along the whole system $d_s = 0.055 \text{ meter}$. The length of shaft between the two motors is $L = 1.6 \text{ mtere}$, whereas the length of shaft between second motor and the load is considered to be very short and it will be negligible in the coming calculations and accordingly the masses of second motor and the load can be lumped together in the calculations as one mass.
- All materials in propeller shaft system shown in figure no. considered as steel with density $\rho = 7800 \text{ Kg/m}^3$ and shear modulus is $G = 8 \times 10^{10} \text{ N/m}^2$.
- The input torques generated from the first motor and second motor are supposed to be $T_1 = 12000 \text{ K.N.m}$ and $T_2 = 8000 \text{ K.N.m}$ respectively.

As illustrated in below figure (3.3), the rotors and the shaft comprise a semi-definite system that has no stiffness or inertia element connected to ground.

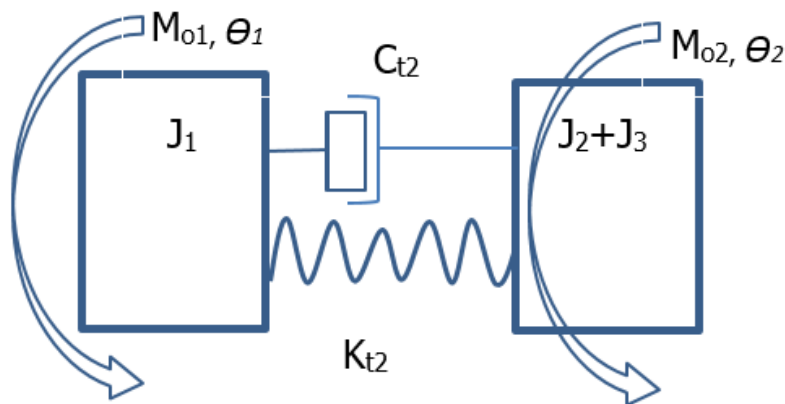


Figure 3.3: Mass Moment of Inertia of Some Shapes

3.2.2 General equation of torsional motion:

Generally, the equation describes the torsional motion for any system can be given by:

$$J_n \ddot{\theta}_n + C_{tn} \dot{\theta}_n + K_{tn} \theta_n = M_{on} \cos \omega_{on} t$$

The mass torsional inertia matrix is given by:

$$J = \frac{\rho \cdot \pi}{32} \begin{bmatrix} h_1 D_1^4 & 0 \\ 0 & h_2 D_2^4 + h_3 D_3^4 \end{bmatrix}$$

$$K_{t2} = \frac{G}{L2} \left(\frac{\pi \cdot d_s^4}{32} \right)$$

The stiffness matrix

$$K_t = \begin{bmatrix} K_{t2} & -K_{t2} \\ -K_{t2} & K_{t2} \end{bmatrix}$$

The eigenvalue of the system is:

$$\lambda = \text{sort}(\text{eigenvalues}(J^{-1} \cdot K_t)) = \begin{pmatrix} 0 \\ 383.356 \end{pmatrix}$$

$$\lambda = \begin{pmatrix} |\lambda_1| \\ |\lambda_2| \end{pmatrix} = \begin{pmatrix} 0 \\ 383.356 \end{pmatrix}$$

And hence the angular natural frequency can be given by:

$$\omega = \sqrt{\lambda} = \begin{pmatrix} 0 \\ 19.579 \end{pmatrix}$$

The first natural frequency is zero, which means in semi definite system no oscillating is occurring in the first mode, and the shaft design is based on second mode only.

Hence for $i = 1, 2$

$$\Phi^{(i)} = \text{eigenvalua} (J^{-1} \cdot K_t \cdot \lambda_i)$$

The mode shape matrix is:

$$\Phi = \begin{bmatrix} 0.707 & -0.855 \\ 0.707 & 0.518 \end{bmatrix}$$

And the torque frequencies of the system are:

$$\omega_{01} = 0 \text{ and } \omega_{02} = 0$$

For constant torque, the torque frequency should be zero and the design of the shaft is governed by static analysis, and the torque matrix could be described by:

$$M_0 = \begin{pmatrix} M_{01} \\ M_{02} \end{pmatrix}$$

$$M_1(t) = \begin{pmatrix} M_{01} \cdot \cos(t \cdot \omega_{01}) \\ M_{02} \cdot \cos(t \cdot \omega_{02}) \end{pmatrix}$$

The evaluation of damping matrix is shown in the next modal analysis.

3.2.3 Model equations for torsional Vibration:

The modal forced damped equations for two modes $n = 1, n = 2$ and the modal matrices are as shown below:

$$I_n \ddot{q}_n + C_n \dot{q}_n + K_{tn} q_n = T_{on} \cos \omega_{on} t$$

The modal torsional inertia matrix is given by:

$$I = \Phi^T \cdot J \cdot \Phi = \begin{bmatrix} 249.333 & 0 \\ 0 & 221.05 \end{bmatrix}$$

Whereas the stiffness matrix is given by:

$$K = \Phi^T \cdot K_t \cdot \Phi = \begin{bmatrix} 0 & 0 \\ 0 & 8.474 \times 10^4 \end{bmatrix}$$

Hence the damping ratio for first and second mode is:

$$\zeta = \begin{pmatrix} 0.01 \\ 0.11 \end{pmatrix}$$

Obtained classical damping matrix through using superposition method:

$$\zeta = \frac{2 \cdot \zeta_1 \cdot \omega_1}{I_{1,1}} \cdot J \cdot \Phi_1 \cdot \Phi_1^T \cdot J + \frac{2 \cdot \zeta_2 \cdot \omega_2}{I_{2,2}} \cdot J \cdot \Phi_2 \cdot \Phi_2^T \cdot J$$

$$C_t = \begin{bmatrix} 504.71 & -504.71 \\ -504.71 & 504.71 \end{bmatrix}$$

The formula to approve the damping matrix is classical damping matrix is:

$$C_t \cdot J^{-1} \cdot K_t - K_t \cdot J^{-1} \cdot C_t = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \Phi^T \cdot C_t \cdot \Phi = \begin{bmatrix} 0 & -0 \\ -0 & 952.17 \end{bmatrix}$$

The modal damping matrix is:

$$C = \begin{bmatrix} |C_{1,1}| & |C_{1,2}| \\ |C_{2,1}| & |C_{2,2}| \end{bmatrix} = \begin{bmatrix} 0 & -0 \\ -0 & 952.17 \end{bmatrix}$$

$$T_0 = \begin{pmatrix} \Phi^{(1)T} M_o \\ \Phi^{(2)T} M_o \end{pmatrix} = \begin{pmatrix} 1.414 \times 10^4 \\ -6.115 \times 10^3 \end{pmatrix}$$

The modal torque matrix is:

$$T(t) = \begin{pmatrix} T_{01} \cdot \cos(\omega_{01}) \\ T_{02} \cdot \cos(\omega_{02}) \end{pmatrix}$$

For first mode:

$$I_1 = I_{1,1} = 249.333$$

$$K_1 = K_{1,1} = 0$$

$$\omega_{n1} = \sqrt{\frac{K_1}{I_1}} = 0$$

Hence, no oscillation and relative angular displacement by this mood, so it's neglected.

For Second mode:

$$I_2 = I_{2,2} = 221.05, \text{ modal torsional mass inertia}$$

$$C_2 = C_{2,2} = 952.169, \text{ Mode damping coefficient}$$

$$K_2 = K_{2,2} = 8.474 \times 10^4 \text{ Mode stiffness value}$$

$$T_{02} = T_{2,2} = -6.115 \times 10^3, \text{ mode torque magnitude}$$

$$\omega_{02} = 0, \text{ mode torque frequency}$$

$$\omega_{n2} = \sqrt{\frac{K_2}{I_2}} = 19.579, \text{ angular natural frequency}$$

$$C_{c2} = 2 \cdot I_2 \cdot \omega_{n2} = 8.656 \times 10^3, \text{ mode critical damping coefficient}$$

$$Q'_2 = \frac{T_{02}}{\sqrt{(K_2 - I_1 \cdot \omega_{02}^2)^2 + C_2^2 \cdot \omega_{02}^2}} = -0.072$$

$$\Phi'_2 = \text{atan}\left(\frac{C_2^2 \cdot \omega_{02}^2}{K_2 - I_1 \omega_{02}^2}\right) = 0 \text{ deg}, \text{ mode Shift angle.}$$

$$q_{p2}(t) = Q'_2 \cdot \cos(\omega_{02} \cdot t - Q'_2), \text{ mode particular solution for angular displacement}$$

Figure (3.4)_below showing the particular angular displacement with time, the time range of plotting is $t = 0, 2.1 \times 10^{-5} \text{ to } 10 \times 10^{-1}$

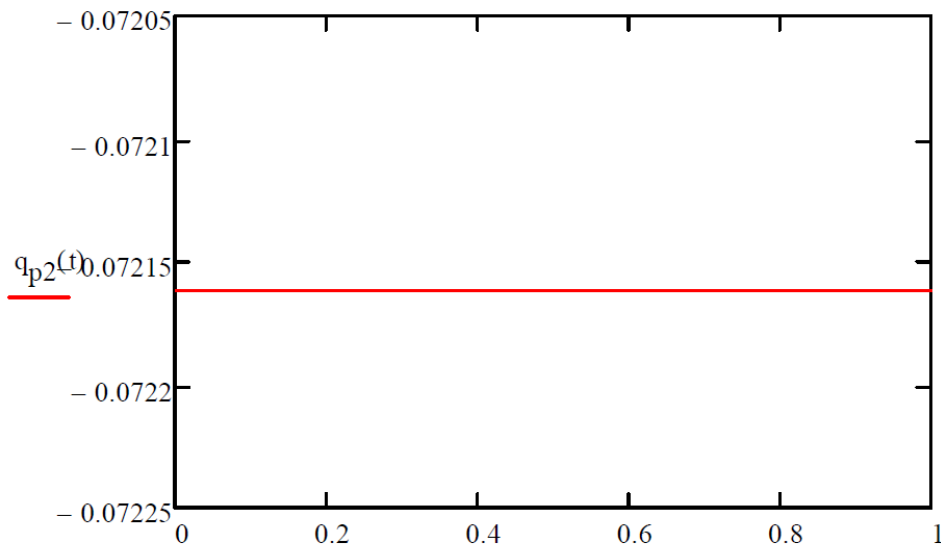


Figure 3.4: Particular angular displacement with time

$$\zeta_2 = \frac{c_2}{c_{c2}} = 0.11, \text{ The mode damping ratio}$$

$$\omega_{d2} = \omega_{n2} \cdot \sqrt{1 - \zeta_2^2} = 19.461, \text{ mode damped natural frequency}$$

Assuming that the initial condition of system at time $t = 0$ for $Q_0 = 0$, and $V_0 = 0$ for angular displacement and velocity, then the mode maximum transient angular displacement is given by:

$$D = \sqrt{Q_0^2 + \left(V_0 + \frac{\zeta_2 \cdot \omega_{n2} \cdot V_0}{\omega_{d2}}\right)^2} = 0.01$$

And the transient shift angle is $\Phi = \text{atan}\left(\frac{\omega_{d2} \cdot Q_0}{\zeta_2 \cdot \omega_{n2} \cdot V_0}\right)$, $\Phi = 90$

And $q_{c2}(t) = D \cdot (\exp(-t \cdot \zeta_2 \cdot \omega_{n2}) \cdot \sin(t \cdot \omega_{d2} + \Phi))$ is the transient complementary solution for angular displacement, as shown in the figure (3.5) below:

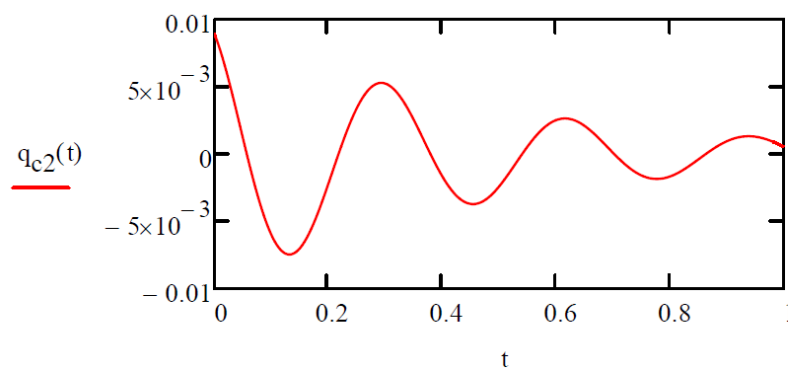


Figure 3.5: Transient complementary solution of angular displacement

The equation which showing the general solution of angular displacement is shown in figure (3.6)

and given by the equation:

$$q_2(t) = q_{c2}(t) + q_{p2}(t)$$

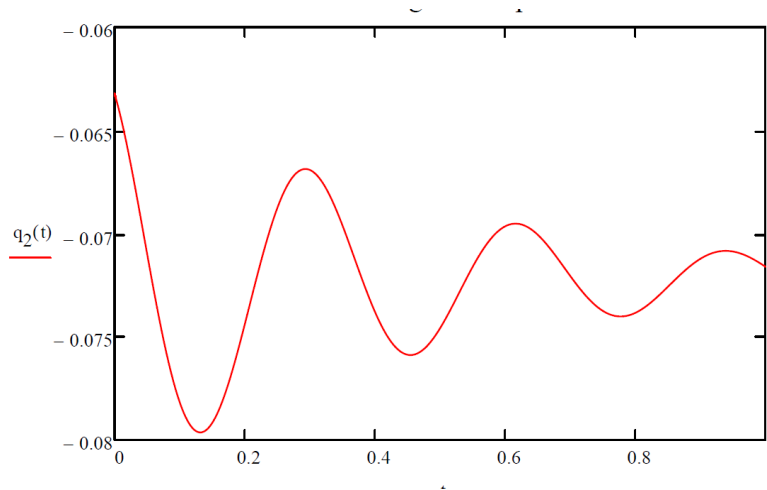


Figure 3.6: General solution of angular displacement

From the above figure no. , it is noticed that at $t=0.16$ second from the start time, the maximum amplitude is $q_{max} = q_2(0.16) = -0.0786$. the maximum angular amplitude in nodal system is given by:

$$\theta^{(2)} = \Phi^{(2)} \cdot q_{max} = \begin{pmatrix} 0.067 \\ -0.041 \end{pmatrix}$$

$$\theta_{1,2} = (\Phi^{(2)})_1 = 0.067$$

$$\theta_{2,2} = (\Phi^{(2)})_2 = -0.041$$

The maximum relative angular displacement in the shaft is:

$$\Delta\theta = \theta_{1,2} - \theta_{2,2} = 0.108$$

And , the maximum torsional shear outmost fiber of the shaft in N/m^2 is :

$$S = \frac{G \cdot d_s \cdot (\Delta\Phi)}{2 \cdot L_2} = 1.484 \times 10^8$$

$$\Rightarrow SHEAR = \frac{|S|}{10^6} = 148.409$$

The allowed shear stress is $S_a = 267 \text{ N/mm}^2$, and if the factor of safety considered will be:

$$FS = \frac{S_a}{SHEAR} = 1.799$$

If the required factor of safety is 1.5, then shaft diameter is under acceptable levels.

3.3 Study of open loop response of propeller shaft system:

The derived transfer function of propeller shaft system was derived in section (3.1) and given by the equation:

$G(D)$

$$= \frac{\begin{bmatrix} \frac{J_3 D^2 + C_2 D + K_1}{L_1 D + R_1} & \frac{K_1}{L_2 D + R_2} \\ \frac{K_1}{L_1 D + R_1} & \frac{J_1 D^2 + C_1 D + K_1}{L_2 D + R_2} \end{bmatrix}}{J_1 J_3 D^3 + (J_3 C_1 + J_1 C_2) D^2 + (J_3 K_1 + C_1 C_2 + J_1 K_1) D + (K_1 C_1 + K_1 C_2)} \quad (3.5)$$

After applying the parameters provided in section 3.2 for of transfer function $G(s)$, and considering the damping coefficients to be $C_1 = 20, C_2 = 250$, then following formula will be concluded:

$$G(S) = \frac{\begin{bmatrix} 188.0S^2 + 250.0S + 8.474 \times 10^4 & 8.474 \times 10^4 \\ 8.474 \times 10^4 & 310.0S^2 + 20.0S + 8.474 \times 10^4 \end{bmatrix}}{2.914 \times 10^4 S^3 + 5.249 \times 10^7 S^2 + 3.789 \times 10^{10} S + 2.058 \times 10^{10}},$$

The transfer function can factorized to be written in the following form:

$G(S)$

$$= \frac{\left[\frac{0.0064516(S^2 + 1.33 S + 450.5)}{2.9067} \quad \frac{2.9067}{0.010638(S^2 + 0.06452 S + 273.2)} \right]}{(S + 1800)(S + 0.5425)(S^2 + 0.8519S + 723.4)} \quad (3.6)$$

In order to study the open loop response of the propeller shaft system, a unit step input change in angular velocity is applied from both motors to the transfer function. Using MATLAB simulation, the output of the system is shown in figure (3.7) for both motors, putting into consideration that both responses are examined for a duration of 20 seconds.

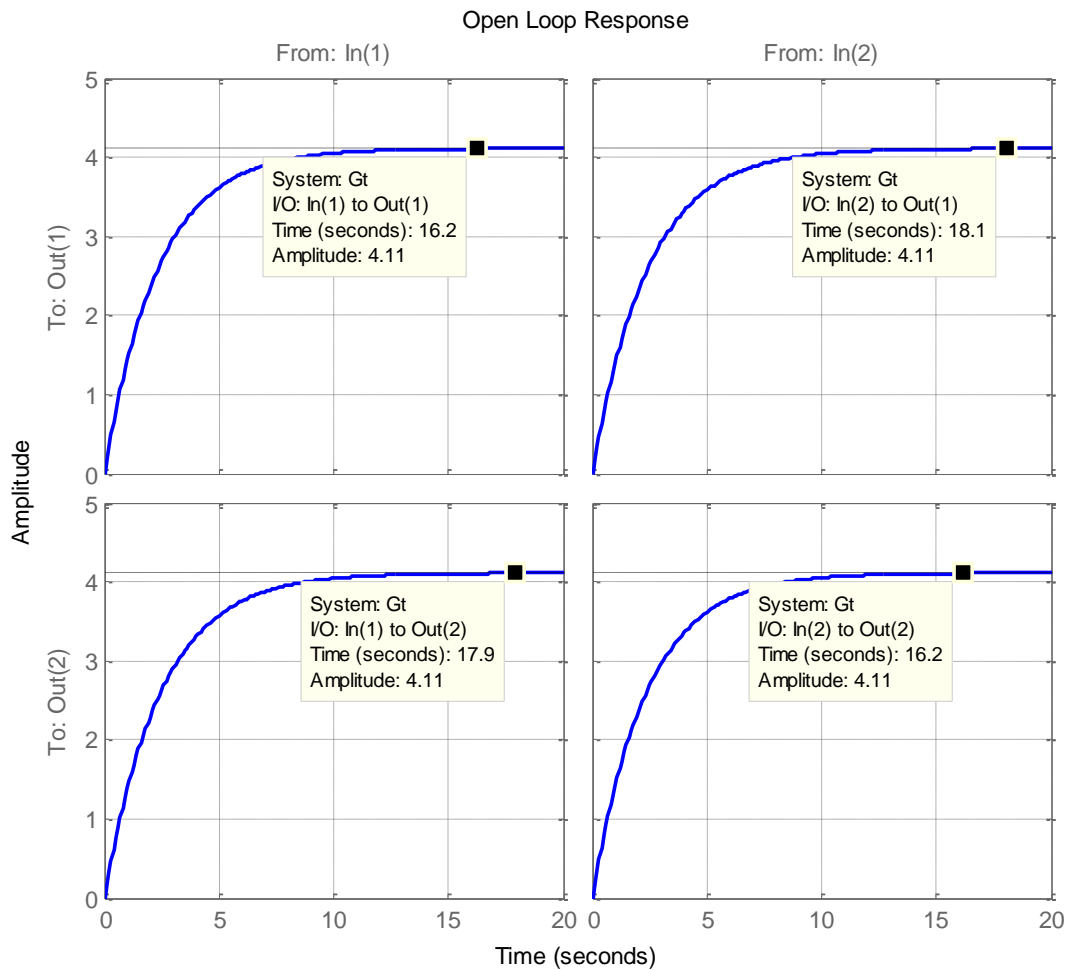


Figure 3.7: Open loop response of propeller shaft system

Considering the open loop response in figure (3.7), the transfer function can be re-written as follows:

$$G(S) = \begin{bmatrix} \frac{4.11}{2.34S + 1} & \frac{4.11}{2.43S + 1} \\ \frac{4.11}{2.45S + 1} & \frac{4.11}{2.36S + 1} \end{bmatrix}$$

Open loop response in figure (3.7) shows two major problems should be resolved:

1. Input/output interaction: since each inputs has a direct impact on both outputs, whereas systems should show a minimum coupling reponse between inputs, i.e. and outputs and each inputs control the signal of one output only.
2. The output is not reaching the input value at anytime.

The response require improvement, minimum coupling of outputs, reonable settling time and fast response. System mathematical model after applying the controller should have the ability to reduce and eliminate the impact of input disturbcnes. Energy consubtion by controller itself is an important aspect will be considred in chapter (6).

3.4 Control methods superimposed in the study:

Improving the reponse of open loop response is acomplished in this research using two techniques, H infinity control as well as loop shaping. The pros and cones of each methodology will be highlighted to choose the proper controler based on requirements.

(4)

Control of Propeller Shaft System using H-Infinity Method

4.1 Introduction:

As a part of frequency domain analysis, the H-infinity control technique was introduced for the first time in the late 1970s by the Polish physicist and mathematician George Zames “born 1934 – 1997”. This controller came up to resolve some problems related to system stability, robustness and performance. H-infinity controller is effective for those problems related to system output coupling in the case of multi-variable systems. The main disadvantage of this technique is that it is not necessary to produce the best performance of the controlled system, moreover it requires a high order controller.

The characteristic equation of H-infinity controller is given by the equation (4.1):

$$1 + G(s)K(s) = 0 \tag{4.1}$$

The system is stable once all the poles of above equation located in the left hand side of the S plane. The below equation (4.5) describes the performance of the system, whereas the performance is getting better when the sensitivity is minimum at any given frequency.

4.2 Theory of H-Infinity Controller:

Figure (4.1) shows block diagram of H-infinity controller.

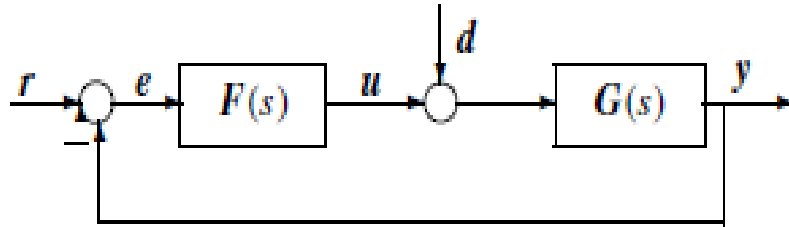


Figure 4.1: General structure of control system

The controller of H-infinity can be represented by the following matrix:

$$F_c = \begin{bmatrix} A_f & \vdots & -ZL \\ \dots & \dots & \dots \\ F & \vdots & 0 \end{bmatrix}$$

$$A_f = A + \gamma^{-2}B_1B_1^T X + B_2F + ZLC_2, F = -B_2^T X, Z = (I - \gamma^{-2}YX)^{-1} \text{ and } L = -YC_2^T$$

The configuration shows the robust process is shown in figure (4.2). The plant $p(s)$ with two inputs, the first represents both the reference input and the outside disturbances and denoted by the symbol $u_1(t)$, whereas the second input represents manipulated variables and denoted by the symbol $u_2(t)$. On other side, there are two outputs for this process; first the error signal $y_1(t)$ generated by the process and the variables $y_2(t)$ with measured variables. $y_2(t)$ is multiplied by $F(s)$ matrix to get manipulated variables.

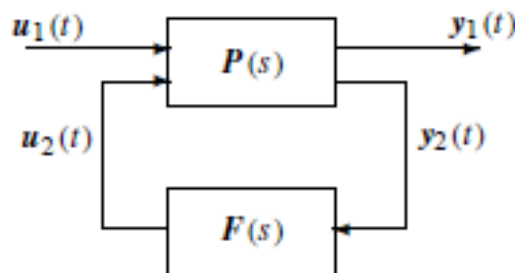


Figure 4.2: Block diagram of control system

The matrix equation describes the process shown in figure (4.2) can be given by:

$$\begin{bmatrix} s\dot{x}(s) \\ y_1(s) \\ y_2(s) \end{bmatrix} = P(s) \begin{bmatrix} x(s) \\ u_1(s) \\ u_2(s) \end{bmatrix}$$

And,

$$P(s) = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}$$

$$s\mathbf{x}(s) = \mathbf{A}\mathbf{x}(s) + [B_1 \quad B_2] \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \mathbf{x}(s) + \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

Whereas $P(s)$ is the transfer function of the plant, $x(s)$ represent state space variables equation and $y(s)$ represent system output. The relation between input and output can be presented by the equation:

$$T_{y_1 u_1}(s) = P_{11}(s) + P_{12}(s)[I - F(s)P_{22}(s)]^{-1}F(s)P_{21}(s)$$

The property of H-infinity property is described by the equation:

$$\|T(s)_{y_1 u_1}\|_{\infty} < 1$$

On other hand, figure (4.3) shows 3 blocks which makes filtration for the signals from three different areas. The first makes filtration for the error signal, the second makes filtration for the

controlled signal before feeding it to plant and the third make filtration for the output signal. The three blocks are called the weighting functions.

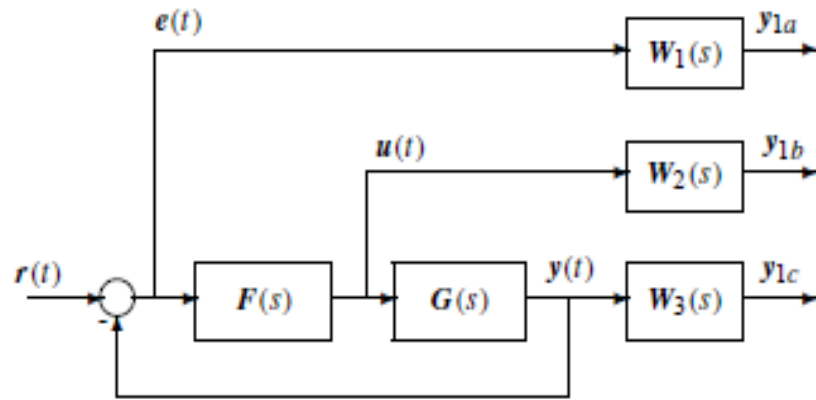


Figure 4.3: Block diagram of control system showing weighting functions

The equation describes the represent the integration between plant equations and block diagram shown in figure (4.3) can be given by:

$$P(s) = \begin{bmatrix} W_1(s) & \vdots & -W_1(s)G(s) \\ \mathbf{0} & \vdots & W_2(s) \\ \mathbf{0} & \vdots & W_3(s)G(s) \\ \dots & \vdots & \dots \\ \mathbf{I} & \vdots & -G(s) \end{bmatrix}$$

$$T_{y1u1} = \begin{bmatrix} W_1(s)S(s) \\ W_2(s)F(s)S(s) \\ W_3(s)T(s) \end{bmatrix}$$

$$S(s) = [\mathbf{I} + F(s)G(s)]^{-1}$$

$$T(s) = \mathbf{I} - S(s) = F(s)G(s)[\mathbf{I} + F(s)G(s)]^{-1}$$

4.3 Design of H-Infinity Controller:

H-infinity design starts with choosing weighting functions as following:

$$W_1(s) = \begin{bmatrix} \frac{1000}{s + 0.5} & 0 \\ 0 & \frac{1000}{s + 1} \end{bmatrix}$$

$$W_2(s) = \begin{bmatrix} 10^{-5} & 0 \\ 0 & 10^{-5} \end{bmatrix}$$

$$W_3(s) = \begin{bmatrix} \frac{s}{1000} & 0 \\ 0 & \frac{s}{200} \end{bmatrix}$$

<< H-Infinity Optimal Control Synthesis >>

No	Gamma	D11<=1	P-Exist	P>=0	S-Exist	S>=0	lam(PS)<1	C.L.
1	1.0000e+00	OK	OK	FAIL	OK	OK	OK	UNST
2	5.0000e-01	OK	OK	OK	OK	OK	OK	STAB
3	7.5000e-01	OK	OK	OK	OK	OK	OK	STAB
4	8.7500e-01	OK	OK	FAIL	OK	OK	OK	UNST
5	8.1250e-01	OK	OK	FAIL	OK	OK	OK	UNST
6	7.8125e-01	OK	OK	FAIL	OK	OK	OK	UNST
7	7.6563e-01	OK	OK	OK	OK	OK	OK	STAB
8	7.7344e-01	OK	OK	OK	OK	OK	OK	STAB
9	7.7734e-01	OK	OK	OK	OK	OK	OK	STAB

Iteration no. 9 is your best answer under the tolerance: 0.0100 .

Table 4.1: Different values of gamma for H-infinity controller

If the chosen value of gamma is 7.7734×10^{-1} , then the H-infinity controller transfer function

$F(c)$ can be given by:

$$F_c(s) = \begin{bmatrix} F_{11}(s) & F_{12}(s) \\ F_{21}(s) & F_{22}(s) \end{bmatrix}$$

And each element in the above matrix can be given by following equations:

$$F_{11}(s) = \frac{8.29e06s^5 + 5.25e09s^4 + 1.18e10s^3 + 9.23e09s^2 + 3.08e09s + 3.74e08}{s^6 + 204s^5 + 8.94e05s^4 + 1.71e06s^3 + 1.00e06s^2 + 1.86e05s + 5.40}$$

$$F_{12}(s) = \frac{-7.98e06s^5 - 5.06e09s^4 - 1.14e10s^3 - 9.03e09s^2 - 3.05e09s - 3.74e08}{s^6 + 204s^5 + 8.94e05s^4 + 1.71e06s^3 + 1.00e06s^2 + 1.86e05s + 5.40}$$

$$F_{21}(s) = \frac{-1.61e06s^5 - 2.28e09s^4 - 4.00e09s^3 - 2.63e09s^2 - 7.68e08s - 8.38e07}{s^6 + 204s^5 + 8.94e05s^4 + 1.71e06s^3 + 1.00e06s^2 + 1.86e05s + 5.40}$$

$$F_{22}(s) = \frac{1.67e06s^5 + 2.36e09s^4 + 4.11e09s^3 + 2.68e09s^2 + 7.74e08s + 5.38e07}{s^6 + 204s^5 + 8.94e05s^4 + 1.71e06s^3 + 1.00e06s^2 + 1.86e05s + 5.40}$$

After factorizing H-infinity transfer function, the equation can be written as below:

$$F_{11}(s) = \frac{8.288e06 (s + 631.5) (s + 1.0) (s + 0.4255) (s + 0.4115)(s + 0.4082)}{(s + 1.409e03) (s + 631.4)(s + 1.0) (s + 0.5) (s + 0.4172) (s + 2.91e - 05)}$$

$$F_{12}(s) = \frac{-7.9837e06 (s + 631.5) (s + 1.0) (s + 0.4255) (s + 0.4237) (s + 0.4115)}{(s + 2.14e04) (s + 631.4) (s + 1) (s + 0.5) (s + 0.4172) (s + 2.91e - 05)}$$

$$F_{21}(s) = \frac{-1.6133e06 (s + 1411) (s + 0.5) (s + 0.4255) (s + 0.4237) (s + 0.4082)}{(s + 2.14e04) (s + 631.4) (s + 1) (s + 0.5) (s + 0.4172) (s + 2.91e - 05)}$$

$$F_{22}(s) = \frac{1.6685e06 (s + 1411) (s + 0.5) (s + 0.4237) (s + 0.4115) (s + 0.4082)}{(s + 2.14e04) (s + 631.4) (s + 1) (s + 0.5) (s + 0.4172) (s + 2.91e - 05)}$$

The controller is of high, and hence it is difficult to implement practically.

4.4 Simulation of H-Infinity Controller:

4.4.1 Closed Loop Response:

Once applying H-infinity controller which has been designed to the propeller shaft system; the response improves as shown in below in figures (4.4) and (4.5).

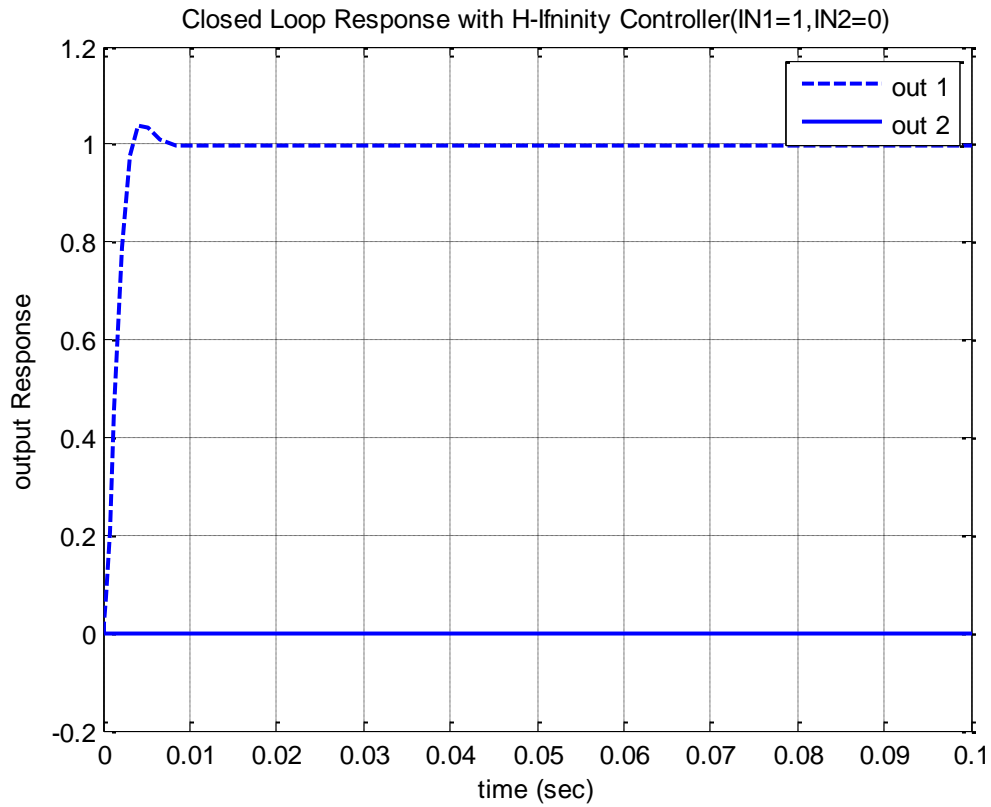


Figure 4.4: Closed loop response with H-infinity controller (in1=1, in2=0)

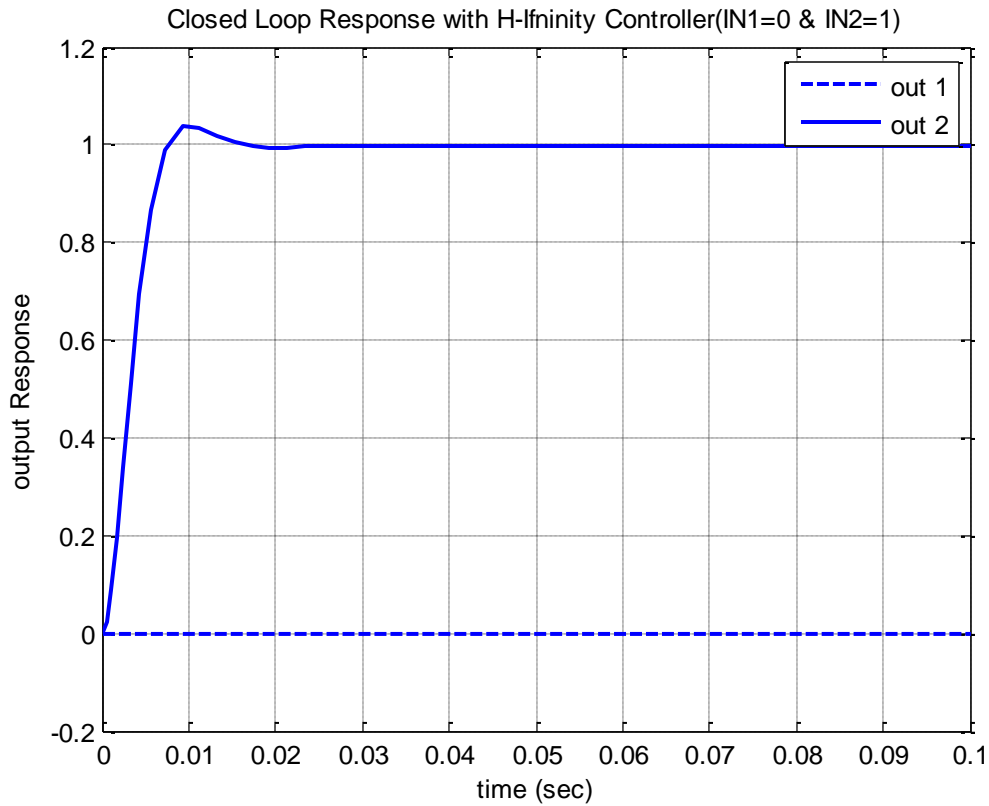


Figure 4.5: Closed loop response with H-infinity controller (in1=0, in2=1)

Response clearly shows slight acceptable overshoot, and the system reaches steady state rapidly "approximately after 0.15 seconds". Accordingly, the settling time as well as time constant are obviously improved. System interaction which was occurring in the open loop response are effectively eliminated by the controller.

4.4.2 Disturbance Rejection:

In order to consider the disturbance rejection exhibited by the controller, the two inputs are set to be $V_1(t) = 0$ and $V_2(t) = 0$, and unit step disturbance inputs is injected to the system as shown in appendix (A2) $d_1(t)$ and $d_2(t)$. Figures (4.6) and (4.7) show the response of shaft propeller system with loop shaping controller ability to eliminate the disturbance.

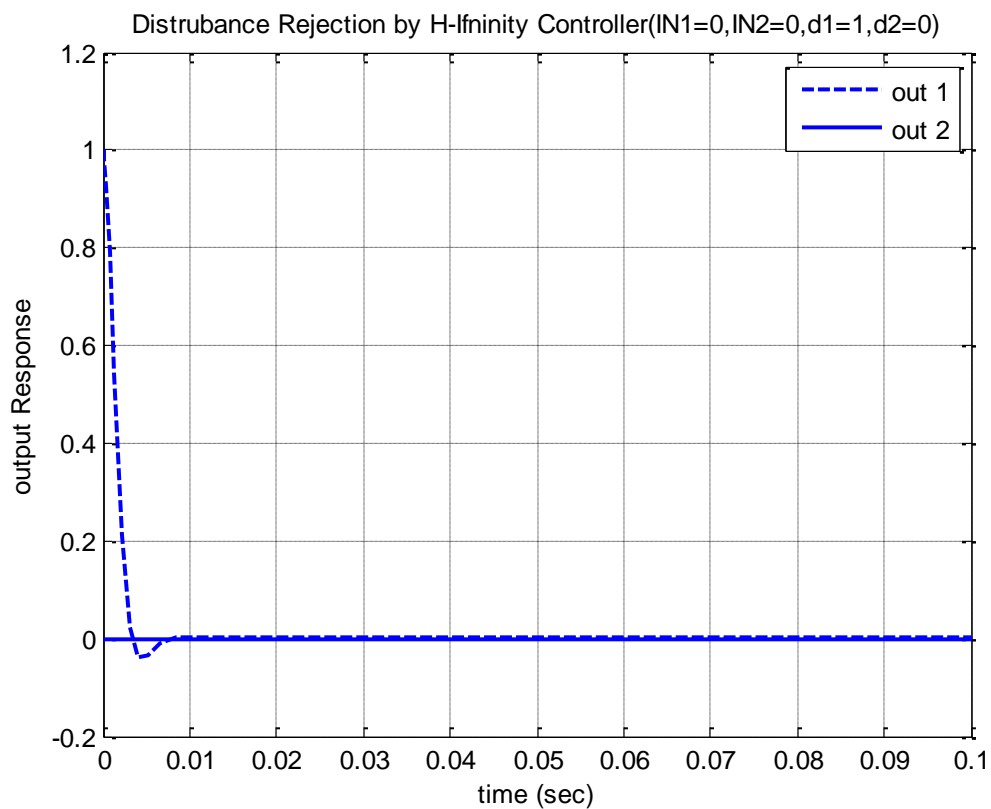


Figure 4.6: Disturbance rejection by H-infinity controller (d1=1, d2=0)

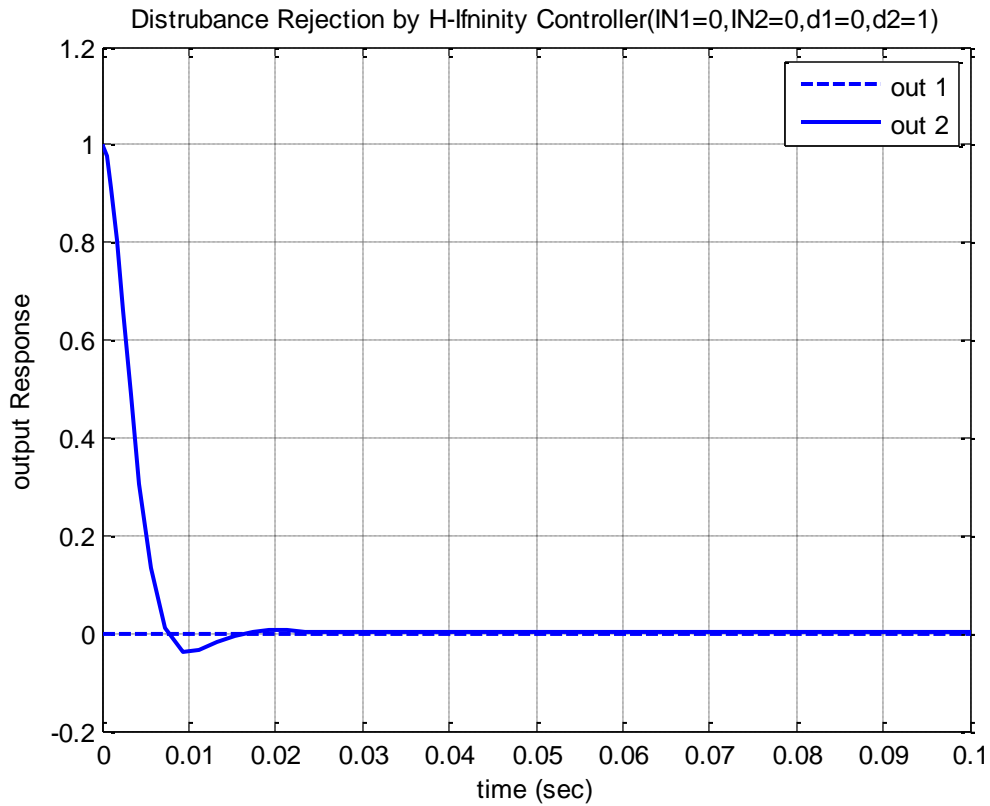


Figure 4.7: Disturbance rejection by H-infinity controller (d1=0, d2=1)

Above figures showing that loop shaping controller exhibits a rapid elimination of disturbance and drives to equal approximately “after only 0.007 seconds for input 1 and after 0.02 seconds for input 2”.

(5)

Control of Propeller Shaft System using Loop Shaping Method

5.1 Introduction:

As a part of frequency domain analysis, this technique is based on shaping the open loop response of a multivariable system with a transfer function $G(s)$ to a required loop shape which satisfy the performance as well as robustness. Figure (5.1) shows the general specification of loop shaping technique.

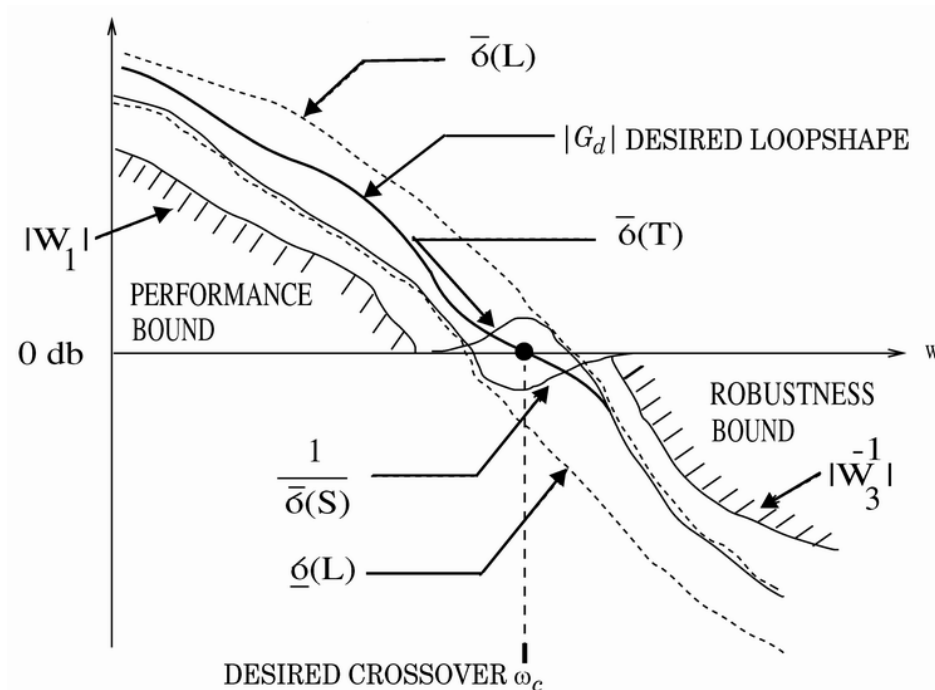


Figure 5.1: General Specification of loop shaping

As shown in above figure (2.1), $G_d(s)$ represents the desired open loop shape, which should be identified as a first step in the controller design. Three specifications determine the required loop shape, first is performance bound, which can be satisfied when the loop shape is less than 0DB

at high frequency. Second is robustness bound which means that the loop shape should have large gain at the areas of performance. And the last is desired crossover which means that $G_d(s)$ must go through the $0dB$ when comes between the performance bound and robustness bound.

The equation represent the required loop shape can be given by:

$$G_d(s) = \frac{W_c}{s}$$

whereas W_c represent the crossover point.

5.2 Theory and design of Loop Shaping controller:

In order to get the design of controller through this technique, the procedures should be started with understanding the plant itself with all dynamic parameters, responses and the location of poles and zeros. Identifying the required loop shape $G_d(s)$ is second, including the required rise time and crossover frequency point. Figure (5.2) show that 8 is the chosen frequency.

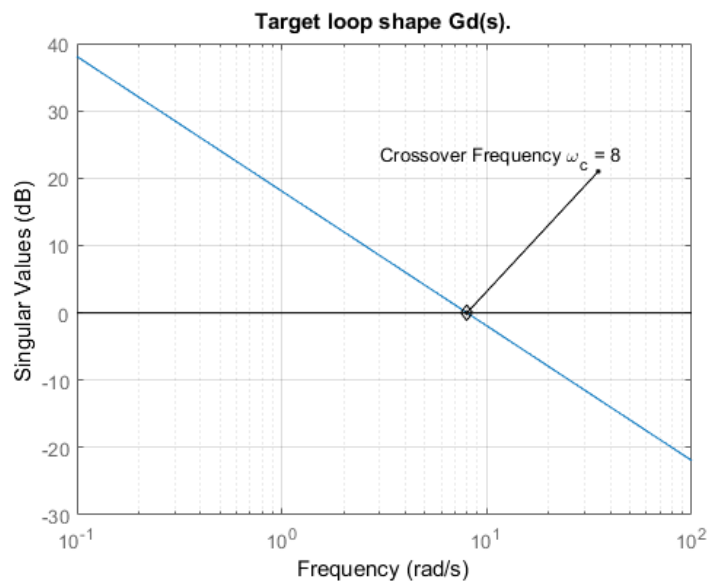


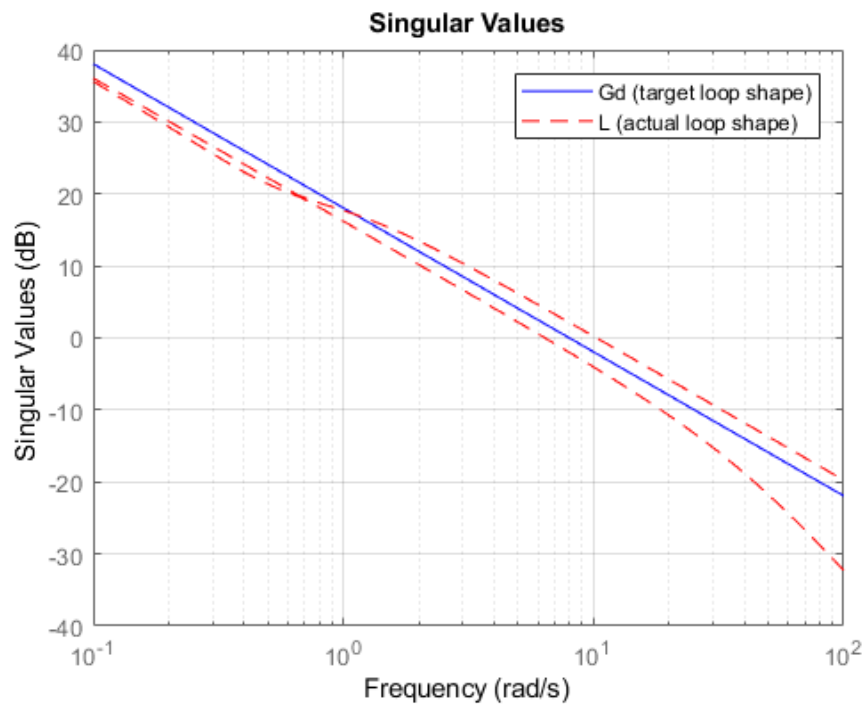
Figure 5.2: Target loop shaping

A proper controller should be designed so the “the open loop” $G(s)K(s)$ response will satisfy the required loop shape $G_d(s)$. The following code can be used on matlab:

```
[K,CL,GAM] = loopsyn(G,Gd);
GAM
```

The following code can be used on MATLAB to make comparison between the required loop shape and the actual loop shape of the propeller shaft system:

```
L = G*K;           % form the compensated loop L
sigma(Gd,'b',L,'r--',{.1,100});
grid
legend('Gd (target loop shape)','L (actual loop shape)');
```

**Figure 5.3:** Actual loop shape with target loop shape

At the last step of loop shaping controller design, the following code is utilized on MATLAB to generate a comparison between all system characteristics as following:

```
T = feedback(L,eye(2));
T.InputName = {'alpha command','theta command'};
S = eye(2)-T;

% SIGMA frequency response plots
sigma(inv(S),'m',T,'g',L,'r--',Gd,'b',Gd/GAM,'b:',...
      Gd*GAM,'b:',{.1,100})
legend('1/\sigma(S) performance',...
      '\sigma(T) robustness',...
      '\sigma(L) open loop',...
      '\sigma(Gd) target loop shape',...
      '\sigma(Gd) \pm GAM(dB)');

% Make lines wider and fonts larger

% set(findobj(gca,'Type','line','-not','Color','b'),'Linewidth',2);
h = findobj(gca,'Type','line','-not','Color','b');
set(h,'Linewidth',2);
```

Figure (5.4) shows the comparisons between system's characteristics.

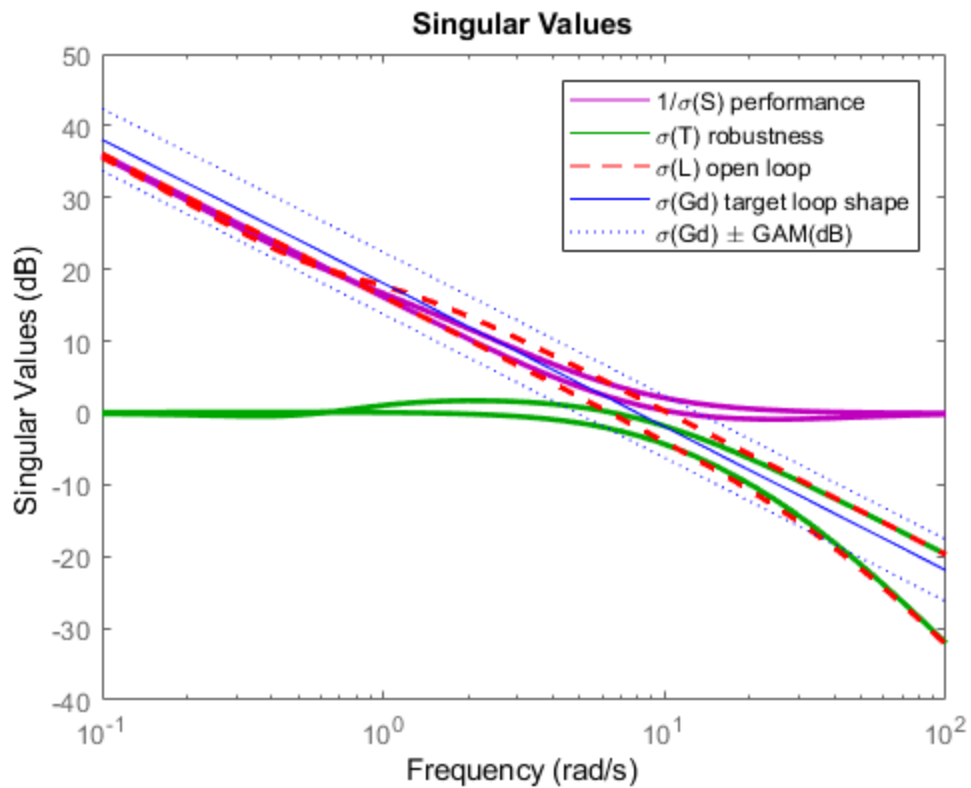


Figure 5.4: Singular values with different frequencies

Accordingly, The transfer function of loop shaping controller $\mathbf{K}(s)$ is given by the following matrix equation:

$$\mathbf{K}(s) = \begin{bmatrix} \mathbf{K}_{11}(s) & \mathbf{K}_{12}(s) \\ \mathbf{K}_{21}(s) & \mathbf{K}_{22}(s) \end{bmatrix}$$

Where:

$$K_{11}(s) = \frac{8.1673e06 (s^2 + 3.815s + 340.20)}{s(s + 4112)(s + 0.002106)}$$

$$K_{12}(s) = \frac{0.005379(s + 8.07e05) (s - 6.401e05)}{s(s + 4112) (s + 0.002106)}$$

$$K_{21}(s) = \frac{0.18683(s + 1.247e05) (s - 1.192e05)}{s(s + 4112) (s + 0.002106)}$$

$$K_{22}(s) = \frac{7.2489e06 (s^2 + 3.62s + 383.3)}{s(s + 4112) (s + 0.002106)}$$

Accordingly,

$$\mathbf{K}(s) = \frac{\begin{bmatrix} 8.1673e06 (s^2 + 3.815s + 340.20) & 0.005379(s + 8.07e05) (s - 6.401e05) \\ 0.18683(s + 1.247e05) (s - 1.192e05) & 7.2489e06 (s^2 + 3.62s + 383.3) \end{bmatrix}}{s(s + 4112) (s + 0.002106)}$$

5.3 Simulation of Loop Shaping Controller:

5.3.1 Closed Loop Response:

Once applying loop shaping controller which designed earlier in previous section to propeller shaft system; the response gets improved as shown in below Figure (5.5).

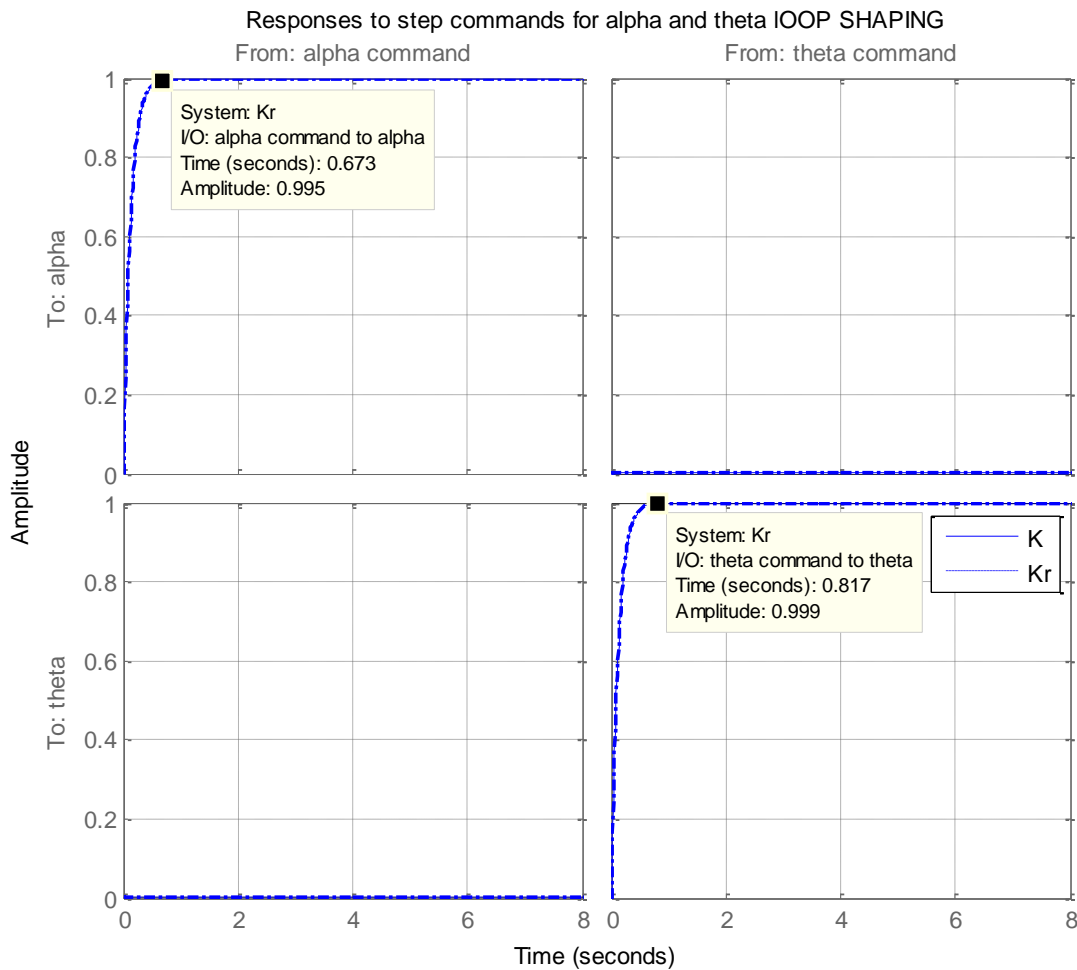


Figure 5.5: closed loop response with loop shaping controller

Response clearly shows that there is no overshoot occur to the system, and the system reaches the steady state rapidly “approximately after 0.3 seconds”. Accordingly, the settling time as well as time constant is obviously improved. System interaction which occurred in the open loop response are effectively eliminated by the controller.

5.3.2 Disturbance Rejection:

In order to consider the disturbance rejection exhibited by the controller, the two inputs are set to be $V_1(t) = 0$ and $V_2(t) = 0$, and unit step disturbance inputs is injected to the system as shown in appendix (A2) $d_1(t)$ and $d_2(t)$. Figures (5.6) and (5.7) show the response of shaft propeller system with H-infinity controller ability to eliminate the disturbance.

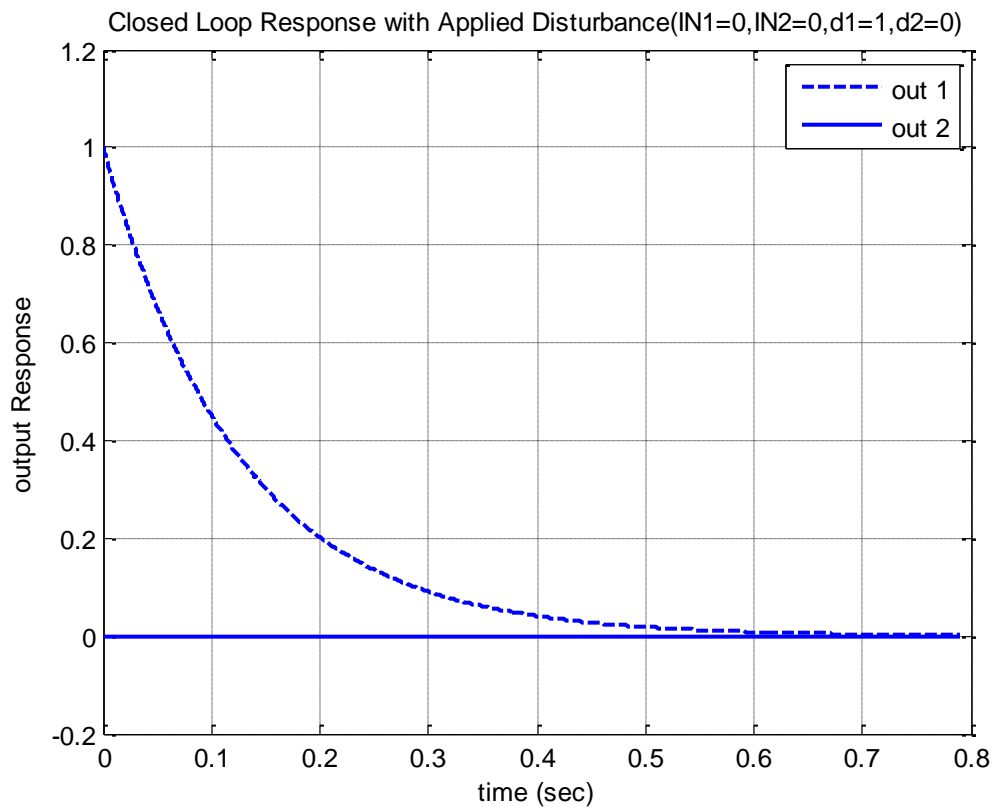


Figure 5.6: Disturbance rejection by loop shaping controller ($d_1=1, d_2=0$)

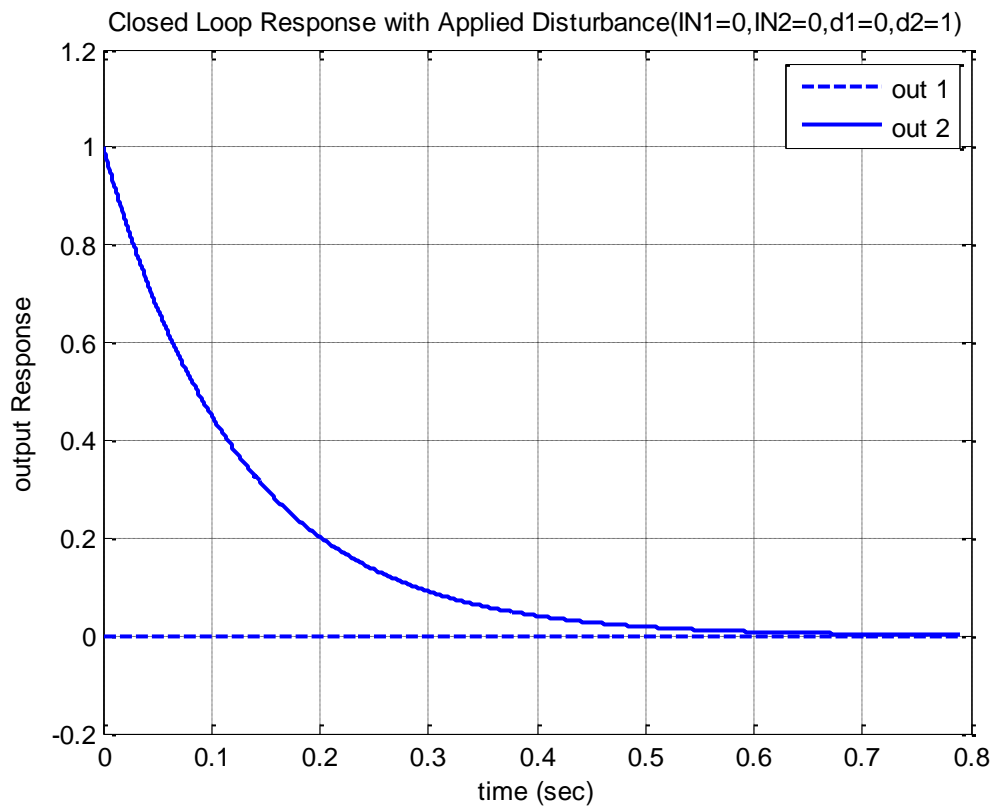


Figure 5.7: Disturbance rejection by loop shaping controller ($d1=0, d2=1$)

Above figures H-infinity controller exhibits a rapid elimination of disturbance and drives it to equal approximately “after only 0.8 seconds for input 1 and input 2”.

(6)

Results Comparison and Discussion

The two techniques developed in this study to control and improve the response of multivariable input/output propeller shaft system are compared thoroughly. The pros and cons of each technique is highlighted as a comparison to stand on the best controller which suits the application targeted by end user. Comparisons are done based on two aspects; energy consumption and disturbance rejection.

6.1 Energy Consumption:

Energy consumed by controller gives an indication of controller to work efficiently. High energy consumption leads to producing heat in internal parts of system, high level of noise, heat and wear of internal components and them high operational cost. R. Whalley and M. Ebrahimi, 2006 present a formula for the calculation of energy consumption and given by the equation:

$$E(t) = \int_{t=0}^{t=1} (u_1(t)^2 + u_2(t)^2) dt$$

Simulation is carried out as shown in figures (6.1) and (6.2) to present the energy consumed by each controller as below:

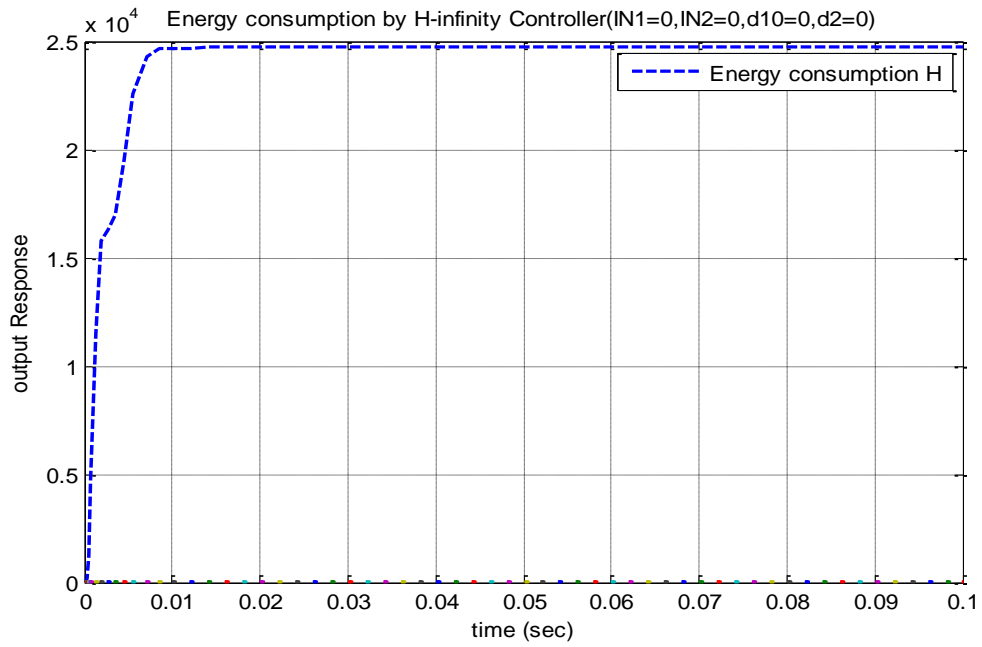


Figure 6.1: Energy consumption simulation of H-infinity controller

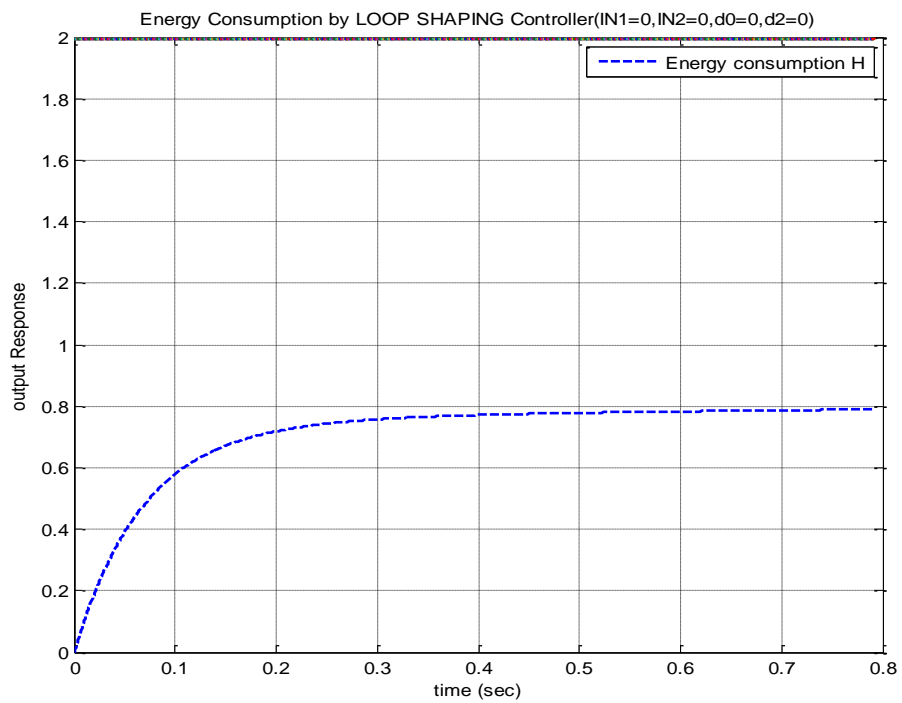


Figure 6.2: Energy consumption simulation of loop shaping controller

H-infinity controller consumes a very high energy compared with loop shaping controller, due to the high order of controller transfer functions.

6.2 Disturbance rejection comparison:

Refer to figures to previous figures in chapter 4 and 5; it is shown obviously that H-infinity exhibits very rapid of disturbance elimination. H-infinity suppresses the disturbance impact on system and returns the system to its steady state conditions effectively. Compared with H-infinity controller, Loop shaping controller requires much more time to eliminate the disturbance totally.

6.3 Other specifications:

Both controllers are showing good decoupling characteristics between inputs/outputs, hence no interaction between inputs and outputs signals. H-infinity shows a slight acceptable overshoot while loop shaping shows no any overshoot at transient state. Both techniques eliminate the steady state error and lead it to zero, while both controllers speeding up the response of systems.

(7)

Conclusion and Recommendation

This research introduces a study for the design, modeling and control of a propeller shaft system of a marine vessel. The transfer function of the system was derived and the open loop response to unit step input was generated.

The importance of using the controller appeared clearly once the open loop response signal was generated. The open loop response shows high steady state error, slow response system, and system input/output interaction. Accordingly, two techniques are introduced in this research to resolve these issues; H- infinity and loop shaping controllers.

Derivation of H-infinity controller shows a high order transfer function, which indicates that the implementation of transfer function practically difficult. Moreover, and as shown in simulations, high order transfer function consumes a very high amount energy which reduces system life and increase operational cost. On other hand h-infinity shows an effective tool to eliminate the disturbance and steady state error with less settling time.

The loop shaping technique shows a slow response regarding the rejecting of disturbance inputs, whereas the energy consumed by the controller is satisfactory. The implementation of this technique is impractical due to the high gains of the controller. Moreover, the loop shaping controller shows input/output interaction elimination, fast response, negligible steady state error and no overshoot.

For both of the control techniques introduced in this research, the controllers are theoretically satisfactory. However, it is obvious that the implementation of those controllers are impossible

due to the high gains required and complexity. If reduced the transfer functions of both of the controllers would be unable to guarantee stability, let alone optimality. Obviously, the use of integrator affects the possibility of saturation if the error condition persists.

Marine vessels work for long operational hours and maintenance is difficult to be carried out in heavy sea. Accordingly; Energy consumption by the controller is critical due to the impact of generating heat, noise and wear limiting the durability of the system.

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Appendix

H-infinity:

```

s = tf('s');

J1= 310
J3= 188
C1= 20
C2= 250
k1= 8.47*10^4

V1=1
V2=1
L1=.5
L2=.5
R1=900
R2=900

G=[J3*s^2+C2*s+k1 k1;k1 J1*s^2+C1*s+k1]
Ge=[1/((L1*s)+R1) 0;0 1/((L2*s)+R2)]
Gt1=(G*Ge)/((J1*J3)*s^3+((J3*C1)+(J1*C2))*s^2+((J3*k1)+(C1*C2)+(J1*k1))*s+(C1*k1)+(k1*C2))

t = (0:.1:20)';

step(Gt1,t)
title('Open Loop Response old')
figure
%tfsys = tf(sys)

Gt=[4.11/(2.35*s+1) 4.11/(2.43*s+1);4.11/(2.45*s+1) 4.11/(2.36*s+1)]
step(Gt,t)
title('Open Loop Response new')
figure
%tfsys = tf(sys)

step(Gt1,t)
step(Gt,t)
title('Open Loop Response old & new')
figure

[num,den] = tfdata(G,'v')

gt11=tf(Gt(1,1))
gt12=tf(Gt(1,2))
gt21=tf(Gt(2,1))
gt22=tf(Gt(2,2))

Gtm=[gt11 gt12;gt21 gt22]

sys=ss(Gtm)

SS=ss(Gtm)

%A=SS.a

```

```

%B=SS.b
%C=SS.c
%D=SS.d

A=[0 1 0 0;-0.171497 -0.828331 0 0;0 0 0 1;0 0 -0.174374 -0.835251]
B=[0 0;1 0; 0 0;0 1]
C=[0.704853 1.72689 0.716677 1.69136;0.704853 1.67755 0.716677 1.74153]
D=[0 0;0 0]

[numGtm11,denGtm11] = tfdata(Gtm(1,1))
[numGtm21,denGtm21] = tfdata(Gtm(2,1))
[numGtm12,denGtm12] = tfdata(Gtm(1,2))
[numGtm22,denGtm22] = tfdata(Gtm(2,2))

set_param('desertation2full2ss2inf/TraFcn
11','Numerator','numGtm11{1}','Denominator','denGtm11{1}'); % TF=H(s)
set_param('desertation2full2ss2inf/TraFcn
21','Numerator','numGtm21{1}','Denominator','denGtm21{1}');
set_param('desertation2full2ss2inf/TraFcn
12','Numerator','numGtm12{1}','Denominator','denGtm12{1}');
set_param('desertation2full2ss2inf/TraFcn
22','Numerator','numGtm22{1}','Denominator','denGtm22{1}');

set_param('desertation2full2ss2inf/IN1Step1','after','1')
set_param('desertation2full2ss2inf/IN2Step2','after','0')

set_param('desertation2full2ss2inf/d1','after','0')
set_param('desertation2full2ss2inf/d2','after','0')

W1=[1000/(s+0.5),0; 0,1000/(s+1)];
W2=[tf(1e-5),0; 0,tf(1e-5)]; W3=[s/1000,0; 0,s/200];
Tss=augtf(Gtm,W1,W2,W3); [g,Gc]=hinfopt(Tss); zpk(Gc(1,2))

Hs=Gc

Hs(1,1)

[numh11,denh11] = tfdata(Hs(1,1))
[numh21,denh21] = tfdata(Hs(2,1))
[numh12,denh12] = tfdata(Hs(1,2))
[numh22,denh22] = tfdata(Hs(2,2))

set_param('desertation2full2ss2inf/CTF11','Numerator','numh11{1}','Denominator','denh11{1}'); % TF=H(s)
set_param('desertation2full2ss2inf/CTF21','Numerator','numh21{1}','Denominator','denh21{1}');
set_param('desertation2full2ss2inf/CTF12','Numerator','numh12{1}','Denominator','denh12{1}');
set_param('desertation2full2ss2inf/CTF22','Numerator','numh22{1}','Denominator','denh22{1}');

sim('desertation2full2ss2inf')

```

```

step(feedback(Gtm*Gc,eye(2)),0.1)
title('H infinity')
figure

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response conventional H inf(IN1=1,IN2=0)')
grid on
figure

set_param('desertation2full2ss2inf/IN1Step1','after','0')
set_param('desertation2full2ss2inf/IN2Step2','after','1')
sim('desertation2full2ss2inf')

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response conventional H inf(IN1=0 & IN2=1)')
grid on

figure

set_param('desertation2full2ss2inf/IN1Step1','after','0')
set_param('desertation2full2ss2inf/IN2Step2','after','0')
set_param('desertation2full2ss2inf/d1','after','1')
set_param('desertation2full2ss2inf/d2','after','0')
sim('desertation2full2ss2inf')

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response conventional H inf(IN1=0,IN2=0,d1=1,d2=0)')
grid on

figure

set_param('desertation2full2ss2inf/IN1Step1','after','0')
set_param('desertation2full2ss2inf/IN2Step2','after','0')
set_param('desertation2full2ss2inf/d1','after','0')
set_param('desertation2full2ss2inf/d2','after','1')
sim('desertation2full2ss2inf')

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')

```

```
title('system response conventional H inf(IN1=0,IN2=0,d1=0,d2=1)')
grid on

figure

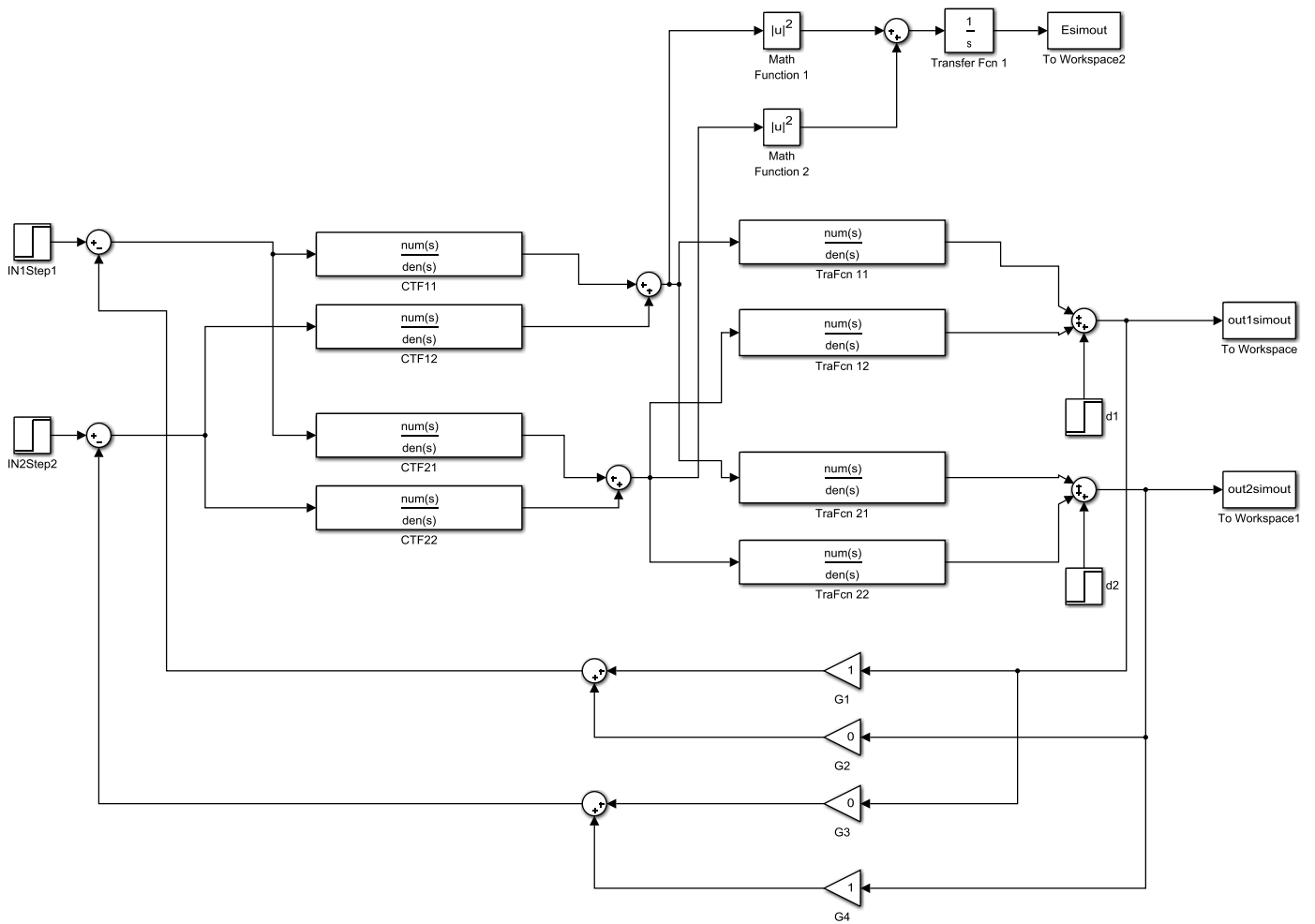
set_param('desertation2full2ss2inf/IN1Step1','after','1')
set_param('desertation2full2ss2inf/IN2Step2','after','1')
set_param('desertation2full2ss2inf/d1','after','0')
set_param('desertation2full2ss2inf/d2','after','0')
sim('desertation2full2ss2inf')

p=plot(tout,Esimout,'b--',tout,2)

legend('Energy consumption H')
xlabel('time (sec)')
ylabel('output Response')
title('Energy consumption H inf(IN1=0,IN2=0,d0=0,d2=0)')
```

grid on
Loop shaping

```
s = tf('s');
```



J1= 310
 J3= 188
 C1= 20
 C2= 250
 k1= 8.47*10^4

V1=1
 V2=1
 L1=.5
 L2=.5
 R1=900

```

R2=900

G=[J3*s^2+C2*s+k1 k1;k1 J1*s^2+C1*s+k1]
Ge=[1/((L1*s)+R1) 0;0 1/((L2*s)+R2)]
Gt1=(G*Ge)/((J1*J3)*s^3+((J3*C1)+(J1*C2))*s^2+((J3*k1)+(C1*C2)+(J1*k1))*s+(C1*k1)+(k1*C2))

t = (0:.1:20)';

step(Gt1,t)
title('Open Loop Response actual')
figure
%tfsys = tf(sys)

Gt=[4.11/(2.35*s+1) 4.11/(2.43*s+1);4.11/(2.45*s+1) 4.11/(2.36*s+1)]
step(Gt,t)
title('Open Loop Response reduced')
figure

step(Gt1,t)
step(Gt,t)
title('Open Loop Response actual and reduced')
figure

[num,den] = tfdata(G,'v')
gt11=tf(Gt(1,1))
gt12=tf(Gt(1,2))
gt21=tf(Gt(2,1))
gt22=tf(Gt(2,2))

Gtm=[gt11 gt12;gt21 gt22]

sys=ss(Gtm)

SS=ss(Gtm)
A=SS.a
B=SS.b
C=SS.c
D=SS.d

G = ss(A,B,C,D);
G.InputName = {'elevon','canard'};
G.OutputName = {'alpha','theta'};

clf

plant_poles = pole(G)
plant_zeros = tzero(G)

clf, sigma(G,'g',{.1,100});
title('Singular value plot for aircraft model G(s)');

```

```

s = zpk('s'); % Laplace variable s
Gd = 8/s;
sigma(Gd,{.1 100})
grid
title('Target loop shape Gd(s).')

% create textarrow pointing to crossover frequency Wc
hold on;
plot([8,35],[0,21],'k.-');
plot(8,0,'kd');
plot([.1,100],[0 0],'k');
text(3,23,'Crossover Frequency \omega_c = 8');
hold off;

[K,CL,GAM] = loopsyn(G,Gd);
GAM

L = G*K; % form the compensated loop L
sigma(Gd,'b',L,'r--',{.1,100});
grid
legend('Gd (target loop shape)','L (actual loop shape)');

T = feedback(L,eye(2));
T.InputName = {'alpha command','theta command'};
S = eye(2)-T;

% SIGMA frequency response plots
sigma(inv(S),'m',T,'g',L,'r--',Gd,'b',Gd/GAM,'b:',...
      Gd*GAM,'b:',{.1,100})
legend('1/\sigma(S) performance',...
      '\sigma(T) robustness',...
      '\sigma(L) open loop',...
      '\sigma(Gd) target loop shape',...
      '\sigma(Gd) \pm GAM(dB)');
% Make lines wider and fonts larger

% set(findobj(gca,'Type','line','-not','Color','b'),'LineWidth',2);
h = findobj(gca,'Type','line','-not','Color','b');
set(h,'LineWidth',2);

step(T,8)
title('Responses to step commands for alpha and theta()');

%Controller Simplification

size(K)
hsv = hankelsv(K);
semilogy(hsv,'*--')
grid
title('Hankel singular values of K')
xlabel('Order')

Kr = reduce(K,9);
order(Kr)

```



```

sigma(K, 'b', K-Kr, 'r-.')
legend('K', 'error K-Kr')

Tr = feedback(G*Kr, eye(2));
step(T, 'b', Tr, 'r-.', 8)
title('Responses to step commands for alpha and theta ( )');
legend('K', 'Kr')

figure

[numGtm11, denGtm11] = tfdata(Gtm(1,1))
[numGtm21, denGtm21] = tfdata(Gtm(2,1))
[numGtm12, denGtm12] = tfdata(Gtm(1,2))
[numGtm22, denGtm22] = tfdata(Gtm(2,2))

set_param('desertation2full2ss2/TraFcn
11', 'Numerator', 'numGtm11{1}', 'Denominator', 'denGtm11{1}'); % TF=H(s)
set_param('desertation2full2ss2/TraFcn
21', 'Numerator', 'numGtm21{1}', 'Denominator', 'denGtm21{1}');
set_param('desertation2full2ss2/TraFcn
12', 'Numerator', 'numGtm12{1}', 'Denominator', 'denGtm12{1}');
set_param('desertation2full2ss2/TraFcn
22', 'Numerator', 'numGtm22{1}', 'Denominator', 'denGtm22{1}');

set_param('desertation2full2ss2/IN1Step1', 'after', '1')
set_param('desertation2full2ss2/IN2Step2', 'after', '0')

set_param('desertation2full2ss2/d1', 'after', '0')
set_param('desertation2full2ss2/d2', 'after', '0')
Hs=Kr
Hs(1,1)

[numh11, denh11] = tfdata(Hs(1,1))
[numh21, denh21] = tfdata(Hs(2,1))
[numh12, denh12] = tfdata(Hs(1,2))
[numh22, denh22] = tfdata(Hs(2,2))

set_param('desertation2full2ss2/CTF11', 'Numerator', 'numh11{1}', 'Denominator',
'denh11{1}'); % TF=H(s)
set_param('desertation2full2ss2/CTF21', 'Numerator', 'numh21{1}', 'Denominator',
'denh21{1}');
set_param('desertation2full2ss2/CTF12', 'Numerator', 'numh12{1}', 'Denominator',
'denh12{1}');
set_param('desertation2full2ss2/CTF22', 'Numerator', 'numh22{1}', 'Denominator',
'denh22{1}');
sim('desertation2full2ss2')
p=plot(tout, out1simout, 'b--', tout, out2simout, 'b-', 'LineWidth', 2)
legend('out 1', 'out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response LOOP SHAPING (IN1=1, IN2=0)')
grid on
figure

```

```

set_param('desertation2full2ss2/IN1Step1','after','0')
set_param('desertation2full2ss2/IN2Step2','after','1')
sim('desertation2full2ss2')
p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)
legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response LOOP SHAPING (IN1=0 & IN2=1)')
grid on
figure
set_param('desertation2full2ss2/IN1Step1','after','0')
set_param('desertation2full2ss2/IN2Step2','after','0')
set_param('desertation2full2ss2/d1','after','1')
set_param('desertation2full2ss2/d2','after','0')
sim('desertation2full2ss2')

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response LOOP SHAPING (IN1=0,IN2=0,d1=1,d2=0)')
grid on

figure

set_param('desertation2full2ss2/IN1Step1','after','0')
set_param('desertation2full2ss2/IN2Step2','after','0')
set_param('desertation2full2ss2/d1','after','0')
set_param('desertation2full2ss2/d2','after','1')
sim('desertation2full2ss2')

p=plot(tout,out1simout,'b--',tout,out2simout,'b-','LineWidth',2)

legend('out 1','out 2')
xlabel('time (sec)')
ylabel('output Response')
title('system response LOOP SHAPING (IN1=0,IN2=0,d1=0,d2=1)')
grid on

figure

set_param('desertation2full2ss2/IN1Step1','after','1')
set_param('desertation2full2ss2/IN2Step2','after','1')
set_param('desertation2full2ss2/d1','after','0')
set_param('desertation2full2ss2/d2','after','0')
sim('desertation2full2ss2')

p=plot(tout,Esimout,'b--',tout,2)

legend('Energy consumption H')
xlabel('time (sec)')
ylabel('output Response')
title('Energy LOOP SHAPING (IN1=0,IN2=0,d0=0,d2=0)')

```

grid on

