# STEP MOTOR SELECTION AND CONTROL: AN INDUSTRIAL CASE STUDY

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**Abstract**— The process of selecting a step motor to an industrial application is not straightforward. Several aspects need to be considered at the beginning of the design, specially when dealing with a step motor due to its peculiar $Speed \times Torque$ relation. This paper presents a case study of a step motor selection for a food industry problem, introducing the main aspects to be taken into account and the challenges this type of motor poses to meet the requirements. The intention is to describe the selection and design process and compare two different control approaches, first a classical approach using a lead/lag compensator, then a robust control approach using a $H_\infty$ control.

**Keywords**— Step motor, industrial applications, lead/lag compensator, $H_\infty$ control.

**Resumo**— O processo de seleção de um motor de passo para uma aplicação industrial não é direto. Vários aspectos precisam ser considerados no início do projeto, especialmente se tratando deste tipo de motor, que possui uma relação *velocidade* $\times$ *torque* peculiar. Este artigo apresenta um estudo de caso de seleção de um motor de passo para um problema da indústria alimentícia, apresentando os principais aspectos a serem considerados e os desafios que este tipo de motor apresenta para cumprir os requisitos. A intenção é descrever o processo de seleção e projeto, além de comparar duas abordagens de controle diferentes, primeiro usando controle clássico, utilizando um compensador por avanço/atraso de fase, e por último usando controle robusto por meio de um controlador $H_\infty$.

**Palavras-chave**— Motor de passo, aplicação industrial, compensador de avanço/atraso de fase, controle $H_\infty$.

## 1 Introduction

Step motors have been widely studied recently, since they first came to be in the early 1960's (Khan et al., 2014). There is, however, a lack of applicability information in the sense of how to dimension and properly choose a step motor to a specific industrial application. The first point to be established is how to be sure which is the correct type of motor to be utilized. Step motors are mainly applied to motion problems due to a number of benefits: high precision (synchronous), simple control, can be used in open loop (with restrictions), low cost, low heat, low noise and low maintenance.

Step motors present, however, a very critical downside which is the loss of torque as speed grows, so high speed applications that require high torque are not suitable for step motors. They still are a very interesting alternative to complex and expensive servo motor systems in applications with low torque demand.

### 1.1 Open loop x closed loop

Step motors are synchronous motors, in the sense that a pulse of specific length moves the motor by one step. The angle of the step depends on the motor's construction, the most common being a $1.8^o/step$, which is the same of the motor used in this case study. Thus, one can establish that a pulse corresponds to a rotation of step angle $\Delta\phi$. To this extent, counting the number of steps gives the total displacement of the rotor, and their frequency will regulate the rotor's speed, assuming that the motor can move the load without stalling.

However, step motors tend to drastically loose torque as speed increases, which means that moving a heavy load on a high speed can be challenging to accomplish without position feedback. To achieve the desired level of confidence in a high accuracy operation, a closed-loop is required to ensure that the target position will always be reached.

Speed feedback, on the other hand, is delicate on step motors, because the controller may increase the speed too much when trying to compensate the error. This can lead to a torque delivered to the axis lower than the minimum required for the scenario. The system would enter in an invalid state trying to increase the frequency of the steps, but without the proper motion of the motor.

## 2 Related work

Step motors have been studied thoroughly over the past fifty years. In (Morar, 2015), the authors propose and validates a model to be used in $Matlab^©$ for dynamic simulation. (Morar, 2003) and (Kelemen et al., 1987) are older publications on the same line of research, where the authors propose and validate a dynamic model for the step motor.

Several techniques have been used to perform feedback control of a step motor, such as PID, PI, STR (Self Tunning Regulation) and Artificial Neural Networks (Khan et al., 2014). There are also techniques developed recently that use sensorless estimation of position by measuring the current and the voltage phase of the windings (Acarnley and Watson, 2006), (Derammelaere et al., 2016), (Lin et al., 2016). It is valid to point out that the majority of the control techniques control the current on the motor's windings. In (Chudasama et al., 2013) the authors present a low cost topology that also uses voltage to perform speed and torque control. In (users.ece.utexas.edu, 2000), it is shown in details how to choose a proper driver for a step motor and additionally, a complete analysis of the selection process is done.

The main objective and contribution of this work is to present a case study of a real industry problem, providing an overview on the process of choosing the right step motor for a given application, as well as proposing different control approaches to meet the design requirements.

Section 3 makes a review of the step motor's construction types and the driver circuits normally used. Section 4 describes the process of choosing the correct motor to meet the application's requirements, as well as an introduction to the paring problem. Section 5 shows the selected control approaches to drive the motors in closed loop, and sections 6 and 7 present the conclusion and future work possibilities, respectively.

## 3 Step motor review

A step motor is a synchronous electrical motor which moves in a well defined angle (step angle - $\Delta\phi$) according to the excitation sequence on its windings. There are three types of construction for the step motor: 1) Permanent Magnet (PM), 2) Variable Reluctance (VR) and 3) Hybrid. The motor used in this work belongs to the hybrid type and is described in more details in the sequel. Figure 1 shows a section perpendicular to the axis of the hybrid motor, the sequence of excitation of the coils being A, B, 2A, 2B.

### 3.1 *Hybrid step motor*

A hybrid step motor is a combination of the permanent magnet and the variable reluctance motors, having magnetized toothed rotor and stator. It often provides a smaller step angle (most hybrid step motors available have a $1.8^o$ step angle). The axis construction is different from the PM, and is made of two sections of magnet: the south pole and the north pole. There is an offset of one tooth between them.

### 3.2 *The $\gamma$ factor*

To choose the step motor for an application one must consider its *torque* $\times$ *speed* limitations. The motor can stall and loose synchronism due to disturbances or a change in the load's torque, for example. To overcome this problem, one must select a motor with higher torque. The question is: *how much higher?*

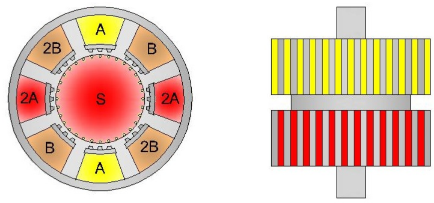


Figure 1: Hybrid Step motor view (*Source: The authors*).

The $\gamma$ factor is used to quantify the previous question and is in practice greater than one. It regulates the maximum torque that needs to be delivered by the motor, specifying a new requirement to motor selection.

Defining $T_f$ as the torque needed to move the load and $T_m$ the torque of the motor, Equation 1 gives the new value to be pursued when selecting the motor:

$$T_m = \gamma T_f. \tag{1}$$

### 3.3 *Step motor model*

In (Morar, 2003), the authors show the relation between torque and current, given by Equation 2:

$$T_{m_j} = K_t sin(n\theta(t) + \phi_j) i_j(t), \tag{2}$$

where:

- $n$ is the number of rotor pole pairs.
- $K_t$ is a constant of the motor.
- $i_j(t)$ is the current on the *coilj* through time.
- $\theta(t)$ is the position of the rotor through time.
- $\phi_j$ is the location of the coils in the stator.
- $T_{m_j}$ is the torque generated by *coilj*.

The total torque is a sum of the torques generated by all the coils. The relation between the voltage and current on the coils is given by Equation 3:

$$Vm_j = emf_j + Ri_j(t) + L\frac{di_j(t)}{dt}, \tag{3}$$

where:

- $R$ is the resistance of the coils (the same value for all).
- $L$ is the inductance of the coils (the same value for all).
- $emf_j$ is the induced electromotive force on phase $j$, given by Equation 4 (Morar, 2003):

$$emf_j = K_t sin(n\theta(t) + \phi_j)\omega, \quad (4)$$

where $\omega$ is the angular velocity of the rotor.

## 4 Step motor in a paring system

PLCs (Programmable Logic Controllers) or microcontrollers are the most common ways to operate step motors in an industrial environment. There are two main factors when considering either solutions: microcontrollers are cheaper, but require more programming experience and have limited processing power, while PLCs are more expensive but require less programming experience and have more processing power available.

The first aspect to take into account when starting a project with step motors is the implementation of the motion algorithms. The expertise of the team and how much the manager is willing to spend on hiring will determine the technology used for development and, therefore, its computational limitations, which will imply directly on the control techniques chosen to drive the application. After this phase, one needs to choose the driver to be used combined with the step motor. The driver selection is of utmost importance for the motion algorithm to extract the maximum power/torque relation from the motor.

Other factors contribute for the motor to perform the desired trajectory, such as the inductance of the coils. They need to be as low as possible for the motor to achieve the current in time, therefore delivering the desired torque. Another factor is the rotor's inertia, which will have an impact in the acceleration/deceleration of the motor. The lower the inertia, the faster the motor can accelerate/decelerate (Acarnley, 2002).

### *4.1 The paring problem*

This work is based on a case study from the coconut industry, where a machine is being developed to perform the task of automatically pare the coconut's skin. Figure 2 shows the layers of the fruit. The machine can be divided into two parts: the paring table and the feeder arm. The first is responsible to scan the surface of the coconut and do the paring whereas the second is responsible to position the fruit and to guarantee that the coconut is always positioned in the same way.

The feeder consists of a rigid arm, represented by the segment $\overline{E_1F_1}$ in Figure 3, with a nipper at the end to perform the task of grabbing and positioning the coconut for paring. It grabs the coconut and releases it on the claw of the paring table. The two systems are independent from each other, but work coordinated to achieve minimum processing time. The principle is to analyse the coconut surface by image processing and convert the result to positions of the paring table.

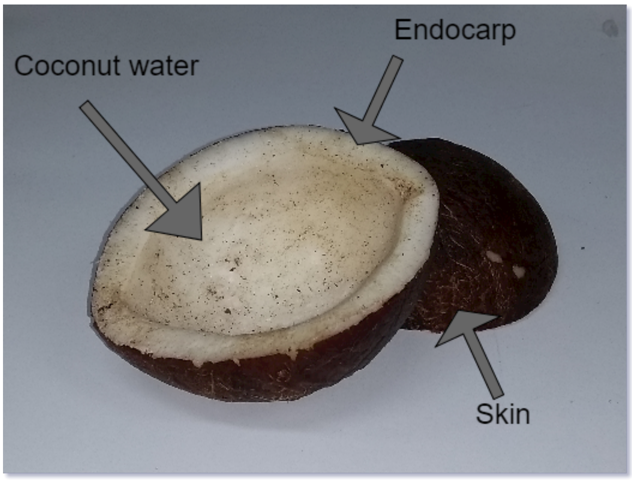


Figure 2: Coconut's layers (*Source: The authors*).

The paring table consists of three main elements:

1. A rigid arm driven by a servo motor, which rotates the claw system around the axis defined by the segment $\overrightarrow{BA}$;
2. The claw system, that consists of:
   (a) A step motor responsible to apply a torque in the claw in order to hold the coconut;
   (b) A step motor, which rotates the claw around the axis defined by the segment $\overrightarrow{GP}$;
3. The table: A servo motor that will move a linear table, represented by $T_1$ in Figure 3, which moves forward and backward along the axis defined by the segment $\overrightarrow{WR}$, and holds the AC motor, which rotates the grater around the $\overrightarrow{QR}$ segment that pares the coconut grabbed by the claw system.

### *4.2 Why use a step motor in the feeder arm*

The movements performed by the feeder arm are in both directions and require several starts and stops per hour. The initial estimation is that the full cycle is to be performed in every five seconds. Thus the step motor should have very low inertia, in order to minimize the energy required when moving from the rest. Its construction must endure several changes in direction of rotation and a heavy duty and warm environment.

Considering these requirements and the advantages listed previously, the chosen step motor has an encoder in order to implement a closed loop system that provides position control as accurate as possible. The encoder is of incremental type,

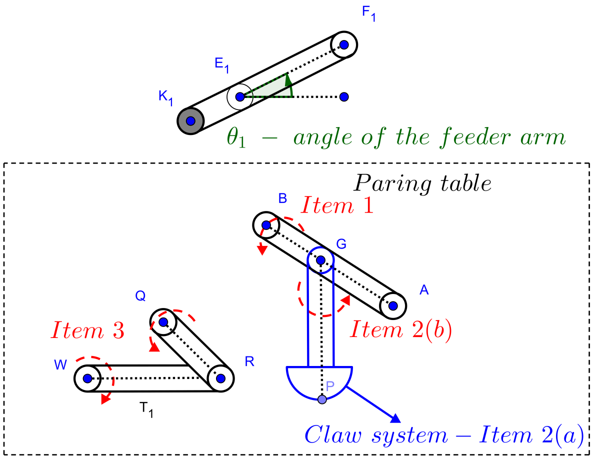


Figure 3: General representation of the machine (*Source: The authors*).

without zero and with resolution of 200 pulses per revolution, which is the same as the chosen step motor.

*4.3 Choosing the step motor for the paring machine*

Several technical features need to be considered in the process that will result in the right step motor for the application: 1) Driver selection, 2) Programming platform (PLC x Microcontroller), 3) Physical space, 4) Total cost, 5) Speed x torque.

The correct choice will provide a system that delivers the maximum torque, without overloading and preserving its full lifetime. In the following, we present the criteria used to select the driver and the gearbox.

### 4.3.1 Driver selection

When using an encoder to read the position feedback from the axis in a system with gearbox, it is necessary to compare the encoder's resolution and the backlash from the gearbox. If the encoder resolution is higher than the backlash, the closed loop system will naturally try to compensate the backlash all the time, wasting power to perform an error correction that can not be done, due to the system's dynamics. To avoid this, one should first estimate the gearbox backlash and either select an encoder with lower resolution or include a minimum error tolerance in the controller before it actuates.

According to Equations 2 and 3, the higher the current on the windings, the higher the torque, and the higher the supply voltage, the higher is the torque. (Geckodrive Motor Controls (GMC), n.d.). On the case study presented in this paper, the driver selected is common PCB (Printed Circuit Board) driver and has a limit of 4.0 A current, which is a very common value for different sizes of motors, and 50 VDC of supply voltage.

The PCB driver is cheaper, although less robust, compared to external drivers (mainly due to heat dissipation issues).

### 4.3.2 Gearbox selection

The gearbox is a resource widely used by many applications, as it multiplies the torque on the axis. But to achieve this, it imposes a speed reduction on the motor. The gearbox reduction rate is defined in Equation 5:

$$\eta = \frac{\omega_m}{\omega_f}, \tag{5}$$

where $\omega_m$ is the speed of the motor and $\omega_f$ is the desired speed.

The gearbox chosen for this case study is a worm gearbox type, with speed reduction of $1 : 7.5$, meaning the motor must run 7.5 times faster to achieve the desired speed. The backlash of the gearbox is 45 $arcmin \equiv 0.75^o$, which is less than the encoder's resolution of $1.8^o/step$, in order to not generate a pulse at the encoder when the backlash is at its maximum.

### 4.3.3 Step-by-step guide of step motor selection

Figure 4 shows an example of a $torque \times speed$ graph for the motor $86HS82-4504A14-B35-02$ (*by Policomp*©). The given curve was obtained by the manufacturer using a 48 VDC power source, 4.45 A current, and 1/8 micro stepping configuration.

| speed (rpm) | 30 | 60 | 120 | 180 | 240 | 300 | 450 |
|---|---|---|---|---|---|---|---|
| torque (kg.cm) | 28.5 | 31.5 | 30.75 | 28.00 | 27.00 | 24.5 | 21.75 |

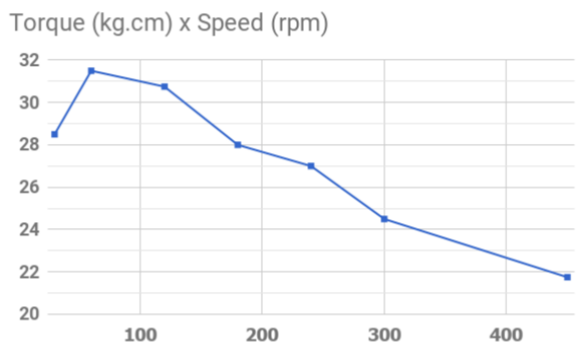


Figure 4: Torque x Speed graph of the step motor 86HS82-4504A14-B35-02 (*Source: The authors*).

Since the curve presented by the manufacturer is obtained empirically under different operating conditions, it would be impractical to precisely estimate the $torque \times speed$ relation to the desired operating conditions for each candidate motor.

To find the motor that fits the requirements, one should essentially estimate the motor curve on the desired operation conditions and verify if the selected motor has the required torque at the required final speed.

In order to select the motor-gearbox setup, Equation 6 must be satisfied:

$$T_m \eta > \gamma T_f. \tag{6}$$

where $T_m$ is the torque of the motor, $T_f$ is the required torque to the axis, $\eta$ is defined in Equation 5, and $\gamma$ in Equation 1, and $\gamma$ must be either "1.3" or "1.5" (those values are explained in the following). If Equation 6 is not satisfied, the setup must be changed.

The authors propose a step-by-step guide to select a step motor for a given application:

1. Calculate the torque needed on the axis, $T_f$;
2. Define technology (PLC or microcontroller) to be used on the project;
3. If the system will operate in closed-loop, with position feedback from an encoder, then go to 4. If the system is open-loop, then go to 5;
4. Define $\gamma = 1.3$, then go to 6;
5. Define $\gamma = 1.5$, then go to 6;
6. Estimate the speed of operation;
7. Select a step motor and/or a gearbox, and calculate $T_m$ by using the *speed* $\times$ *torque* graph (like in Figure 4).
8. If Equation 6 is met, then go to 10, else go to 9
9. Compare the *speed X torque* curve of the motor with the relations available for the chosen gearbox and evaluate if the motor, the gearbox or both should be changed, then go back to 7.
10. Test the motor/gearbox setup on site and verify whether all the necessary variables were considered in step 1. If the test is successful, then the process is complete, otherwise go to 1.

The torque $T$ can be calculated as a force $F$ applied at a distance $d$ away from the rotation point. Equation $T = F.d$ can be used to find the value of $T_f$. Considering that the arm's center of mass is at its center, $T_f$ is composed of the torque needed to lift the arm plus the torque needed to lift the grip, $T_f = T_a + T_g$. Considering an ideal counterweight corresponding to the weight of the arm + grip, the final value of $T_f$ is given by Equation 7:

$$T_f = \frac{T_a + T_g}{2}. \tag{7}$$

The values of $\gamma$ suggested in items 4 and 5, respectively for closed-loop and open-loop, were determined experimentally by the authors.

### *4.4 Model of the feeder arm*

The model of the feeder arm is shown in Figure 3. A counterweight is used to balance the heavy weight of the arm when performing the movement of lifting the arm. This counterweight is assumed to be ideal, hence the torque needed to move the arm drops by half. The model of the feeder arm presented in Figure 3 is detailed below. All the lengths are given with respect to the center of the rotating axis:

- $E_1F_1 = d = 360mm$ $\rightarrow$ length of the arm.
- $E_1K_1 = d_c = 173mm$ $\rightarrow$ length from the point of rotation to the counterweight.
- $M = 12870g$ $\rightarrow$ total mass of the system.
- $M_b = 12200g$ $\rightarrow$ mass of the arm.
- $M_g = 670g$ $\rightarrow$ mass of the grip.
- $M_{cp} = 6100g$ $\rightarrow$ mass of the counterweight.

The speed required for the feeder arm is 60 $rpm$ and after comparing several types of motors, the relation chosen was $\eta = 7.5$. From Figure 4 it is possible to verify that the torque at $450 = 7.5 * 60$ $rpm$ is $T_{m_{450rpm}} = 21$ $Kgf.cm$. From Equation 7, $T_f = 122$ $Kgf.cm$. Equation 6 is then satisfied in this case, as $\gamma = 1.3$ was assumed, and $21\eta = 157.5 \cong 1.3 \times 122 = 158.6$. The moment of inertia of the arm is $J_1 = M_1 d^2 = 1.66$ $Kg.m^2$.

In order to develop a state space model of the form described by Equation 8:

$$\begin{aligned} \dot{\mathbf{x}} &= A\mathbf{x} + B\mathbf{u}, \\ \mathbf{y} &= C\mathbf{x}, \end{aligned} \tag{8}$$

let us define the state variables $\theta_1(t) = x_1$, $\dot{\theta_1}(t) = x_2$, $i(t) = x_3$, control variable $u_1 = V_m$, and output variable $y = x_1$.

Substituting the state and control variables in Equations 2, 3 and 4, one can achieve the Equations 9a, 9b and 9c. For simplicity, only one phase will be considered in this work ($j = 0$ and $\phi_0 = 0$), which is a valid simplification because in general only one phase is active each time:

$$\dot{x_1} = x_2, \tag{9a}$$

$$\dot{x_2} = \frac{K_t sin(x_1(t)n + \phi_0)x_3}{J}, \tag{9b}$$

$$\dot{x_3} = \frac{u_1 - K_t sin(x_1(t)n + \phi_0)x_2 - Rx_3}{L}. \tag{9c}$$

To use linear control techniques for designing the controller, the system is linearized using Taylor series around $\theta = 90^o$, which results in Equations 10 and 11:

$$\begin{bmatrix} \dot{x_1}(t) \\ \dot{x_2}(t) \\ \dot{x_3}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{K_t}{J} \\ 0 & \frac{-K_t}{L} & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix} u_1, \tag{10}$$

$$[y] = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}. \tag{11}$$

## 5 Feeder arm feedback control

The control objective is position feedback control, in which a position setpoint $\theta_{in}$ is delivered to the system, and the load is positioned in this angle in minimum time. The step response settling time for this type of application is crucial, because the step's frequency dictates the speed.

The specifications necessary to this application are: settling time $t_s \leq 5\ ms$ and overshoot $OS \leq 20\%$. Using Equations 12 and 13 to calculate the natural frequency and the damping ratio and substituting them in Equation 14a (Nise, 2011), one can find the locations of the dominant poles for these requirements (Equation 14b).

$$t_{s_{2\%}} = \frac{4}{\zeta\omega}. \tag{12}$$

$$\zeta = \frac{-ln(\frac{\%OS}{100})}{\sqrt{\pi^2 + ln^2(\frac{\%OS}{100})}}. \tag{13}$$

$$s = -\zeta\omega_n \pm \omega_n\sqrt{1-\zeta^2}. \tag{14a}$$

$$s = -800 \pm 1561.6i. \tag{14b}$$

If the requirements are satisfied, considering $\gamma = 1.3$, the system will move correctly to each step input in time before the next step arrives. Until now, only position feedback was used. Despite the fact that we can measure velocity and current, they are not used for control purposes for now.

Figure 5 shows the block diagram of the system, where:

1. $\boldsymbol{\theta_{in}}$ : the input setpoint position;
2. **u** : the voltage applied to the system by the controller;
3. **d** : the vector of disturbances signals (i.e, vibrations, mechanical wear of the arm's components, noise in the signals read by the controller);
4. $\boldsymbol{\epsilon}$ **:** the error signal (i.e, the difference between the desired position and the actual position);
5. $\boldsymbol{\theta_1}$ **:** the measured output (signal from the encoder).
6. $\mathbf{D(s)}$ : the disturbances transfer function.

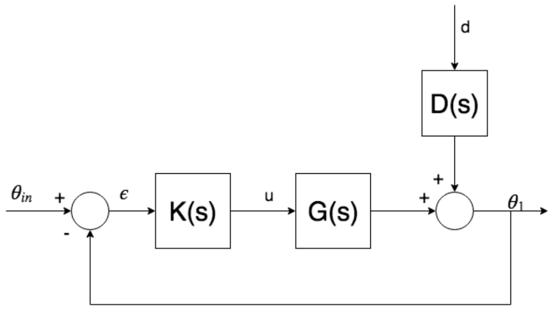


Figure 5: Block diagram of the system (*Source: The authors*).

### 5.1 Lead/lag controller

A lead/lag compensator was designed for the model in Equations 10 and 11, however it did not accomplished the desired specifications. Figure 6 shows a comparison between the compensated and the uncompensated step response.

The minimum settling time obtained is $t_{s_{2\%}} = 1.75s$, which is much larger than the desired $5ms$. The overshoot of $OS = 20\%$ is within the requirement, however the settling time is far from acceptable for the application. The compensator also introduced a steady-state error of $e(\infty) = 2\%$ in the system. Since this approach was not sufficient to achieve the desired specifications, a robust approach is proposed and is presented next.

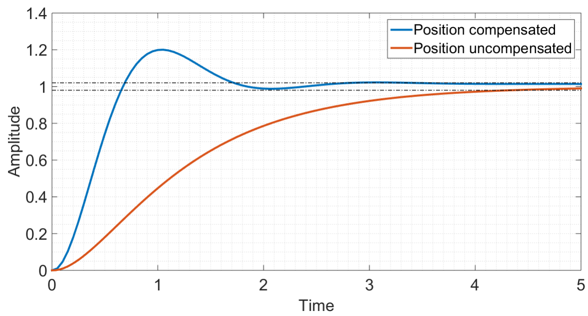


Figure 6: Step response of the system with and without lag compensator $y_1 = \theta_1$ (*Source: The authors*).

### 5.2 $H_\infty$ controller

The $H_\infty$ controller is a robust control method developed in the 1980's and it has been studied ever since due to its capability of producing a very robust controller in the sense of disturbance rejection, reference tracking, stability and performance. It provides the possibility to include different types of uncertainties in the model. Its synthesis is however non trivial, as a couple of Riccati equations (Reid, 1963) need to be solved to achieve the controller.

Now, it is presented the design of a $H_\infty$ controller for the system in Equations 10 and 11 by the method of mixed sensitivity S/T/KS. Prior to designing the controller, one should identify the uncertainties and include them in the model. This case study presents three parametric uncertainties : 1) $R$ - resistance of the coil, 2)$L$ - inductance of the coil and 3) $K_t$ - the motor constant. In practice, this is important due to construction imperfections of the motor, as one motor is never equal to another.

In (Skogestad and Postlethwaite, 2005), the authors propose to model these as multiplicative uncertainties, to be added to the model as $G_p(s) = G(s)(I + w_I(s)\Delta_I(s))$, where $G_p \in \Pi$, being $\Pi$ the set of possible plants and $G(s)$ is the nominal plant (Equations 11 and 10), $w_I(s)$ is the weight functions for the uncertainties and $\Delta_I(s)$ is the perturbation matrix with $||\Delta_I(s)||_\infty \leq 1$.

For this case, the parameters variations are: 1)$R$ $\pm$ 10%, 2)$L$ $\pm$ 20%, 3)$K_t$ $\pm$ 15%. Figure 7 shows the relative errors $l_m(j\omega) = \frac{G_p(j\omega)-G(j\omega)}{G(j\omega)}$ on dotted lines and the continuum line shows the weight function $w_m(j\omega) = \frac{4s+0.2}{5s+1}$, that is a superior limit to the relative errors. The criteria $|w_m(j\omega)| \geq |l_m(j\omega)|$, $\forall\omega$ is then met.

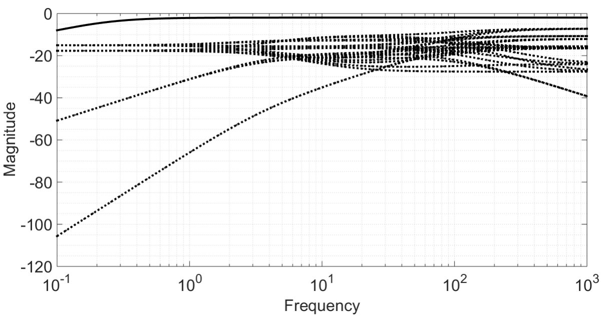


Figure 7: Uncertainties relative error (*Source: The authors*).

The transfer function $W_p(s)$ is the weight for the sensitivity S, and $W_u(s)$ and $W_n(s)$ are the weights for the control and noise, respectively. Those last functions were chosen to be constants equal to $W_u = 1 \times 10^{-1}$ and $W_n = 0.1$.

The weight function $W_p(j\omega)$ chosen for this design is shown in Equation 15 with $A = 8 \times 10^{-4}$ , $M = 50$ , $\omega_b = 12000\ rad/s$:

$$W_p(s) = \frac{\frac{s}{M} + \omega_b}{s + \omega_b A} = \frac{0.2s + 12000}{s + 9.6}. \qquad (15)$$

Figure 8 shows the step response for the closed loop system with the controller obtained from the $H_\infty$ framework. The systems achieves the design criteria of 20% overshoot and settling time smaller than 5.0 $ms$. Figure 9 shows that the system presents robust stability, as $|W_m(j\omega)T(j\omega)| \leq 1$, $\forall\ \omega$. The order of the obtained controller is thirteen and was not reduced, but in practical implementations, it could be necessary. This will be subject of future works.

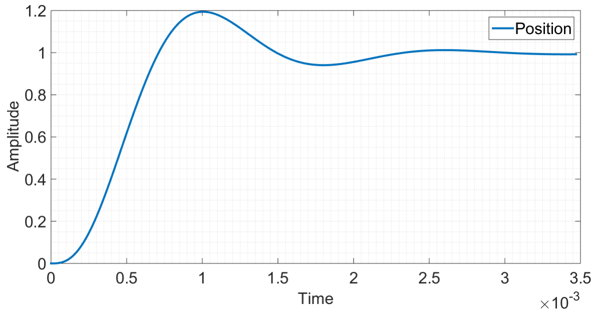


Figure 8: Step response of the closed-loop system using $H_\infty$ controller (*Source: The authors*).

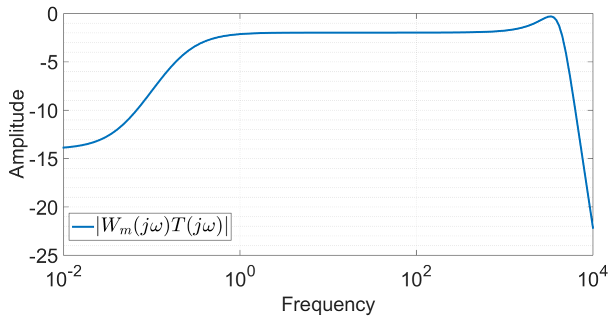


Figure 9: Robust stability criteria of the $H_\infty$ controller (*Source: The authors*).

## 6 Conclusions

The process of choosing a step motor for an industrial application is non trivial and does not have a closed formula, so one must consider as much variables as possible, such as, robustness, operation conditions, the motor's driver (current and voltage), gearbox, among others.

The $H_\infty$ controller synthesized using the mixed sensitivity approach proved to be a satisfactory alternative over classical methods, even though order reduction could be necessary. It presented robust stability and the design requirements were met, so it will be studied more carefully. Despite its modelling complexity, it provides the designers with a complete representation of the system and the ability to test the model for different types of disturbances and uncertainties.

## 7 Future work

Improve the system's model to include the speed and current as controlled variables as well as the dynamics of the arm, since acceleration is fundamental to drive the motor properly.

This is essential to develop an optimal control law for the application, which is the main goal of the feeder arm design. Considering it is responsible to feed the coconuts to the paring table, this process must be done at minimum time when the machine is operating at it's highest capacity.

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