DESIGN AND VALIDATION OF A POSITION CONTROLLER IN THE
PRICE-PAÏDOUSSIS WIND TUNNEL

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ABSTRACT
Conventional or brushed DC motors are often used for many industrial applications. A large variety of these motors is found in automation, medical, robotics and aeronautical fields. In this paper, the design and experimental validation of a position controller for a morphing wing design application is presented. Matlab/Simulink was used to design the Proportional Integral Derivative controller. For experimental validation, tests were carried out in the Price-Païdoussis subsonic blow down wind tunnel. The upper wing surface was deformed by means of a mechanical system consisting of two eccentric shafts. Both are connected to electrical actuators. Comparisons of two sets of results are provided in this paper. The first set is related to control validation and the second set is related to aerodynamic validation.

KEY WORDS
Controller, morphing wing, aerodynamics, actuators, wind tunnel.

1. Introduction

Technology progress enables human kind to improve his environment. Obviously, the aeronautical industry benefits from this continuous engineering evolution. Innovative solutions such as soundless propulsion systems will be embedded in future aircraft. In addition, the composite materials used in aircraft manufacturing are more needed. These needs are essential for aircraft design. Another main need is the reduction of airplane fuel consumption. This need is seen in green technology development that has the aim to improve the aircraft performance while reducing fuel consumption. Morphing wing technology is a solution to reach this target. It is predicted a fuel burn reduction from 5 to 10 % thanks to morphing aircraft technologies [1].

In a previous project called CRIAQ 7.1, a morphing wing was manufactured and tested in wind tunnel. Bombardier Aerospace, Thales Canada, École de Polytechnique and the Institute for Aerospace Research at the National Research Council Canada have collaborated in this project [2] in which the laminarity of the airfoil was extended by delaying the transition point. A part of the upper surface of the wing airfoil was made of composite material. The composite material was able to be morphed under actuator force. Shape memory alloy (SMA) was used to actuate the flexible skin. A model of the laminar airfoil that was used is shown in figure 1. To achieve the desired skin displacement, different control algorithm was used to control the SMA.

Figure 1 CRIAQ 7.1: Laminar airfoil [7]
Abdullah, Bil and Watking developed a tuned Proportional-Integral-Derivative algorithm to control a SMA actuator to morph the structure of an Unmanned Aerial Vehicle.

In the CRIAQ 7.1 project, firstly, the desired skin deformation was not perfectly matched because the flexible skin was able to move slightly at the rear end. Secondly, many drawbacks using SMA were pointed out. Severe hysteresis in the SMA behaviour was observed and the cooling phase of SMA was long. In addition, to energize the SMA, high electrical energy is necessary.

To actuate surface controls such as slats, flaps, ailerons, elevators and landing gear, hydraulic systems are used in many aircraft. These systems have the disadvantage to increase the aircraft weight. For this reason, electrical actuators systems are preferred to the hydraulic systems, as they have the advantage to be lighter. An electrical actuator is a device able to change the physical appearance of a system.

In this paper, the application and the control design of an electrical actuator used to realize the morphing on the ATR-42 airfoil in the wind tunnel Price-Païdoussis is presented. In addition to their stability, electrical actuators can be easier to control and integrate than other types of actuators, such as smart material actuators, such as Shape Memory Alloy that were analysed in the CRIAQ 7.1 project where their disadvantages were found for the morphing wing application. It is also possible to have such actuators with small size and high efficiency. Absolute accuracy can be achieved with electrical actuators.

The wing upper surface in this study is modified by a mechanical system, as shown in figure 2. The ATR-42 is shown in figure 3.

In this study, DC motors are used to move the eccentric shafts. Equations (1) and (2) are involved in the modeling of the actuator model. Figure 4 shows the electro-mechanical model of the used actuator. The obtained transfer function is implemented in Matlab/Simulink and analysed. Equation (1) describes the electrical properties of the motor and equation. (2) describes the mechanical characteristics of the torque on the motor shaft.

The controller design, simulation and experimental validation are described in this study.

2. Modeling of the system

A numerical approach of the system is developed in this part. The system is composed of an electrical actuator with gearbox and a mechanical load. The first actuation line is located at 30% and the second at 50% of the chord. The flexible skin is located between 10% and 70% of the chord. A Computer Aided Design (CAD) model of the airfoil with the integrated mechanical system is shown in figure 2. The ATR-42 is shown in figure 3.

2.1 Actuator modeling

In this study, DC motors are used to move the eccentric shafts. Equations (1) and (2) are involved in the modeling of the actuator model. Figure 4 shows the electro-mechanical model of the used actuator. The obtained transfer function is implemented in Matlab/Simulink and analysed. Equation (1) describes the electrical properties of the motor and equation. (2) describes the mechanical characteristics of the torque on the motor shaft.
where $V = \text{Motor voltage [Volt]}$  
$R = \text{Motor resistance [Ohm]}$  
$L = \text{Motor inductance [Henry]}$  
$i_m = \text{Motor current [Ampere]}$  
$w_m = \text{Motor speed [rad/second]}$  
$k_e = \text{Speed constant [revolution per minute/volt]}$

$T_e = \text{Motor torque [Newton*meter]}$  
$k_f = \text{Friction coefficient [Pas]}$  
$L = \text{Load torque [Newton*meter]}$

Laplace transformation of equations (1) and (2) give:

$$V(s) = RLsI_m(s) + L\frac{di_m}{dt} + k_e w_m(s)$$

where $s$ is the Laplace operator.

In the absence of loads (for $T_L = 0$), equation (4) becomes:

$$W_m(s) = \frac{k_f w_m(s) - k_t i_m(s)}{j s}$$

From equation (5), the current in the armature of the actuator is obtained and given by equation (6).

$$I_m(s) = \frac{s W_m(s) + \frac{k_t}{j} W_m(s)}{k_f}$$

Using equation (6) the motor voltage (equation 3) is rewritten as:

$$V(s) = R \frac{s W_m(s) + \frac{k_t}{j} W_m(s)}{k_f} + Ls \frac{s W_m(s) + \frac{k_t}{j} W_m(s)}{k_f} + k_e W_m(s)$$

Form equation (7) the expression of equation (8) is obtained.

$$G(s) = \frac{W_m}{V} = \frac{k_t}{s^2 L + (Rj + k_f L)s + k_f R + k_e k_t}$$

To validate the simulation model of the actuator, the simulation results were compared with data provided by the manufacturer. Table 1 shows the parameters of the motor used for modeling. The simulation model gives the same values as the values shown in the datasheet for the motor current ($i_m$) and the motor speed ($w_m$), as indicated in table 2.

<table>
<thead>
<tr>
<th>Terminal resistance (R)</th>
<th>11.4 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal inductance (L)</td>
<td>0.0316 H</td>
</tr>
<tr>
<td>Torque constant ($k_f$)</td>
<td>0.119 NmA$^{-1}$</td>
</tr>
<tr>
<td>Inertia (J)</td>
<td>65.9e-7 kg.m$^2$</td>
</tr>
<tr>
<td>Friction coefficient ($k_f$)</td>
<td>1.01738*10$^{-5}$Pas</td>
</tr>
</tbody>
</table>

Table 2

Comparison between datasheet and simulation

<table>
<thead>
<tr>
<th></th>
<th>$i_M$ [mA]</th>
<th>$w_M$ [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datasheet</td>
<td>34.2</td>
<td>3820</td>
</tr>
<tr>
<td>Simulation</td>
<td>34.2</td>
<td>3820</td>
</tr>
</tbody>
</table>

3. Control scheme

This study is focused on the development of the position control. Although position control is desired, it is needed to integrate a torque control to guarantee that the right torque is always supplied to the load by the motor. Torque control is realized with a current controller. The final architecture of the whole control system (position, current control and load) is presented in figure 5. In figure 5, it shown that the inner loop is realized by the current controller and the outer loop is realized by the position controller. The actuator voltage is provided by a programmable source voltage. Unit feedbacks are used to determine the error for both controllers. The current set-point or reference is provided by the position controller. Overvoltage protection is integrated inside the current controller to protect the actuator.
3.1 Design of the current controller

The motor torque is defined as

\[ T_e = k_l i_M \]  
\( (9) \)

Laplace transformation of equation (9) give:

\[ T_e(s) = k_l I_M(s) \]  
\( (10) \)

Using equation (10), equation (2) is rewritten as

\[ k_l I_M(s) = k_f W_m(s) + j s W_m \]  
\( (11) \)

From equation (11), the motor speed can be calculated as

\[ W_m(s) = \frac{k_f I_M(s)}{j s + B} \]  
\( (12) \)

Using Equation (12) in equation (2) and substituting the variables with their numerical values from table 1 the following expression is obtained:

\[ G_i(s) = \frac{I_M}{V} = \frac{4.616 \times 10^{-4} s + 7.12 \times 10^{-4}}{1.459 \times 10^{-5} s^2 + 5.264 \times 10^{-3} + 1} \]  
\( (13) \)

The system being stable (poles of the system are located in the left half plane), a Proportional-Integral (PI) methodology is used to control the current. The equation of the controller is assumed to be

\[ G_i(s) = K_p \left( 1 + \frac{1}{s T_i} \right) \]  
\( (14) \)

where \( K_p \) is the proportional gain and \( T_i \) the integral time constant. The controller was designed in the frequency domain. The principle of this design is to change the frequency response of the system in open loop in order to fulfill some desired specifications. Many authors [14], [15], [16], [17], describe with practical examples the way to design a control algorithm in frequency domain. Often, in order to obtain better performance in closed loop, the phase margin in open loop is chosen between 30-70 degrees. Therefore, with a phase margin fixed at 60 degrees for the open loop system and by solving equation (15) the total phase of the system in open loop is determined.

\[ 180^\circ - \left| \varphi_{c_1 g_1} \right| = \theta \]  
\( (15) \)

\[ \varphi_{c_1 g_1} = \varphi_{c_1 o} + \varphi_{g_1 o} \]  
\( (16) \)

here \( \theta \), \( \varphi_{c_1 o} \) and \( \varphi_{g_1 o} \) are the phase margin of the system, phase margin of current controller and phase margin of the system described by equation (13). Figure 6 shows the loop scheme of the current controller. Figure 7 indicates the system response for a step current value of 0.928 A.
3.2 Design of the position controller

Figure 8 shows the control loop extended with the position controller. Because of the integral term in equation (17), a PD controller was designed to control the position. In open loop the transfer function of the system is given by equation (17).

\[ G_{po} = C_i(s) \cdot G(s) \cdot \frac{1}{s} \]  

(17)

where \( C_i(s) \) is the transfer function of the current controller and \( K(s) = G(s) \cdot \frac{1}{s} \) is the transfer function of the plant.

To determine the coefficients of the position controller \( K_{pd} \) and \( T_d \) defined by equation (18), the method of Ziegler-Nichols [18] is used.

\[ P_i(s) = K_{pd} \frac{1 + T_d s}{1 + 0.001 s} \]  

(18)

The measured value of \( T_u \) in Figure 9 is 0.07 second. The system instability characterized by the oscillations (green curve) is obtained by setting the value of \( K_u \) to 0.45. Using the values of \( T_u \) and \( K_u \) the following parameters of the controller are obtained: \( K_{pd} = 0.27 \) and \( T_d = 8.4 \times 10^{-3} \).

4. Results and discussions

The low speed, Price-Paidoussis subsonic wind tunnel located at the LARCASE (Laboratory of applied research in Active Controls, Avionics and AeroServoElasticity) laboratory was used for the control and aerodynamic validations. This wind tunnel was calibrated recently with a new methodology using the combination of neural networks and Extended Great Deluge (EGD). In [19] more details are given about the structure of this wind tunnel and the methodology of calibration is explained. Figure 10 shows the subsonic Price-Paidoussis wind tunnel with the smaller test chamber.

LabView was used for the experimental validation of the controller because the programmable power source used to control the actuator voltage and current was only compatible with this software. Therefore, the designed controllers with Matlab/Simulink were programmed in LabView.

Figure 11 shows the comparison between the measured, simulated and set-point position. It can be seen that the position is reached without overshoot and at about 1 second.
For the aerodynamic validation, the pressure coefficient was measured at different percentages of the chord on the wing upper surface. A Kinetic pressure set as shown in figure 12 was used to measure the static pressure. This pressure set is a portable system that is able to measure and display measured pressure as well as measured temperature, humidity and speed of the wind flow in wind tunnel. A Pitot tube was used for the total pressure measurement. Pressure coefficient curves obtained with XFoil [20] for different flight conditions are compared with those measured during wind tunnel tests. With the XFoil solver, it is possible to estimate aerodynamics coefficients such as drag and lift coefficients as well as transition point locations [21]. Data from XFoil were chosen as reference because of short convergent time, and it works absolutely in two dimensional (2D). This solver distinguishes two types of calculations (inviscid and viscous) and uses the $e^N$ method as transition criterion.

Numerically, these results were predicted on the ATR-42 as seen in [22]. Figures 13 to 15 show the results obtained for three different flight conditions. The angle of attack varies from -1 deg to 1 deg and the wind speed in wind tunnel is kept constant. Sensor number 6 outputs a wrong value because the pressure taps was damaged during assembly of the mechanical system. It can be observed that the predicted aerodynamic results with XFoil agree with the wind tunnel aerodynamic results.

5. Conclusion

In this paper, the design and experimental validation of a control law for morphing wing using electrical actuators was investigated. Aerodynamic studies were realized using XFoil in order to predict numerically the pressure coefficient distributions for different flight conditions. Experimental validation of the control algorithm was done by comparing the XFoil prediction with the measured coefficients during wind tunnel tests. The pressure coefficients were measured at 14 points on the upper surface. The experimental results have shown that the approach used to design the numerical model of the system and of the controller was valid. Future work might involve design of other types of controllers using H2 or
Hinf theories [23] and aeroelastic interactions studies [24].

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