Design and Control of a Shape Memory Alloy Actuator for Flap Type Aerodynamic Surfaces

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Abstract: This paper presents flap control of unmanned aerial vehicles (UAVs) using shape memory alloy (SMA) wires as actuator. In this content, the mathematical model of the SMA wire is obtained through characterization tests then model of the proposed flap mechanism is derived. Later, based on these models, both flap angle and power dissipation of the SMA wire are controlled in two different loops employing compensated proportional-integral type and neural network-based control schemes. The angle commands are converted to power commands through the outer loop controller later which are updated based on the error in the flap angle induced because of the indirect control and external effects. In this study, power consumption of the wire is introduced as a new internal feedback variable instead of generally employed resistance feedback. Constructed simulation models are run and performance specifications of the proposed control systems are investigated. Eventually, it is shown that proposed controllers perform well in terms of achieving small tracking errors.

Keywords: Shape memory alloys and control, antagonistic actuation, power feedback, self-sensing capability.

1. INTRODUCTION

In accordance with the technological advancements, there has been an increasing interest in unmanned aerial vehicles (UAVs). UAVs have found diverse applications for both civil and military applications such as search, rescue and observation missions. Moreover, UAVs provide excellent low-cost test beds for navigation system experiments. Their design and control facilitate the exploration of many new research areas in control theory (Htike et al., 2008).

When the control strategies applied in UAVs are investigated, it is seen that generally classical control schemes regarding P (proportional), PI (proportional and integral), and PID (proportional, integral, and derivative) control actions are employed (Türköğlu et al., 2008). On the other hand, robust control methods are also applied to reduce the negative effects of the variance of the system parameters due to external effects (force, moment, and noise) on the system performance (Aiswailm, 2004). Also, fuzzy logic-based control approaches are proposed (Doitsidis et al., 2004). Generally, hydraulic, pneumatic, or electromechanical actuators are used to realize the command signals generated by the mentioned control systems. The mentioned actuators are utilized to move the aerodynamic control surfaces or flaps of the UAV according to the command signal they received from the main control section of the vehicle (Attar, 2002). As an example of a UAV with flaps as control surfaces, the system developed by TAI-TUSAŞ, TURKEY named Turna can be seen in Fig. 1 (TAI, 2010).

In this work, an actuation system employing shape memory alloy (SMA) elements is proposed as an alternative to the above mentioned conventional methods, where an SMA wire is used as an actuator in an inverted slider crank mechanism, employing the weight and cost reduction advantages of the SMA elements as well as their simplicity. The actuation system called antagonistic in literature is made up of two SMA actuated mechanisms working opposite to each other as schematized in Fig. 2 where the abbreviations SMA1 and SMA2 indicate the mentioned actuation mechanisms (Doitsidis et al., 2004). The system is composed of two control loops: the outer loop gets the angular position of the flap as the feedback variable using an angular position sensor and controlled by PI control scheme while the inner loop utilizes the self-sensing capability of the SMA wire using the power consumption of the wire as the feedback variable and two different control schemes as feed-forward compensated PI and neural network are employed to control the inner loop (Söylemez, 2009). Actually, the control of flap mechanism by means of SMAs regarding power consumption parameter is
probably the most significant contribution of this study to this field. Also, the use of the data acquired by means of a number of characterization tests using the considered SMA wires is another original part of the work. In this content, the related actuator and flap mechanism models are obtained and the designed control systems are simulated.

2. MODELING OF THE SHAPE MEMORY ALLOY WIRE

SMAs are new functional materials used in actuator applications with their high power to weight ratio. The high strength or displacement usage of SMAs makes them suitable for direct-drive applications, which eliminate use of power transmission elements. The shape memory effect in an SMA is based on the transition between two solid phases: low temperature phase martensite and high temperature phase austenite (Wayman et al., 1990). This phase variation induces shape changes in the material, thus the motion can be generated by heating the material as seen in Fig. 3, where stress (σ)-strain (ε) behavior of the two phases and work extraction between them is presented. Shape memory based actuators can either be driven by thermal changes or by passing an electrical current through them (resistive heating). Especially in controlled actuation applications, the later method, i.e. resistive heating, is often preferred (Reynearts and Brussels, 1997).

SMA actuators have traditionally been operated as “on-off-type” electromechanical actuators mainly because of the intrinsic difficulty in controlling accurately the martensite-austenite proportion. This fact is resulted from the reason that the microscopic rearrangements involved in the structural changes take place quite sharply and in a highly complex and nonlinear fashion. One possible solution to this question would imply developing an accurate model for the material thermomechanical behavior as it is made for other materials. However, good models of phase transitions ready to be used in a control loop are by no means easily obtainable. In this study, a Ni-Ti (nickel-titanium) SMA wire is considered as the actuator and characterization tests are performed regarding this configuration. An electric current is applied through the 0.2 mm diameter and 80 mm long wire to heat it and induce the phase transition, thus, the resulting contraction. When the material cools off, the wire is stretched again by the effect of the weight hung on one end.

In this section, current-contraction and current-power characterization conducted using the constructed test apparatus and the resulting model obtained are discussed (Dönmez and Kadioğlu, 2008). The current passing through the wire, the voltage across the wire and elongation-contraction of the wire data are collected by the data acquisition system with a frequency of 100 Hz using MATLAB® SIMULINK®. Current profile saturated at 600 mA as presented in Fig. 4 is supplied to the wire for characterization purposes and the contraction-current and power-current results are obtained as given in Fig. 5 and Fig. 6, respectively. Apart from the triangular reference signal in Fig. 4, different signal profiles like square-type signals were also used for validation purpose (Söylemez, 2009).

Fig. 2. Schematic representation of SMA actuator in antagonistic configuration.

Fig. 3. Diagram for extracting work from SMA elements.

Fig. 4. Current profile supplied for characterization.

Fig. 5. Contraction-current plot of the wire.

In order to generalize the characterization absolute strain (%) instead of contraction, and power dissipated per unit length (W/m) instead of power dissipated are used. The absolute strain-current relation for activation phase is modeled by curve fitting methods using sigmoid type functions. The model for heating curve is given in
equation (1). The model constructed in MATLAB® SIMULINK® and the test results are presented in Fig. 7.

\[ \varepsilon = \varepsilon_f \left[ 1 - \frac{1}{1 + (I - I_A)^2} \right] \]

(1)

where \( \varepsilon \) and \( I \) stand for the strain and current, respectively. Here, firstly activation start current (\( a_i \)), activation end current (\( a_f \)), and the maximum recoverable strain (\( \varepsilon_r \)) values are found; and other parameters used in the model are calculated as \( a_t = 5(a_i-a_f) \) and \( I_A = 0.5(a_i+a_f) \).

Fig. 6. Power dissipated-current plot of the wire.

As mentioned above, the actual variables of the system to be controlled are the tip point angular velocity components while the proposed control system considers the angular speeds of the manipulator links. In order for the guidance commands in the form of tip point velocity terms to transform into the angular speed parameters, the kinematic relationships among the mentioned variables should be used.

The unit power consumption-current relation is obtained using curve fitting of fourth order polynomial on the power data obtained in the characterization tests. The model for power-current relation is given in equation (2) where \( P \) and \( C \) represent power consumption and current passing through the wire, respectively. Also, the data obtained from the tests and the simulation results for the activation are plotted in Fig. 8.

\[ P = 1.057 \times 10^{-10} C^4 - 1.332 \times 10^{-7} C^3 + 7.65 \times 10^{-5} C^2 - 0.06221 C + 0.2503 \]

(2)

Fig. 7. Strain-current model and test results for heating.

Fig. 8. Unit power consumption-current model and test results for heating.

4. DESIGN OF FLAP MECHANISM

In this part of the study, the inverted slider crank mechanism designed to employ the SMA wire trained for contraction as a flap actuator is described. In the proposed configuration, the same mechanism is used mirror-symmetrically on both sides to move the flap towards either direction. The mechanism is designed and analyzed for the upper part and used for both sides. Here, if it is assumed that flap moves \( \pm \alpha \) around zero position, first mechanism yields the movement while rotating from \( -\alpha \) to \( +\alpha \), and while from \( +\alpha \) to \( -\alpha \), the second mechanism is used.

Fig. 9. Schematic view of inverted slider crank mechanism.

The variables shown in the schematic view of the inverted slider crank mechanism given in Fig. 9 is defined as follows:

- \( a_t \): Constant distance from the hinge on the wing to the flap hinge
- \( a_f \): Constant distance from the flap hinge to the start of the flap arm
- \( a_s \): Length of the flap arm
- \( s_f \): Length of the SMA wire (stroke)
- \( \theta_1 \): Angle of the SMA wire from the horizontal axis
- \( \beta \): Flap angle
- \( \alpha \) and \( \beta \) : Constant angle between the flap and the flap arm

The loop closure equation for this mechanism can be written as follows:

\[ a_t \alpha e^{i\theta_1} + a_k \beta e^{i(\theta_1 + \beta)} = s_1 e^{i\theta_1} \]

(3)

The required stroke of the SMA wire for a flap angle of \( \pm 10^\circ \) is presented in Fig. 10 is obtained by solving the loop closure equation given in equation (3) using the parameters specified in Table 1. As it can be understood from the plot, the maximum length of SMA wire is 189.7 mm and the parameter values are selected to assure that the wire contracts 5.6 mm throughout the motion of the flap which corresponds to an absolute strain of 2.95%. 

8140
5. DESIGN OF CONTROL SYSTEM

In order to make the control the angular position of the flap, an inner loop, an outer control loop, and a decision block are designed. The inner loop employs the self sensing capability of the SMA element and it works with the power feedback. The outer loop is utilized to compensate the errors due to external effects and nonlinearity between power and strain of the wire and it works with flap angle as feedback. Finally, a decision block is designed to decide which mechanism should be activated to realize the motion. The working diagram for the constructed control system is presented in Fig. 11 where the symbols \( \theta_c, \theta_f, \) and \( \theta_m \) stand for the command (desired), actual, and measured values of the flap angle with \( \theta_e \) denoting the error between the commanded and actual flap angles. Also, \( P_c \) and \( P_m \) correspond to the command and measured power quantities for the SMA wires, respectively.

Fig. 11. Operating diagram of the control system.

### 5.1 Inner Loop: Power Feedback

In the control studies with the power feedback firstly, a linear approximation of the power-current model is obtained as schematized in Fig. 12. The system is controlled by feedforward loop compensated PI and neural network control schemes.

Fig. 12. Linear power-current model.

#### 5.1.1 Feed-Forward Loop Compensated Proportional-Integral Type Control

In this control scheme, an inverse model for current-power relation is obtained for heating state of the wire using curve fitting toolbox of MATLAB\textsuperscript{®} as given in Fig. 13. Then, this model is integrated to the PI-type control system as given in Fig. 14 where the parameter \( K \) symbolizes the gain of the inverse model. In the PI-type controller, the control signal to be sent to the plant, or the system to be controlled, is generated by multiplying the error between the desired and actual values of the strain and sum of the error within a certain interval with the proportional (P) and integral (I) gains, respectively. The current command from the feedforward loop is adjusted using the gain block to avoid overshooting of the response, and the remaining error is suppressed by the PI controller tuned by means of the pole placement method using the appropriate Butterworth polynomial by selecting the bandwidth value of 0.05 Hz (Kuo, 1995). The following function seems to be best fit to the handled data given in Fig. 14:

\[
C = -0.10816 P^4 + 2.3294 P^3 - 19.813 P^2 + 127.42 P + 70.723 \quad (4)
\]

Here \( C \) is the current in mA and \( P \) denotes the power dissipated by the wire in W/m.
In Fig. 15, the simulation and test results are seen to track the power commands satisfactorily, and the addition of the feed forward loop enhances the speed of response when compared to non compensated PI type control.

5.1.2 Control with Neural Network

The neural network (NN) Narma-L2 controller is implemented to the control system as given in Fig. 16, the controller is trained using the data from the characterization tests. The training performed using the data consists of the current input and the power output of the SMA wire.

The convergence test for determination of the number of layers and the test for selection of maximum number of iterations are performed. In this process, a layer size of 5 and maximum 3000 iterations are chosen to be used.

The computer simulations and the tests performed using the designed controller show that the power commands are tracked very well with an increase in speed of the system response however the overshoots are also amplified (Fig. 17).

5.2 Outer loop: Flap Angle Feedback

The power commands to the SMA wire are updated using the flap angle feedback obtained by the angular position sensor placed on the flap shaft. A PI-type controller is designed for this loop (Fig. 18).

5.3 Antagonistic System

While combining the antagonistic system, a decision block which checks the power command generated by the outer loop controller based on the error of the flap shaft angle is used as shown in Fig. 19. This block is designed using MATLAB® STATEFLOW® toolbox and it sends the power command to either of the mechanisms according to the increase or decrease in the demand. If there is an increase in the power command, the first mechanism works to move the flap to the desired position. On the other hand, if there is a decrease in the demand the second mechanism is activated. Actually, the inner states of the disabled mechanism are not considered in this control structure.

Both feed-forward loop compensated PI- type controller and Narma–L2 controller are used in the computer simulations and very satisfactory tracking results for the flap angle have been achieved (Fig. 20 and Fig. 21).
Fig. 21. Simulation results of the system with Narma-L2 controller.

6. CONCLUSION

In this work, through tests and simulations, it is demonstrated that actuation systems employing SMAs, designed to be used in flap control of flying vehicles with flap type aerodynamic control surfaces like UAVs, can fulfill the desired performance specifications.

The antagonistic structure proposed in this content consists of two inverted slider mechanisms working opposite to each other and they are controlled effectively by means of two control loops. In this scheme, especially the power feedback control in the inner loop eliminates the use of other sensors for displacement of the SMA and it makes use of its unique self-sensing capability. Here, the hysteretic behavior of the SMA wires is neglected with regard of the small displacements of the flap angles. On the other hand, the hysteresis effect should also be taken into account for more agile UAVS because the hysteresis has a strong impact on the achievable working frequencies of the UAV.

Although command tracking property of both systems is very good, it is observed that the performance of the control system that employs Narma-L2 controller is especially satisfactory when speed of response is considered and it can even be improved using an expanded data set for training so that more robustness can be achieved. One of the most significant advantages of the neural network-based controller is the ability to compensate the nonlinear inherent properties of the SMA wires. The speed of response of the feed-forward loop compensated PI control scheme can be enhanced by increasing the feed-forward gain and allowing overshoots in the inner loop.

When the current study is compared to some of the studies found in literature about position control of SMA’s where resistance is used as internal feedback variable (Ma et.al.,2004; Song et.al., 2003), it is observed that using dissipated power as the internal feedback variable not only eliminates the use of sensors in the system but it also gives better results than using resistance of the wire since the calculation of power does not amplify the noise in the data. This work can be adopted for SMA wires with different radii and other flap geometries. It should also be noted that SMA type actuators are not suitable for high bandwidth applications although activation speed is very high, the cooling phase can take much longer before re-actuation.

Another issue which should be pointed out that the activation temperature of the SMA wires has to be selected so that the rapid changes on the temperature exposing the UAV do not cause the actuator to trigger. This problem can be overcome by selecting the SMA wires in a way consistent with the operating conditions of the UAV under consideration.

REFERENCES


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