Home

Previous

Next

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Development of SMA Based Actuator Mechanisms for Deployment of Control Surfaces

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ABSTRACT

The research and development of SMA based actuator mechanisms are being pursued at many places. In this paper the on going research and development efforts at ACD, NAL to realize a SMA based actuator mechanism for deployment of a control surface model is discussed. The mechanism can be modified to either give a rotary or a linear output. The deployment of this control surface model was successfully demonstrated using the SMA based rotary actuator mechanism along with computerised powering devices and controls. This control surface model is deployed only during landing in order to improve the landing characteristics of the aircraft and remains retracted at all other times. The real challenge is the design and development of the SMA based mechanism, which will satisfy the weight and volume budget and more importantly consume minimum power. An innovative 3-gear relay arrangement was chosen primarily to save the power. In this type of arrangement 3 different input gears mounted on 3 independent input shafts are used to drive the same output shaft on which the control surface model is mounted. Independent banks of SMA wires drive each of the 3 input shafts. The actuation of the input shafts is done in a sequential manner and each them rotates the control surface model by different angles. At any given time only one bank of SMA is energized and therefore the power consumption reduces significantly in contrast to a case where the complete rotation of the control surface model has to be effected by a single input shaft power by a single bank of SMA. The state of art electronics and controls in order to achieve the above sequential actuation include miniaturized power devices, data acquisition, and controller of SMA actuation and health monitoring of SMA. The actuators have both hysterisis and non-linearity especially during the phase transformation when the electrical resistance changes abruptly. SMAs can be actuated by heating using external heaters or by resistive heating. For better control, high efficiency, compactness and silent operation, resistive heating is preferred. Individual miniaturized power devices (DC-DC converters) are developed to electrically isolate the SMA actuators. Adequate redundancy in terms of both mechanical actuators and powering devices is built in.

Key Words: Shape memory alloy, DC-DC converter, actuation, control surface, data acquisition and control system.

1.INTRODUCTION

The SMA based actuation in some class of metal alloys is based on an inherent capability to undergo large elastic strains (of the order of 6-8%), which are almost completely recoverable upon heating. These (SMA actuation) technologies have made significant strides in recent years in different fields such as aerospace, medical, automobile, consumer appliances etc. This is despite the fact that their efficiencies are low compared to other actuators due to factors such as high current density requirements to actuate these materials and their low time response characteristics. In fact, in the area of micro actuating devices SMA based technologies are going to score well over many other conventional actuators. Even in applications other than micro-actuations (consider wire diameter in the range of 1 to 12 x 10^{-4} m (0.1 to 1.2mm)), where large mechanical movements are required, SMA is still very much in contention because of its compactness, simplicity, cleanliness and ease of computer based operation compared to other actuating devices. This is particularly true in aerospace applications where the availability of space is often a severe constraint and silent and clean environments are desired. The use of SMA enables the distribution of the actuator mass and the sequential powering of SMA arrays/banks (use of optimum no. of SMA actuators as well as the number of powering devices that are active at any given time) thereby substantially reducing the power

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consumption. Additionally, the use of SMA actuators ensures adequate redundancy apart from being amenable to the software driven computerised actuation. An evolved state of art SMA based actuation of a control surface model is described in this paper.

Several research groups are working on SMA based actuation of control surfaces and related structural devices/components. K.Appa et. al. [1], have investigated the smart concepts based seamless contour aerodynamic surfaces wherein they have brought out the aerodynamic benefits on the control surfaces. Kuduva et al. [2], have made an overview of recent progress in the smart materials and structures development of smart wing program wherein the incorporation of SMAs have resulted in the design of a truly adaptive smart aircraft wing which could provide optimal performance at all points in the flight regime by changing its shape parameters and actively responding to external loads and other operating conditions. Extensive research in the related field of SMA based closed loop actuation and powering is also being carried out at several places. V.Shankar et al. [3], have investigated the scheme for actuating the SMA wires and have discussed the different types of powering schemes. Mohammad H. Elahinia et al. [4], have brought out the scheme of stress-based controller to track the desired angular position of an SMA actuator manipulator.

In this paper as already mentioned a SMA based actuator mechanism and the state of art computer controlled powering devices to actuate the SMA in order to deploy a typical control surface model is discussed. The innovative mechanism is of a generic design and can be modified to either give a rotary or a linear output. The deployment of this control surface model was successfully demonstrated using the SMA based rotary actuator mechanism along with computerized powering devices and controls. This typical control surface is deployed only during landing in order to improve the landing characteristics of the aircraft and remains retracted at all other times.

2.EXPERIMENTAL DETAILS

3.1 Mechanical Setup

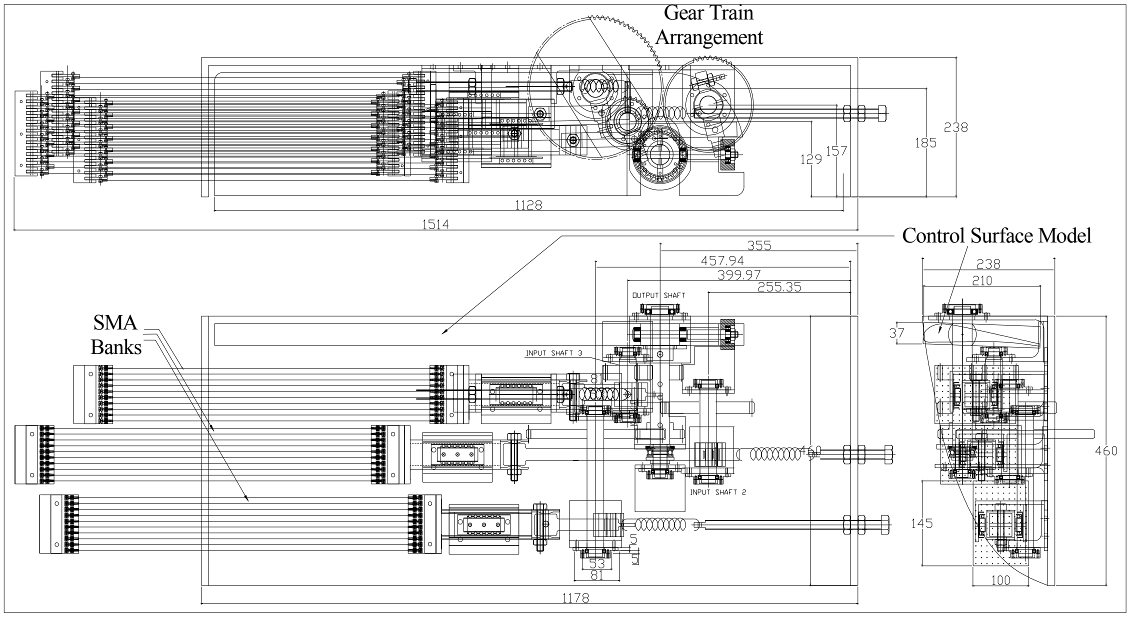

Figure 2.1 Assembly of 3-geared relay mechanism

One of the critical challenges is the design and development of the SMA based mechanism, which will satisfy the weight and volume budget and more importantly consume minimum power. The mechanism has to convert the linear contraction of the SMA wire to a rotary motion for deploying the control surface. After examining several concepts and schemes an innovative 3-geared relay arrangement was chosen primarily to save the power. In this type of arrangement 3 different input gears mounted on 3 independent input shafts are used to drive the same output shaft on which the control surface is mounted. Independent banks of SMA wire drive each of the three input shafts. Each SMA bank consists of 10 wires. In contrast, in a single gear arrangement a single SMA bank consists of 40 wires. The actuation of the input shafts is done in a sequential manner and each of them rotates the control surface by different angles. At any given time only one or two banks (consists of 10 wires each) are energized and therefore the power consumption reduces significantly in contrast to the case where the complete rotation of the control surface model has to be effected by a single input shaft powered by a single SMA bank of 40 wires. This sequential mechanical movement is one of the novel features of this design. Figure 2.1 shows the assembly of 3-gear relay mechanism. The comparisons of the 3-geared relay mechanism over a single geared mechanism are brought out in table 2.1.

Sl. No.	Features	Single gear arrangement	Three gear relay arrangement
1	Torque (Kg-m)	0.24	0.24
2	No. of SMA wires	40	30
3	No. of DC-DC converters	40	20
4	Power (watts)	500	250
5	Time (Sec)	15	53

Table 2.1 Comparison of Single gear and 3-geared relay arrangement

2.2 3-Gear Relay Arrangement

The sequential relayed gear operation of the control surface is illustrated in the Figure 2.2. In this arrangement the deployment of the control surface through a rotary mechanism is in three steps, wherein 3 input gears rotate a common output gear.

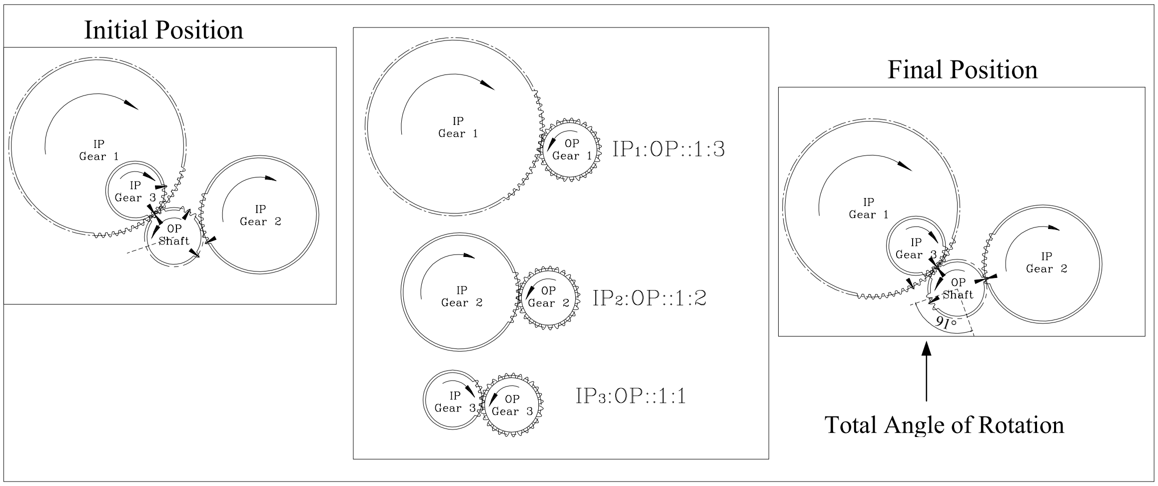

Figure 2.2 3-geared relay arrangements

Sl.No.	Particulars	I set	II set	III set
1	Gear Ratio	1:3	1:2	1:1
2	Angle of Rotation (o/p)	0°-46°	35°-74°	69°-91°
3	Angle of Rotation (i/p)	15.33°	19.5°	22°
4	Arm Length (i/p) (in mm)	45	50	32
5	No. Of SMA wires	10	10	10

Table 2.2 Design details of 3- geared relay arrangement

The input to output ratio for the first engagement of gears is 1:3, for the second engagement is 1:2 and for the third engagement is 1:1. The first input gear rotates by 15.33° hence rotating the output shaft from 0° to 46°. Likewise, the second input gear rotates by 19.5°, rotating the output shaft by 35° to 74°. (i.e.39°). Finally the third gear rotates by 22°, rotating the output shaft from 69° to 91° (i.e. 22°). It can be easily seen that there is an overlap in the gear engagement (35°-46° between 1st and 2nd gear) and (69°-74° between 2nd and 3rd gear). The necessity of the overlap is due to the fact that the aerodynamic load on the control surface continuously increases. The design detail of 3-geared relay arrangement is shown in table 2.2. The expected graph of angle Vs time for input and output gears for the deployment of control surface is as shown in figure 2.3 from which an overlap in the actuation of SMA banks can be seen. As already mentioned while changing over from SMA bank 1 to SMA bank 2 and from SMA bank 2 to SMA bank 3 the aerodynamic load on the control surface is continuously increasing in an assumed linear manner as shown in the Figure 2.4. Therefore it is very important that the actuation scheme and the meshing of different input gears to the output gears accounts for this linear increase in load and also ensures that during the overlap i.e., SMA bank 1 & 2 and SMA bank 2 & 3 (the input shafts and gearing, 1 & 2 and 2 & 3) meet the continuously increasing load requirements. It is also clear that the generated torque from each of the SMA banks should always be higher than the required torque as is shown in the Figure 2.4. The angle diagram also shows the amount of strain in each of the SMA banks.

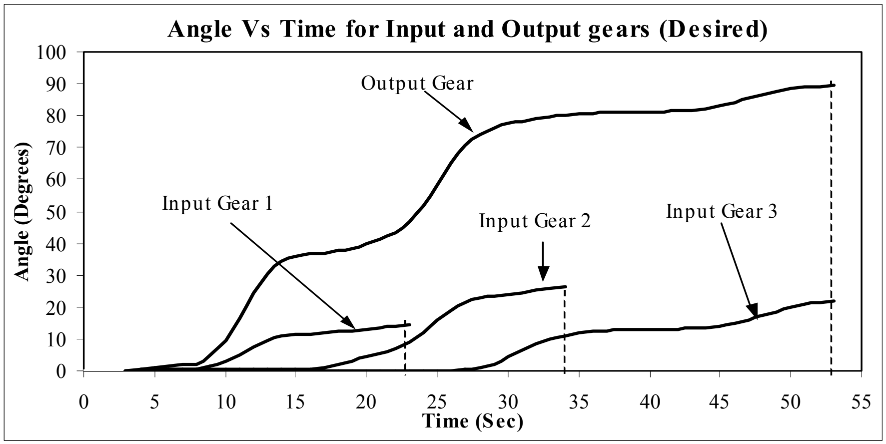

Figure 2.3 Desired graph of angle Vs time for input and output gears.

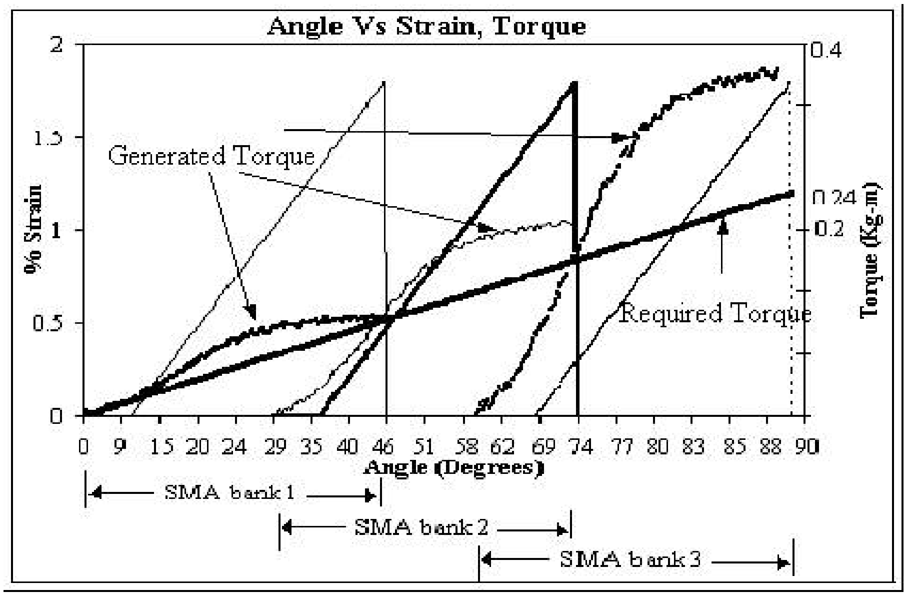

Figure 2.4 Graph of Angle Vs Strain, Torque at output shaft

2.3 Instrumentation Setup

The state of the art electronics and controls in order to achieve the above sequential mechanical actuation of the SMA actuators also has to ensure optimized use of the number of powering devices which include miniaturized powering devices, data acquisition systems and controller for the SMA actuation. The SMA actuators have both hysteresis and non-linearity especially during the phase transformation when the electrical resistance changes abruptly. SMAs can be actuated by heating using external heaters or by resistive heating. For better control, high efficiency, compactness and silent operation, resistive heating is preferred. The resistive heating can be done using constant voltage or constant current type power sources. In both modes of resistive heating, if any SMA wires losses its property or gets cut and falls on any other SMA or SMA bank, the performance of other SMA wires will get affected. Therefore individual miniaturized power devices (DC-DC converters) have been developed to electrically isolate the SMA actuator. Adequate redundancy in terms of both mechanical actuators and powering devices is built in. The electronics, control and mechanical systems also provides for synchronized electronic and mechanical actuation during the deployment of the control surface.

In order to implement the closed loop computer control scheme, it was necessary to conduct some experiments in the open loop scheme in order to ascertain some basic characteristics. An experimental investigation was conducted to study the feasibility of using SMA as actuators for deployment of control surface model and electro mechanical behavior of SMA. A safe current of 2.7A/4.5V was passed through 0.7mm diameter of SMA wire for actuation in constant current mode. During the experiment the load is measured using load cell and LVDT is used to measure the displacement/strain. The figure 2.5 shows the open loop experimental results. These results serves as important inputs for the required time of actuation; number of SMA wires to deploy the control surface model and power requirement is also calculated from the results of this (open loop) experiment.

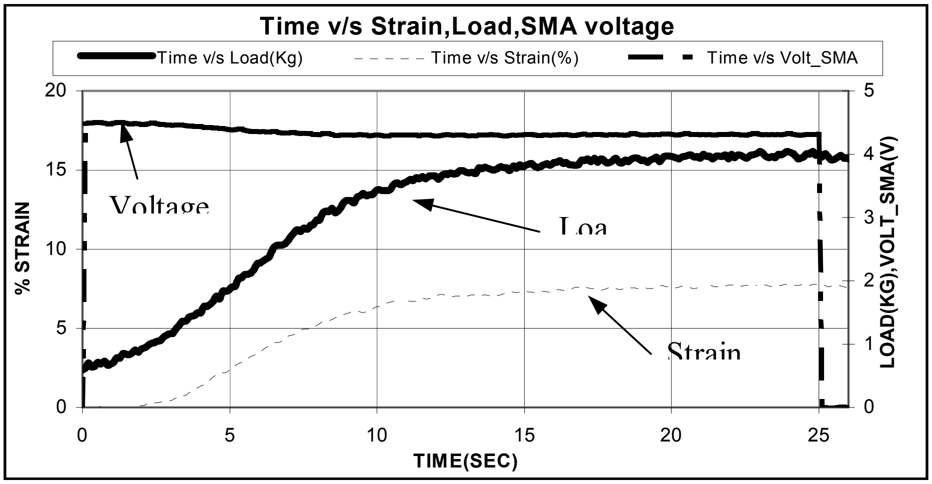

Figure 2.5 Typical SMA wire response of time Vs Strain, Load, Voltage

The closed loop control system has been developed using the results of the open loop scheme. The computerized data acquisition and control system developed consists of national instruments card PCI6014 for deployment of control surface. The system hardware was selected to meet the end user application needs. The most important criterion was the need to support high-speed data acquisition, graphics, display, background applications, program execution and software development. The instrumentation system for actuation of SMA consists of a computer, which is the central processor for the system and an analog sub-system, which provides the required signal conditioning and interfaces with sensor input signals. The closed loop instrumentation setup for deployment of control surface using SMA actuator is shown in the figure 2.6. The Data acquisition system consists of digital input/output signals (DIOs), analog to digital converters (ADCs) and digital to analog converter (DACs). The DIOs, which outputs 0 or +5V, is used to switch ON/OFF relays, which will actuate the SMA banks through DC-DC converters. The ADCs are used to acquire the angular position of the gears based on which the sequential actuation of SMA banks is done. The DACs are used to program the DC-DC converters to output the appropriate current. The miniaturized DC-DC converters used to actuate the SMA banks have analog programming technology where for a given voltage; correspondingly there is an output current. These DC-DC converters take input as 28V from the available battery source and correspondingly output the constant current. The DC-DC converters are operated in constant current mode where a constant current is delivered to actuate the SMA wires. The current requirements for each of the SMA wires based on the diameter and length of the wire is brought out in the reference [5]. The present experimental setup consists of SMA wires of 0.7mm diameter and 670mm length, which requires a constant current of 2.7A. The actuation of SMA banks occurs sequentially by using a relay circuit that switches between the DC-DC converters and SMA banks. Here the system consists of position sensors, which are potentiometers, fixed to each gear. As the gear rotates the spindle of the potentiometer rotates. The angular position of the output shaft is displayed continuously on the computer, based on the voltage signal of the position sensor connected to the output shaft. The closed loop control surface is implemented using programming language VC++.

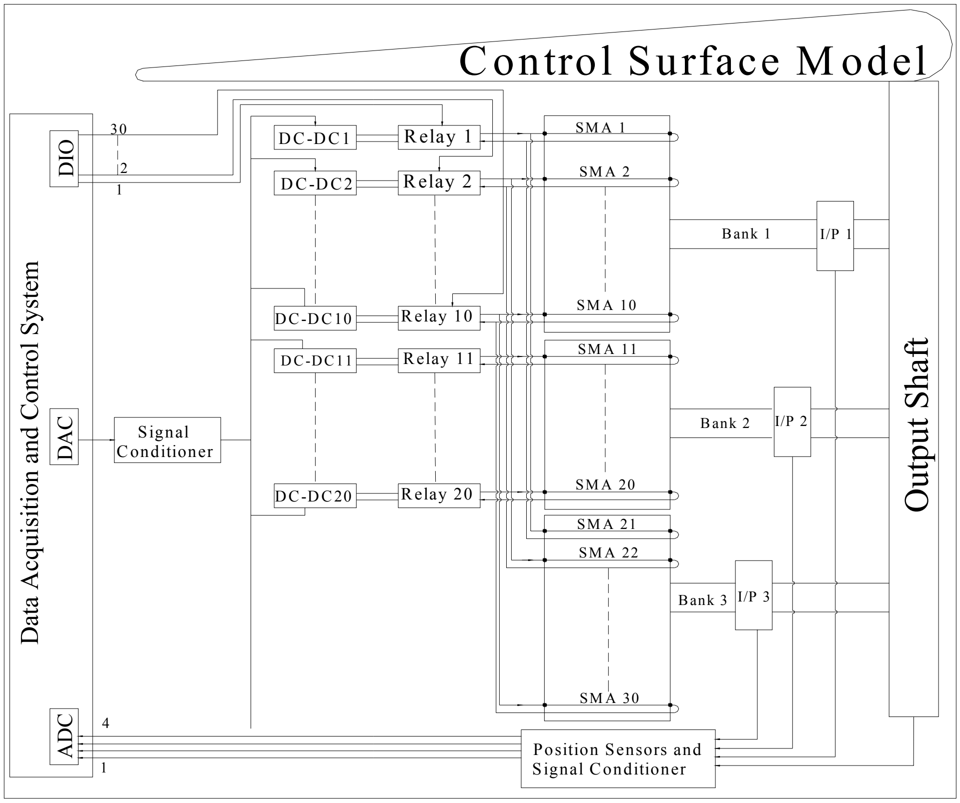

Figure 2.6 Block diagram of Instrumentation setup for deployment of control surface model.

The computer controlled scheme was implemented on the experimental setup explained as follows: A total number of 30 SMA wires is distributed as 10 SMA wires in each bank (totally 3 SMA banks) which in turn powers each input gear. The total number of DC-DC converters to power the 30 SMA wires is 20 and are numbered 1-20. The electromechanical system is configured in such a way that one DC-DC converter will actuate one SMA element in a given bank at a given time. At some other time the same DC-DC converters is used to power the SMA wire in a different bank. The DC-DC converters 1-10 is used to actuate the SMA bank 1, which drives the input gear 1 by an angle of 15.33° (correspondingly the output shaft rotates from 0°-46°). The DC-DC converters 11-20 is used to actuate SMA bank 2, which drives the input gear 2 by an angle of 19.5° (correspondingly the output shaft rotates from 35°-74°). At the output shaft angle of 46°, the DC-DC converters of SMA bank 1 are switched OFF and are again brought into the actuation mode to actuate the SMA bank 3 at an output shaft angle of 69°, which in turn drives the input gear by 22° (correspondingly the output shaft rotates from 69°-91°). Thus the DC-DC converters are configured and powered optimally using a suitable logic such that the same set of 10 DC-DC converters numbered 1-10 are used to actuate both SMA bank 1 and SMA bank 3 at different times. As already mentioned the DC-DC converters 11-20 that power SMA bank 2 cause the rotation of the output shaft from 35°-74°. Therefore only 20 DC-DC converters are sufficient to power 30 SMA's, distributed in 3 banks as 10 SMA wires each. The advantage of the 3-geared relay mechanism is therefore established. Further, the sequential actuation ensures both mechanical synchronization of SMA actuators and electronic synchronization of powering the DC-DC converters.

3. OBSERVATIONS

This is a 3-geared relayed stepper motor consisting of 3 sequential meshing of gears. The first meshing between input gear 1 and output gear results in an amplification of 1:3 giving an output angle of 46° for an input rotation of 15.33°. Likewise the second meshing between the input gear 2 and output gear results in an amplification of 1:2

giving an output of 39° for an input rotation of 19.5° and the output shaft moves from 35° to 74°. In the same way the third meshing between the input gear 3 and output gear results in an amplification of 1:1 giving an output angle of 22° for an input rotation of 22° and the output shaft moves from 69° to 91°. Also during this process of sequential actuation the load generated from SMA wires results in a continuous torque increase as shown in the Figure 2.4 and as explained earlier. The typical control surface has been deployed using the above schemes and the position of the control surface is continuously monitored. The variation in angle Vs time for input and output gears that was realized to deploy the control surface model is shown in figure 3.1. From the figure it is seen that the total time taken to deploy the control surface model is 53 seconds. As is clear from the figure 3.1 initially there is a dead band where there is no angular movement even during the ON period of actuation. Therefore in order to compensate for this during the actuation of second and third input gears this is accounted. Accordingly, the first input gear is actuated at time t=0 seconds, the second input gear is actuated at time t=13 seconds, and the third input gear is actuated at time t=22 seconds. The total time taken to reach the desired maximum angle of 90° is 53 seconds as shown in figure 3.1. It is very clear that there is an overlap between the input gear 1 and input gear 2 and also between input gear 2 and input gear 3. It is this overlap in the input gear actuation (SMA bank actuation) that ensures that the generated torque always remains higher than the required torque as illustrated in the figure 2.4. It is very clear from figure 2.4 and 3.1 that though only input gear 3 (SMA bank 3 consisting of 10 SMA wires) is active during the last 25 seconds of the total deployment time, it is still able to generate the required maximum torque, since only one bank of SMA is actuated during the last 25 seconds when the maximum torque is to be generated. This clearly proves the idea that one can obtain substantial saving in power by using 3geared relay arrangement. Likewise, a similar explanation for sequential switching OFF during retraction can be given and the same is illustrated in a simplified manner in fig 3.2.

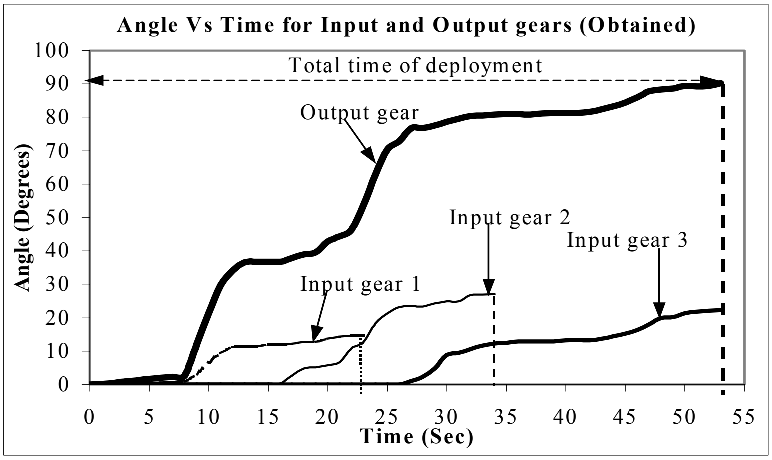

Figure 3.1.Obtained graph of angle Vs time for input and output gears during deployment.

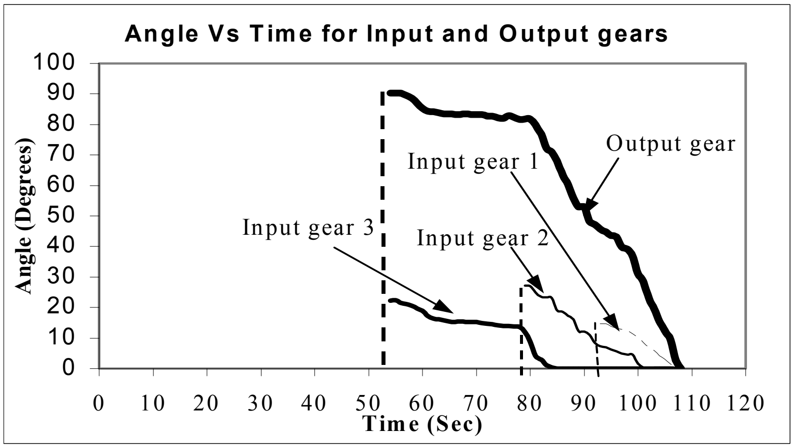

Figure 3.2. Obtained graph of angle Vs time for input and output gears during retraction.

4. CONCLUSIONS

1. A novel 3-geared relay SMA based rotary mechanism has been developed wherein the rotary movement is achieved in stepwise angular rotations of 3 input gears i.e., 0°-46°, 35°-74°, 69°-91° with overlaps between first and second gear (35°-46°) and second and third gear (69°-74°). It is this overlap in the input gear actuation (SMA bank actuation) that ensures that the generated torque always remains higher than the required torque.
2. The DC-DC converters are configured and powered optimally using a suitable logic such that the same set of DC-DC converters numbered 1-10 are used to actuate both SMA bank 1 and bank 3. The DC-DC converters 11-20 actuate SMA bank 2. Therefore, only 20 DC-DC converters are sufficient to power 30 SMAs that are distributed in 3 banks as 10 SMA wires each. Thus the advantage of the 3-geared relay mechanism is established.
3. The closed loop control scheme ensures both electronic and mechanical synchronization in the 3-geared relay mechanism.
4. The power consumption in the 3 gear relay mechanism with 30 SMA wires is minimized compared to the case of the single gear mechanism where 40 SMA wires have to be used to drive the control surface by 90° and generate the same maximum torque.

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