

Design of automatic rotor blades folding system using NiTi shape memory alloy actuator

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Abstract. This present paper will study the requirements for development of a new Automatic Rotor Blades Folding (ARBF) system that could possibly solve the availability, compatibility and complexity issue of upgrading a manual to a fully automatic rotor blades folding system of a helicopter. As a subject matter, the Royal Malaysian Navy Super Lynx Mk 100 was chosen as the baseline model. The aim of the study was to propose a design of SMART ARBF's Shape Memory Alloy (SMA) actuator and proof of operating concept using a developed scale down prototype model. The performance target for the full folding sequence is less than ten minutes. Further analysis on design requirements was carried out, which consisted of three main phases. Phase 1 was studying the SMA behavior on the Nickel Titanium (NiTi) SMA wire and spring (extension type). Technical values like activation requirement, contraction length, and stroke-power and stroke-temperature relationship were gathered. Phase 2 was the development of the prototype where the proposed design of stepped-retractable SMA actuator was introduced. A complete model of the SMART ARBF system that consisted of a base, a main rotor hub, four main rotor blades, four SMA actuators and also electrical wiring connections was fabricated and assembled. Phase 3 was test and analysis whereby a PINENG-PN968s-10000mAh Power Bank's 5 volts, which was reduced to 2.5 volts using LM2596 Step-Down Converter, powered and activated the NiTi spring inside each actuator. The bias spring (compression type), which functions to protract and push the blades to spread position, will compress together with the retraction of actuators and pull the blades to the folding position. Once the power was removed and SMA spring deactivated, the bias spring stiffness will extend the SMA spring and casing and push the blades back to spread position. The timing for the whole revolution was recorded. Based on the experimental analysis, the recorded timing for folding sequence is 2.5 minutes in average and therefore met the required criteria.

1. Introduction

Rotor Blades Folding (RBF) system is a part of the mechanism that has been designed for shipborne operating aircraft, especially helicopter, in order to significantly reduce the rotor disc diameter by transition process from spread to folding position. Suitable disc diameter will enable an aircraft to be stored inside the ship's hangar space. Instability of deck-floor, exposure to the salty environment and confined space working conditions will lead to an increase in safety concern on both personnel and the aircraft. Therefore, fast transition between folding to spread position before flying operation or from spread to folding position for storage is very important. However, most existing helicopters' main rotor blades folding or spread design mechanism in the market are using manual techniques, which fully utilizes human effort, excessive use of special tools and long lists of procedures. There are many



researches and studies by the experts from different backgrounds such as aircraft manufacturers and academicians who aimed to improve the design and techniques. Consequently, an Automatic Rotor Blades Folding System (ARBF) is introduced on modern state-of-the-art helicopters such as Agusta NH90, SH60 Sea Hawk, Eurocopter EH101 and many more [1]. However, the development of such system is only done for newly developed helicopters and not for existing fleet, which are in operation worldwide. Due to high cost of research and development, some manufacturers like Agusta Westland still retain the conservative manual technique approach for their newly produced helicopter model AW159 Wild Cat. The Royal Malaysian Navy (RMN) Super Lynx Mk 100 was the older version of AW159. A conventional hydraulic operated ARBF systems requires 3000 psi utility hydraulic pressure and 28 VDC electrical powers, which adaptation to this system means an introduction of a bulky and complex new hydraulic system to the aircraft [2]. Various published and patented documents have also shown that the development of ARBF was evolving from time to time [2-5].



Figure 1. Typical helicopter with folded main rotor blades capability [5]

2. Problem statement

It was observed that the OEM operating design mechanism and techniques for the manual fold main rotor blade of Super Lynx have a few drawbacks, which would affect the overall performance of the aircraft and operations in term of aircraft mission readiness, crew fatigue, safety working condition and aircraft exposure to salty environment. In average, a full folding sequence by utilizing five trained technical crews could took approximately 30 to 45 minutes. As a comparison, a hydraulic operated automatic rotor blade folding system onboard NH90 would take less than two minutes or 93.3% more efficient for a complete folding sequence. For the five technical crew onboard, their duty is not only to fold or spread the helicopter blade before or after flight operations but also to position the 5330 kilograms machine to the spot or storage hangar. If an average five daily flying sortie was planned with certain interval, repetitious fold-spread sequence has to be carried out to fulfill the requirements and hence will cause the crew fatigue and increase the risk of incident or accident.

Obviously, fully automatic ARBF is not a new technology. Most modern naval aircraft like EH101, Sea Hawk, etc. have utilized the motored driven ARBF. Nonetheless, the present systems' principle is using hydraulic concept and custom made for specific aircraft in term of size and also functionality. Therefore, high weight penalty or it may be totally impossible to impose the technology to present in operation aircraft for upgrading programs because it may involve replacement of major components like main rotor blades and hub, and redesigning of new hydraulic system architecture. Thus cost for retro-fit or upgrade is very high. Another aspect to consider is the compatibility issue in term of size and complexity. Therefore, re-designing a new system with simplified concept seems to be a better option.

3. Methodology

Conceptual system design proposed in this study was derived mainly from accumulated information gathered from need analysis study via e-survey to experience end-user as target group, feasibility study of on-the-shelf systems and various researches that have been published till date. Design parameters selection, which encompasses pulling mechanism, controls, power sources and locking mechanism, was done using Morphological and Pugh Matrix. However, the main focus of this study is design of pulling mechanism or actuators, which have to consider several vital factors like weight, contraction length, shape, complexity and reliability. Since the weight and contraction is part of important factors,

application of SMA materials is found to be the best alternative as compared to conservative hydraulic or pneumatic system mechanism. Although the venture of SMA materials application for large product design is still outnumbered, potential success for this design is found to be bright. Four combinations of actuator's preliminary design concept were proposed and each of the concept was credited based on the previously stated criteria.

- Concept 1 – Combination SMA wire and SMA spring (series)
- Concept 2 – Combination SMA spring and bias spring (series)
- Concept 3 – Combination SMA wire and SMA spring (see diagram below)
- Concept 4 – Combination SMA wire and bias spring (retractable casing)

Concept 4, which is shown in Figure 2, was chosen as the best combination due to largest contraction and meeting the complexity criteria. Its operational concept mechanism is shown in Figure 3.

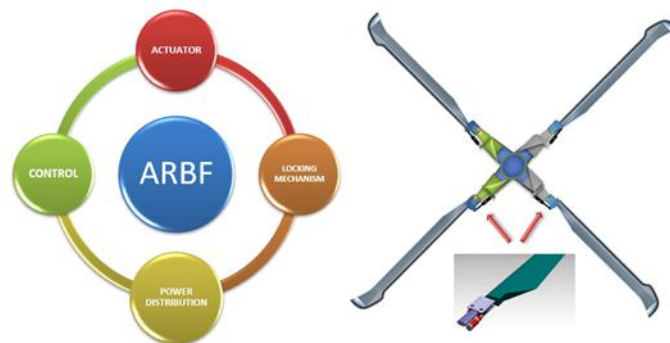


Figure 2. Basic architecture of the developed SMA ARBF system

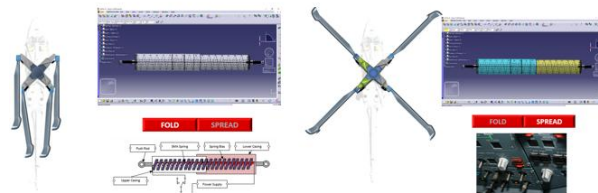


Figure 3. Operational concept mechanism of SMA ARBF system

4. Design calculation and verification

4.1. Power requirement

In this ARBF, SMA will be the main materials application for actuators and Super Lynx will be the subject of concern. The design requirements to be considered have to be calculated and verified. The average weight of one Super Lynx's main rotor blades is 45 kg. Thus, the load required to displace the blades to either approximately 20 degrees or 70 degrees to the back must encounter the down force of approximately 441.45 N. A very special aspect about SMA, with the diameter of 0.51mm, one string is capable to pull up to 3.5 kg. By rough calculation, only less than 20 thin strings are required to do the job, which is such an amazing breakthrough. The electrical power required in activating the SMA is very minimum and can be calculated based on the string diameter. In this actuator design, the SMA is best to be shaped as a spring that will perform dual functions once activated to pull or push the blades to the desired position and act as a spring bias to hold the actuators and blades at locking positions or back to spreading positions. For electrical activation of SMA spring type, the following equations can be used.

$$\text{Resistance: } R = \frac{\rho \cdot L}{A} \quad (1)$$

where ρ = SMA resistivity, L = free length of element and A = cross sectional area.

$$\text{Voltage (Ohm's Law): } V = I \cdot R \quad (2)$$

$$\text{Power Requirements: } W = I \cdot V = I^2 \cdot R \quad (3)$$

4.2. Spring calculation

4.2.1. *SMA spring (extension type)*. A SMA extension spring will behave as shown in Figure 4. At the low temperature the spring will be extended and when heated will contract providing a pulling force.

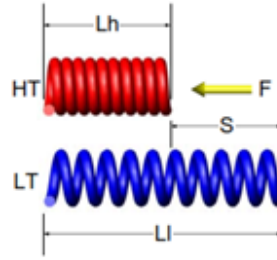


Figure 4. SMA extension spring actuation

With the exception of spring length, the following equations can be used to determine the spring diameters, number of turns, spring rates and reset force. Since the actuation for a spring working in extension is reversed from that in compression, the lengths must be re-evaluated. The spring body length describes a fully compressed spring as in Equation 4.

$$L_b = d \cdot (n + 1) \quad (4)$$

where n is the number of turns of the spring. The free length of the spring or the length at which the shape setting takes place can now be evaluated as a function of the body length as in Equation 5.

$$L_f = L_b + 2 \cdot ID \quad (5)$$

When heated the spring will have a length as calculated by Equation 6.

$$L_h = L_f + \delta_h \quad (6)$$

Since the stroke must be equal to the difference in the high and low temperature lengths, then the low temperature length can be calculated as in Equation 7.

$$L_l = L_h + S \quad (7)$$

where S is the stroke.

4.2.2. *Bias spring (compression type)*. For each actuator, the compression type of spring was used as a bias spring in order to re-position the blades at spreading configuration. The selection of the spring properties is calculated as follows.

$$\text{For compression spring, the spring deflection: } \delta = \frac{8N_a D^3 P}{G d^4} = \frac{8N_a D^3 P}{G d^4} \quad (8)$$

$$\text{The stiffness constant: } k = \frac{P}{\delta} = \frac{G d^4}{8N_a D^3} \quad (9)$$

$$\text{Torsional stress: } \tau_0 = \frac{8DP}{\pi d^3} \quad (10)$$

$$\tau_0 = \frac{G d \delta}{\pi N_a d^2} \quad (11)$$

Corrected torsional stress: $\tau = \chi \tau_0$ where stress correlation factor, $\chi = \frac{4c-1}{4c-4} + \frac{0.615}{c}$ and spring index, $c = \frac{D}{d}$.

$$\text{Diameter of material: } d = \sqrt[3]{\frac{8DP}{\pi \tau_0}} = \sqrt[3]{\frac{8\chi DP}{\pi \tau}} = \text{mm} \quad (12)$$

$$\text{Number of active winding: } N_a = \frac{Gd^4 \delta}{8D^3 P} = \frac{Gd^4}{8D^3 k} \quad (13)$$

$$\text{Alternatively, the number of active winding can be determined as: } N_a = N_t(X1+X2) \quad (14)$$

where X1 and X2 are the number of turns at each end of the coil.

$$\text{Spring-retained energy: } U = \frac{P\delta}{2} = \frac{k\delta^2}{2} \quad (15)$$

For this study, the parameters involved in the spring properties are tabulated in Figure 5.

5. Design analysis

5.1. SMA behaviour

In order to assist in SMA design selection and application, series of experiments have been performed. The specifications of the SMA is listed in Table 1 [6]. A consistent load of 1.206 kg were used for the experiment. All load were hanged vertically to each SMA (wire and spring) with both ends connected to the power supply. The SMA parameters (initial length, length with respect to supplied voltage and SMA samples temperature) was recorded with increment of voltage and current. Temperature sensor of SMA sample were detected via thermocouple wire which connected to LabView Software. The experimental setup is illustrated in Figure 6.

5.2. Prototype development

A prototype of the selected concept of ARBF was fabricated for proof of operational concept, which encompassed the following major components:

- Main rotor hub: made from ply-wood in 1:45 scale. The hub was attached to a base for stability.
- Main rotor blades: made from wood in 1:45 scale. Attached with metal coupler with two holes each to functions as pivot point and lock.
- SMA actuator

The prototype is as shown in Figure 7 and Figure 8. The main components was assembled and tested. The evolution time for fording a spreading sequence was recorded for comparison.

Symbol	Value	Unit
N_a	17	
D	18	mm
G	78×10^3	N/mm ²
P	6.8	N
d	7.5	mm
δ	9.22	mm
k	0.74	N/mm
τ		N/mm ²
τ_0	0.739	N/mm ²
C	2.4	
χ	1.0875	
U	31.35	N/mm

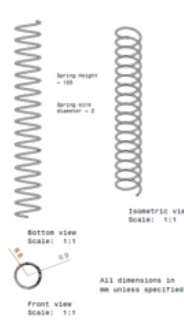


Figure 5. Symbols used in spring design formula

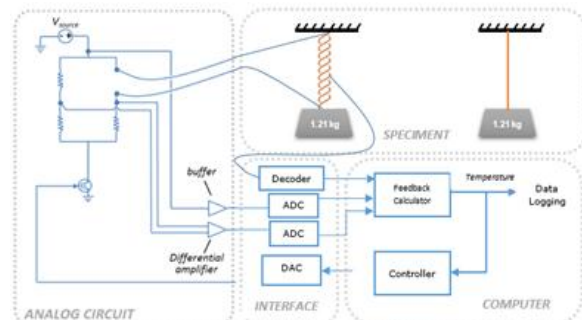


Figure 6. Experimental setup

Table 1. Specification of SMA samples

TYPE	WIRE	SPRING (Tension)
Material	Nickel Titanium (NiTi)	Nickel Titanium (NiTi)
Pull Force	1280 grams	Not Stated
Resistance	12.2 Ohm/meter	Not Stated
Length	35 cm	2 cm
Max Deformation	Not Stated	15 cm
Activation Temperature	70 – 90 °C	45 – 50 °C
Outer Diameter (Wire)	0.31 mm	0.75 mm
Outer Diameter (Winding)	N/A	6.5 mm
Number of Windings (Spring)	N/A	21



Figure 7. Prototype of main rotor hub and blades



(a) (b)

Figure 8. (a) SMA actuators and power supply and (b) ARBF assembly

5.3. Hardware in the loop (operation and control)

5.3.1. Experimental block diagram (operation). The analysis of concept of the operations for SMART ARBF was carried out with the layout in Figure 9. Main power supply was supplied by a PINENG PN-968s-10000mAH universal power bank unit with output of 5V DC. Since the power requirement for SMA activations obtained from experiment is 2.4V, a DC-DC Step-Down Converter Module was used to obtain desired output for prototype activations. The activation of folding/spread mechanism was controlled via an ON-OFF switch. All four actuators were connected to power supply module in parallel. The timing for all four blades to fold or spread were recorded and tabulated.

5.3.2. Experimental block diagram (control). For the purpose of proof of the operational concept, the activation was only done via an ON-OFF switch. However, for a better and more accurate control of SMA temperature, the used of PID controller is much better. Simulation of PID control block diagram as shown in Figure 10 is using LabView software to ensure that there is no oversupply of voltage and current or over-heat the SMA spring, which could degrade the overall performance for a long period of operations.

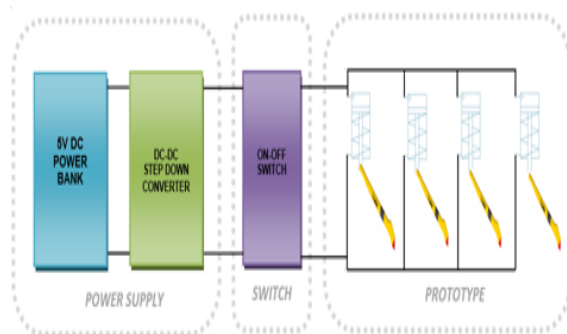


Figure 9. Block diagram (operation)

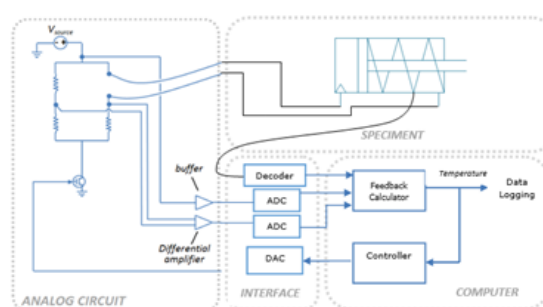


Figure 10. Block diagram (controls)

6. Results and discussion

A series of testing has been carried out using the fabricated and assembled prototype. The results of testing are presented in Table 2. It can be deduced that folding or spreading time of main rotor blades was not proportional to the voltage supplied. This is probably due to the inaccurate control of SMA temperature whereby the value of the temperature might also be influenced by the room temperature. However, the average time still met the design criteria, which is below five minutes. Furthermore, time for spreading sequence was longer than folding and this might be due to the internal resistance inside the actuators casing caused by friction of upper and lower casing, insufficient stiffness coefficient of spring bias in order to counter the stiffness of SMA spring and also slow decreasing of SMA spring temperature with regards to releasing of its pulling force.

Table 2. Average voltage for folding and spreading

TEST	VOLTAGE	TIME (MINUTE)	
		FOLD	SPREAD
RUN 1	2.40	2.3	3.2
RUN 2	2.38	3.1	3.1
RUN 3	2.41	2.2	3.6
RUN 4	2.45	2.2	3.2
RUN 5	2.50	2.1	3.2
RUN 6	2.39	3.3	3.1
RUN 7	2.40	2.6	2.9
RUN 8	2.38	3.3	3.6
RUN 9	2.44	2.5	3.5
RUN 10	2.50	2.4	3.2
AVERAGE	2.425	2.6	3.26

7. Conclusion

This paper presented the requirements for development of a new ARBF systems, which could possibly solve the availability, compatibility and complexity issue of upgrading a manual to fully automatic rotor blades folding system of a helicopter. The Royal Malaysian Navy Super Lynx Mk 100 was chosen as a baseline model. The design of the SMART ARBF's SMA actuator and proof of operating concept using a developed scale down prototype model have been presented. The performance target for full folding sequence is less than 10 minutes. Based on the experimental and numerical analysis, the recorded timing for folding sequence is 2.4 minutes in average and thus met the required criteria.

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