

Helicopter Tail Rotor Driveshaft Design using Shape Memory Alloy (SMA)

[Abhijeet Saxena, Sahil Singh Malik, Kshitij Gupta]

Abstract—This paper focuses on design alternatives of a helicopter tail rotor driveshaft utilizing shape memory alloy (SMA). The conventional tail rotor designs segment the complete shaft into multiple shafts due to its long length which would have low bending natural frequencies. Using multi-segmented shafts introduce multiple in-span bearings and flexible couplings to accommodate misalignment due to manufacturing. This leads to a heavy and maintenance-intensive design. The paper explores the application of Shape Memory Alloy (SMA) and ways it can be introduced in the driveline system to reduce its weight. The proposed design alternatives aim to reduce the number of segments of shaft which leads to lesser number of in-span bearings and flexible couplings. However, the natural frequencies of the system decrease, which may lead to supercritical operation of the driveline. The underlying design ideas have been presented with a specific example of a tail rotor driveline.

Keywords—driveshafts, shape memory alloys, natural frequency, helicopter tail rotor

I. Introduction

Drivelines are crucial components in a rotary-wing aircraft. Current helicopters employ multi-segmented metallic shafts. The reasons multi-segmented shaft is used include bending due to long length and more importantly, smaller natural frequency in case of long length. To connect these segments to act as a single shaft, flexible couplings and in-span bearings are used. These components add considerable weight to the driveline system. Weight reduction is one of the primary requirements in aerospace machines and hence, in the present paper alternative feasible designs for a lightweight driveline using shape memory alloy (SMA) are explored.

The system considered for present study is based on the partial data available in published literature for the CH-47 driveline of Chinook helicopter. The missing data was suitably assumed. Thus the system considered for study in present paper closely resembles the CH-47 driveline.

The aim is to reduce the number of segments which reduces the number of in-span bearings and couplings used and hence the overall weight of the driveline. Reducing these components also reduce the maintenance required as most of the maintenance is focused on these components rather than on the shaft.

The proposed strategy is to induce tension in the shaft segment by activating the embedded SMA member, thereby increasing its stiffness as well as the natural frequencies. This would then allow an increase of the length of each shaft

segment thereby reducing the number of segments and in-span bearings and couplings. Moreover, using SMAs in activated/deactivated states as per requirement also provides a control over the natural frequencies of the system.

The design includes the mechanism of mechanical coupling of the SMA member in the shaft, the forces induced and their effect and the actuation of the SMA. Using SMAs the two way movement of the natural frequency with respect to operating frequency has been exploited to avoid resonance which is described in detail in the later sections.

II. Analysis of Original Design

The partial data about the CH-47 driveline is obtained from Rooz and Bakis^[1], which is summarized in Table I.

TABLE I. DATA OF CH-47 DRIVELINE^[1]

Property	Value
Total shaft length	$L_s = 8.598$ m
Outer radius	$r_o = 0.05715$ m
Bearing mass (each)	$m_b = 5.20$ kg
Flexible coupler mass (each)	$m_{ij} = 0.46$ kg
No. of in-span bearings	$n_b = 6$
Operation speed	$f_{op} = 6912$ rpm = 115.2 Hz
Applied torque	$T_{op} = 4067$ N-m
Operating power	$P = 2983$ kW
Driveline mass	$m_D = 60.1$ kg

A. Material Selection

The first step was to analyze the original design and generate the missing data. The most important detail missing was the material of the original shaft. Considering the application in aerospace driveshafts, two most commonly used materials were shortlisted: Aluminium 7075 and Ti-Al-4V. Wall thickness of the shaft t is obtained from Eqs. 1 and 2. The values of mass per unit length m and outer radius r_o are obtained from Table I. Maximum shear stress τ_{max} based on maximum transmitted torque T_{max} (Table I) is calculated from Eq. 3. This stress was then compared with the shear strength of the materials to get the Factor of Safety (FoS) (Eq. 4). The fundamental natural frequency f_1 in Hz. in the current configuration was also estimated (Eq. 5) to check whether the operating frequency of the shaft was in safe limits.

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$$m = \pi * (r_o^2 - r_i^2) \rho \quad (1)$$

$$t = r_o - r_i \quad (2)$$

$$\tau_{\max} = \frac{2}{\pi} * T_{\max} * \frac{r_o}{(r_o^4 - r_i^4)} \quad (3)$$

$$FoS = \frac{\tau_{\text{strength}}}{\tau_{\max}} \quad (4)$$

$$f_1 = \frac{\pi}{2} \sqrt{\frac{EI}{mL^4}} \quad (5)$$

Here r_o and r_i are outer and inner radii, and EI , ρ and ℓ are flexural rigidity, mass density and length of shaft segment. The results from the above calculations are given in Table II. It can be observed that both the materials satisfy the conditions. But, considering that Titanium alloys are much more expensive than Aluminium alloys and the thickness in Ti-6Al-4V is very less leading to difficult manufacturing, it was concluded that Aluminium 7075 is the original shaft material, as also confirmed from Chinook Familiarization Manual^[3].

TABLE II. COMPARISON OF ALUMINIUM 7075 AND TI-6AL-4V

Parameter	Aluminium 7075	Ti-6Al-4V
Thickness (mm)	3.1	1.9
FoS in torsion	4.7	5.1
Fundamental natural frequency (Hz)	205.8	209.4

B. Span and Natural Frequencies

After concluding the material to be Aluminium 7075, the first four natural frequencies for different number of spans of the shafts were calculated (Table III). Simple support condition was assumed. The objective was to get an idea of the natural frequencies (in Hz) in case the number of spans is decreased so that the operating frequency is in a safe zone with regard to the natural frequencies to avoid failure. Since the operating frequency is 115.2Hz, the separation margin

TABLE III. NATURAL FREQUENCIES

No. of Spans	f 1	f 2	f 3	f 4
Single span	4.2	16.8	37.8	67.2
2 spans	16.8	67.2	151.2	268.8
3 spans	37.8	151.2	340.2	604.8
4 spans	67.2	268.8	604.8	1075.2
5 spans	105	420	945	1680
6 spans	151.2	604.8	1360.8	2419.2
7 spans	205.8	823.2	1852.2	3292.8

from the nearest natural frequency is about 44% for the seven span driveshaft, which is the existing design. It is a conservative design with sub-critical operation of the shaft and with large separation margin.

From Table III, it can be observed that reducing the number of spans leads to decrease in the natural frequencies which can be attributed to the fact of increasing length of spans. The operating frequency lies between the 2nd and 3rd natural frequencies for a 2-span driveline and between 1st and 2nd natural frequencies for a 3-span driveline. Hence, these two cases seem feasible if supercritical operation of the shaft is permitted.

III. Design Idea with SMA

Application of SMA in the driveshaft can be utilized to generate sufficiently large axial tension due to its property of shape memory effect (SME). The mechanism of generation of tension is explained in a later section.

A. Effect of Axial Load on Natural Frequency

The aim of using SMA is to create axial load F on the shaft, which leads to increase in the natural frequencies (Eq. 6) of the shafts. This gives the scope of increasing the length of the segments thereby decreasing the total number of segments. If axial force F is applied on the shaft, then the natural frequency of the shaft increases according to Eq. 6.

$$f_n = \frac{1}{2\pi} \left(\frac{n\pi}{L} \right)^2 \sqrt{\frac{EI}{m}} \sqrt{1 + \frac{F}{EI} \left(\frac{L}{n\pi} \right)^2} \quad (6)$$

B. Supercritical Operation

From Table III, it can be seen that the operating frequency (115.2 Hz) lies between the first (37.8 Hz) and second (151.2 Hz) natural frequencies for a 3-span shaft. If the number of spans is reduced to 2, the operating frequency will lie in the supercritical region. This application has one major hurdle for safe operation which is resonance. If the operating frequency becomes equal to the natural frequency of the shaft, the phenomenon of resonance will take place leading to failure of the driveline. To reach the operating frequency from the state of rest, the shaft will have to cross its first natural frequency which becomes the critical issue.

Switching mode of operation i.e., a two way movement of fundamental natural frequency is proposed as shown in Fig. 1. As the rotor starts spinning, the SMA is activated. Activated SMA applies tension on the shaft segment thereby increasing its natural frequency. In this way, the operating frequency passes the first natural frequency of the deactivated shaft without any resonance. As soon as it passes the first natural frequency, the SMA is deactivated near about the crossing frequency. The activated natural frequency starts to decrease gradually as the tension on the shaft starts decreasing. The natural frequency of the shaft will finally reach the original first natural frequency gradually. In this process, the increasing operating frequency and the natural frequency will coincide in between but the overlap time will be sufficiently small to prevent a buildup of large vibration amplitude. This overlap

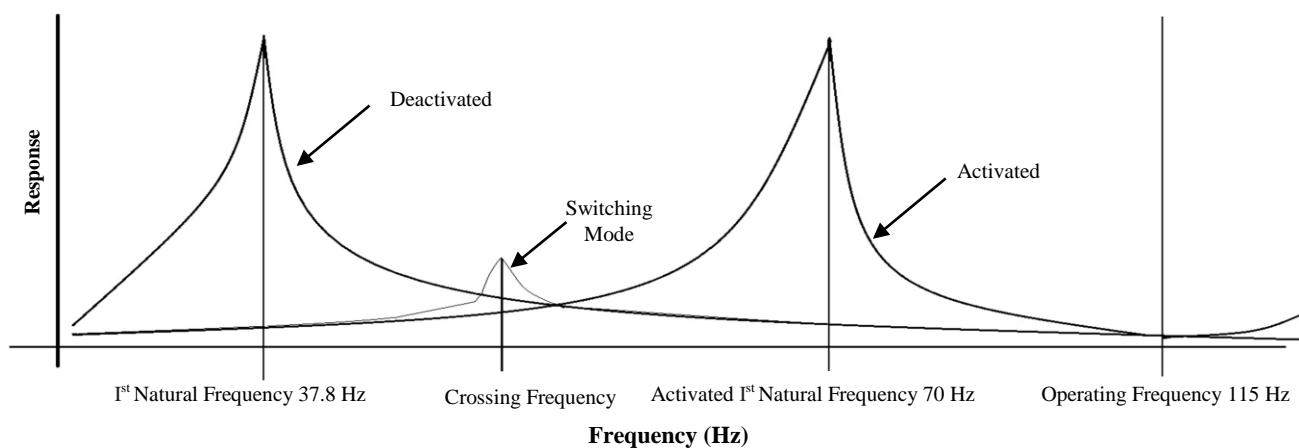


Figure 1. Supercritical operations

can further be handled by introduction of some damping mechanisms thereby decreasing the response in the overlap region.

In the present case, the natural frequency in activated state is taken to be around 70 Hz. A greater shift in natural frequency would require greater force to be generated through SMA, which may not be desirable for the Aluminum shaft. Hence, the force to be applied is taken to be such that the natural frequency increases to 70Hz.

Hence, the number of spans of the driveline shaft can be reduced to 3 from 7 thereby reducing the number of bearings and couplings by 4 which would result in considerable weight reduction of the driveline.

Using SMA to generate tension to change the natural frequency of the system provides controllability over the system. The natural frequency of the system can be changed through external mechanisms. It helps in avoiding the resonance and allows supercritical operation of the shafts. Using Eq. (6) and substituting ω_r as the activated natural frequency and ω_0 as the deactivated natural frequency in rad/sec, the force required is found by Eq (7).

$$F = \frac{mL^2}{\pi^2} (\omega_r^2 - \omega_0^2) \quad (7)$$

It works out to be around 350 kN, which can be generated in SMA using the property of shape memory effect (SME).

C. SMA Application

The SME^[2] of SMAs is to be used to generate the axial force in the shafts. If in the detwinned state, a SMA member is clamped at both the ends and heated above Austenite start temperature (A_s), it will tend to reduce in length and reach its original (memorized) shape. However since it is clamped at both ends, the strain recovery is not physically possible and hence, it will generate tension.

This same idea can be used to generate tension in the shaft segments. For this, the SMA has to be attached at the ends of the shafts and clamped to it (Fig 2). When it will be heated above A_s it will generate the axial tension in the shaft. This can be achieved by Joule heating i.e., by passing current. A scheme proposed and shown in Fig. 3 and Fig. 4 appears promising. An SMA cylindrical member is attached to the shaft using flanges on both side. The connection on

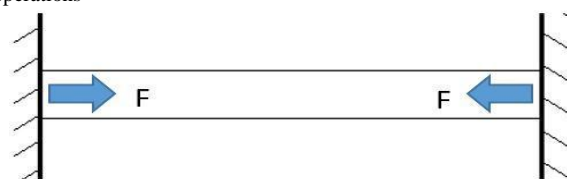


Figure 2. SMA member clamped at both ends

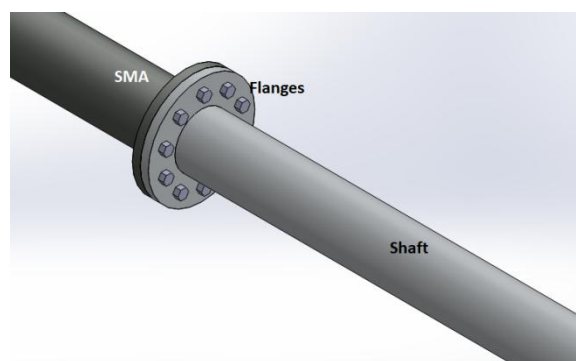


Figure 3. Clamping of SMA member on shaft

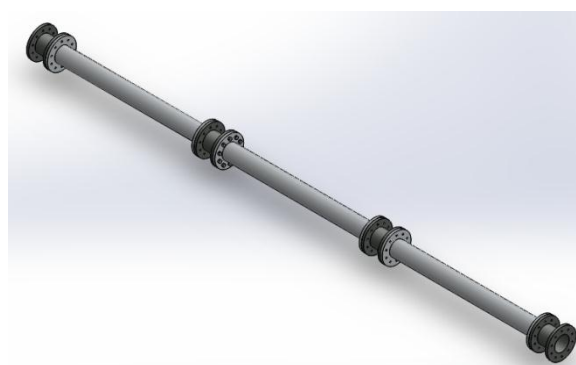


Figure 4. Complete driveline with SMA

the flanges can be made using fasteners. The other end of the SMA can either be clamped to a structure coming out of the chassis or even the end of adjacent shaft.

Two way shape memory effect (TWSME) is a phenomenon observed in SMA material which has repeatedly undergone thermo-mechanical cycling to eliminate the consecutively accumulating permanent strain

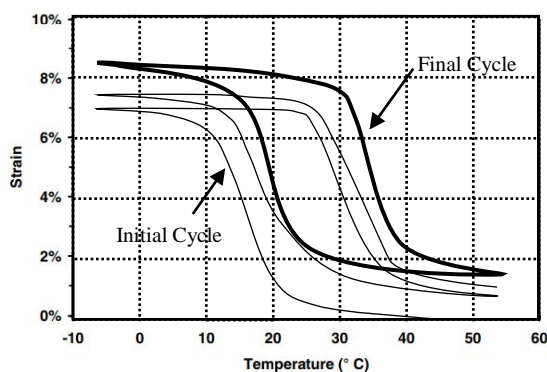


Figure 5. Cyclic training of Ni-Ti SMA wire^[2]

as shown in Fig. 5. Repeated loading along a load path can induce changes in the microstructure of the material which causes macroscopically observable changes in the material. To be used as per design the hysteretic nature of the material needs to be stabilized. This is achieved by training the SMA which involves repeatedly loading the SMA in thermo-mechanical cycles until the inelastic strain stops to saturate.

TWSME is a result of defects introduced during training. These permanent defects create a residual internal stress, thereby facilitating the formation of preferred martensitic variants upon cooling the SMA. During training small permanent strain remains after each thermal cycle is completed. Over the span of repetition of the cycles the accumulating strain with each cycle goes on reducing and ultimately ceases to practically accumulate as shown by 'final cycle' in Fig. 5.

It is finally decided to use a trained SMA which will be coupled to Aluminium drive shaft through flanges connected via nut and bolt. At the start of operation, the SMA is activated by Joule heating which increases the tension in the Aluminium drive shaft. The shaft is operated along the path of activated SMA in Fig. 1. As the fundamental frequency of the non-activated state Aluminium shaft is crossed, heating is reduced and eventually at the point heating is stopped. Following this the normal state corresponding to a non-activated one is followed with the fundamental frequency already crossed. There still exists a peak in the path but as the control is two way i.e., the operating frequency increases and the tension is released. The transition takes place fast and a very small duration is spent near the peak. The second peak is fairly away from operating frequency and no further control is required. As the SMA has TWSME, it returns to original state (cooled state) bringing an easily operable cyclic mechanism.

IV. Conclusions

- Present study explores the possible alternative designs for the existing helicopter tail rotor driveshaft. The material of the original shaft is found to be Aluminium 7075.
- The possibility of designing a supercritical shaft in Aluminium is explored and results show that it is possible to design a shaft with 3 shaft segments as compared to 7 shaft segments in existing design.
- Axial tension on the shaft will increase its natural frequency. The possibility of generating tension in the shaft using the Two Way Shape Memory Effect

(TWSME) property of SMA is explored. A scheme for the same is proposed.

- The heating of the SMA member can be carried out by resistive heating mechanism.
- Introducing the SMA provides controllability of the driveline by control over the natural frequency of the system.
- Application of SMA allows avoiding resonance and let the shaft operate in supercritical regime.
- This leads to decrease in the number of bearings and couplings by 4. This would lead to considerable weight reduction of driveline.

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