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Stiffness Characteristics of Fibre-reinforced Composite Shaft Embedded with Shape Memory Alloy Wires

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ABSTRACT

Frequent coast up/coast down operations of rotating shafts in the power and aerospace industry expose the flexible rotors to the risk of fatigue failures. Resonant vibrations during passage through critical speeds induce large stresses that may lead to failures. In this paper, the use of nitinol [shape memory alloy (SMA)] wires in the fibre-reinforced composite shaft, for the purpose of modifying shaft stiffness properties to avoid such failures, is discussed. A setup has been developed to fabricate the composite shaft (made of fibre glass and epoxy resin) embedded with pre-stressed SMA wires. Experiments have been carried out on the shaft to estimate the changes in the natural frequency of the composite shaft due to activation and deactivation of SMA wires. The comparison of the experimental results with the established analytical results indicates feasibility of vibration control using the special properties of SMA wires.

Keywords: Composite shaft, shape memory alloy, fatigue failure, fibre-reinforced composites, vibration control, SMA wires

1. INTRODUCTION

Advanced composite materials of high stiffness and strength-to-weight ratios along with other properties, such as environmental resistance, are being used for design of high performance structures. In addition to high specific stiffness and strength, the designer has several parameters like the fibre angle, the number of layers and their stacking sequence, fibre volume fraction, etc., under his control. This enables superior tailor-made designs for optimum performance.

The recent trend in design of high performance rotating machinery is towards higher operating speeds, leading inevitably to supercritical operation of shafts, which gives rise to the problems of high vibration amplitudes, stability, and stress. Resonant stresses near critical speed can lead to cracks and delamination and pose danger of even catastrophic failures. Application of flexible composite shaft for such high speed applications poses a problem of large amplitudes of vibration near critical speed during coast up/coast down operations.

Shape memory alloy (SMA) is another class of materials that demonstrate the ability to return to some previously defined shape or size when subjected to an appropriate thermal procedure and are now being considered for special engineering applications. Wayman and Shimizu[1] found that these materials can be plastically deformed at relatively low temperatures, and on exposure to some higher

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temperatures will return to their shapes prior to deformation.

It is proposed to embed pre-stressed/stretched nitinol [a common nickel-titanium shape memory alloy, (55% *Ni*) and (45% *Ti*)] wires in a composite shaft. On activation, the nitinol wires try to contract because of shape memory effect, which is restrained by the composite shaft. This results in generation of large tensile stress in the shaft, thereby increasing its bending stiffness. Also, the Young's modulus of nitinol wires increases three to four times on activation. This also tends to increase the shaft stiffness.

The strategy to avoid resonant vibrations during passage through critical speed is elucidated in Fig. 1. During the coast up operation, the wires are initially in an activated state (shaft having a higher natural frequency, p_{act}). When the rotor nears a speed ω^* approaching the resonance at p_{act}, the wires are deactivated, thus reducing the shaft natural frequency to p_{un}. The further coast up beyond the speed ω^* then takes place without encountering any resonance as the rotor-bearing system has its natural frequency suddenly lowered to p_{un} from p_{act}. During the coast-down operation, the wires are kept initially in an unactivated state and when the rotor reaches ω^*, the wires are activated. The coast down path is along the dotted arrows.

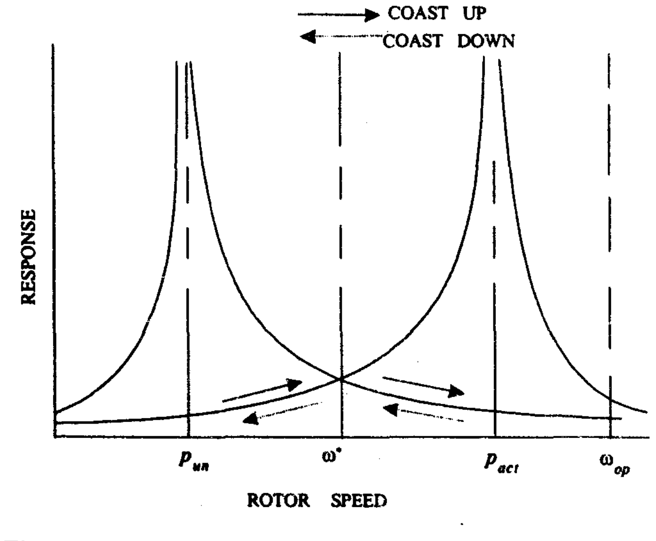

Figure 1. Activation and deactivation strategy for coasting up/coasting down of rotor.

Several attempts to combine the advantages of both the composite material and the SMA to build smart structures are reported in literature. Rogers[2] suggested embedding of nitinol wires into fibre-reinforced composite structures to control static deformation, vibration, buckling, acoustic radiation, and transmission characteristics. Baz and Chen[3] have developed a smart shaft, which can actively stiffen in response to increased rotational speed or increased amplitudes of vibration. They analysed a composite rotor embedded with nitinol wires by theoretical as well as experimental means. Their results showed a reduction of about 50 per cent in vibration amplitudes by activating nitinol wires. Gupta[4] studied by theoretical means, the combined effect of embedding the SMA wires in a rotor shaft (to alter the shaft bending stiffness) and change of support stiffness using the SMA, on rotor critical speeds. He has discussed the strategy to avoid resonance during rotor coast up/coast down operations by activating or deactivating the SMA members. Recently, Sawhney and Jain[5] carried out fabrication and experimental investigations on the fibre-reinforced composite shaft embedded with the SMA wires.

2. PROPERTIES OF NITINOL WIRES

The shape memory effect is described as follows: A component in the low-temperature martensite condition, when plastically deformed and the external stresses removed, will regain its original (memorised) shape when heated beyond a particular temperature A_f, the austenite transformation temperature. The phenomenon is the result of a martensitic transformation during heating. This process of regaining original shape is basically associated with a reverse transformation of the martensitic phase to the higher temperature austenitic phase.

Nitinol has good electrical and mechanical properties, long fatigue life, and high corrosion resistance. The behaviour of SMA is governed by the diffusionless transformation between a high temperature, low strain austenite phase and a low temperature, high strain martensite phase. The Young's modulus of nitinol on activation increases by more than three times (from 25 GPa in martensite phase to around 80 GPa in austenite phase). Plastic strains of typically 6 per cent to 8 per cent may be completely recovered by heating the material so as to transform it to its austenite phase. The shape memory effect does not simply mean that the previous shape will be restored freely when nitinol is heated. Restraining the material from regaining its memory shape can yield recovery stresses as high as 70 ksi (approx. 500 MPa), which is much higher than the yield strength of nitinol, i.e., around 12 ksi (approx. 84 MPa).

The ability of SMA to change its mechanical properties under the action of stress and temperature changes is exploited in the present work to investigate the feasibility of changing composite shaft stiffness and its natural frequency/critical speed. In the present study, nitinol wires of 2.5 mm diameter are used and the austenitic transformation temperature (A_f) is about 77 °C.

3. FIBRE-REINFORCED COMPOSITE SHAFT EMBEDDED WITH SMA (NITINOL) WIRES

For the SMA wires to aid in the stiffening process, the wires should be pre-strained/stretched before these are embedded in the fibre-reinforced composite shaft matrix, so that when the wires are activated by increasing their temperature beyond A_f, these would try to contract to the original length. However, the surrounding matrix will restrain the wires. Thus, large recovery tensile stresses in the shaft will develop, thereby increasing its stiffness. The phase transformation at A_f also leads to an increased Young's modulus, thereby stiffening the wires. This increased stiffness causes an increase in the natural frequency of the shaft that can be exploited for rotor vibration control.

3.1 Fabrication of Shaft

The setup for shaft fabrication (Fig. 2) contains a screw jack for providing tension in the wires. Supports are provided to avoid movement of jack in vertical direction. A ½° tapered mandrel is used for fabrication of hollow composite shaft. A plate with four holes of diameter 3.2 mm for holding the wires can be moved vertically by the screw jack to induce strain in the wires.

For fabrication of composite shaft with these pre-strained nitinol wires, sheets of fibre glass of 50 cm × 30 cm are used. The mandrel is cleaned and wrapped with plastic sheets and then sprayed with non-stick spray. Hardener (HY951) and epoxy resins (LY556) mixed in the ratio 1:10 by weight, respectively were used to cure the rotor shaft at the room temperature. The mixture was uniformly spread over the fibre glass sheets on a flat surface. The sheet was then wound over the mandrel carefully and the successive layers were wound until the outer diameter of the composite shaft reached 34 mm. The shaft was then put on the setup for embedding the pre-strained nitinol wires. The wires were given an extension of 5 mm (which is 1% of the total length), with the help of the screw jack. More layers were rolled on the shaft until its diameter reached 46 mm. The shaft was then allowed to dry for four days. The four wires were thus placed at a pitch circle diameter of 34 mm. The inner and the outer diameters of the shaft were 25.4 mm and

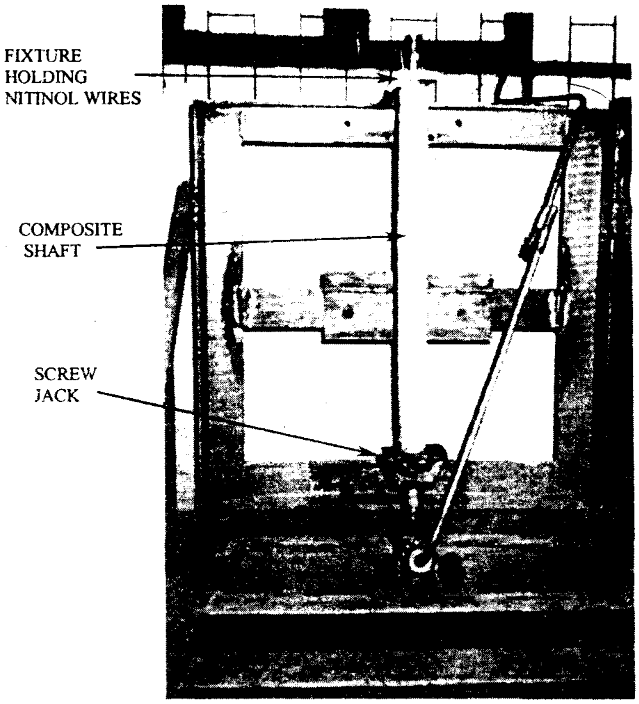

Figure 2. Setup for fabrication of composite shaft with pre-strained SMA wires.

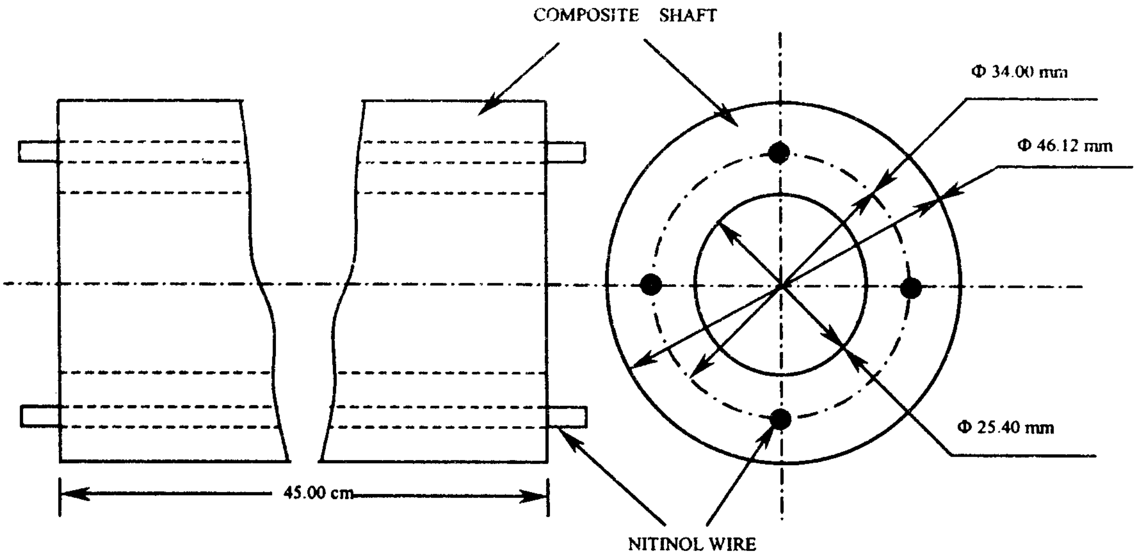

Figure 3. Composite shaft embedded with four SMA wires

46 mm, respectively. The dimensional details of the fabricated composite shaft with embedded nitinol wires are shown in Fig. 3.

3.2 Experimental Investigations

The shaft was fixed on both the ends, restricting all translational and rotational DOFs, on a hard non-vibrating ground. A piezoelectric accelerometer was mounted on the shaft as shown in Fig. 4. Rap test was conducted and the accelerometer signal through charge amplifier was fed into the real-time FFT analyser to find the natural frequency of the shaft. To determine the shaft natural frequency in activated state of SMA wires, the electric current was passed through the wires. For this purpose, an auto transformer along with a rectifier was used to supply the necessary electric voltage. Activation of wires was repeated with different values of voltage, i.e., 8V, 18V, and 25V.

The natural frequency of the shaft in the deactivated state was 344 Hz. When the current was passed through the wires from 8V supply, the shaft's natural frequency in about 30 s was increased to 348 Hz due to activation of wires–an increase of 1.16 per cent. However, when the current was passed for a longer duration, the natural frequency started decreasing. It became 340 Hz after 80 s and reduced to 332 Hz after 180 s–a value even lower than that in unactivated state of wires. This decrease in natural frequency can be explained by degradation of properties of the composite due to heating. It was indeed observed that bulk of the composite shaft became very hot due to heat transfer from the embedded SMA wires. No quantitative estimation of degradation in the properties of composite has been done so far.

3.3 Analytical Estimation

The equivalent modulus of the composite shaft (E_c) in the axial direction can be determined considering the properties of the glass fibre and the resin, as well as their volume fractions. Gupta[6] has shown that E_c strongly depends on fibre angle. It has a larger value for fibres aligned along the shaft (fibre angle of 0°) and a very low value for large fibre angles (fibre angle close to 90°). The volume fraction of nitinol (V_n) is the ratio of the total cross-sectional area of wires to the cross-sectional area of the shaft. The effective longitudinal modulus of the shaft embedded with nitinol wires (E_{sh}) and the material density (ρ_{sh}) in terms of the properties of the composite and the nitinol wires can be written as

$$E_{sh} = E_c + (E_n - E_c)V_n \; ; \; \rho_{sh} = \rho_c + (\rho_n - \rho_c) V_n \quad (1)$$

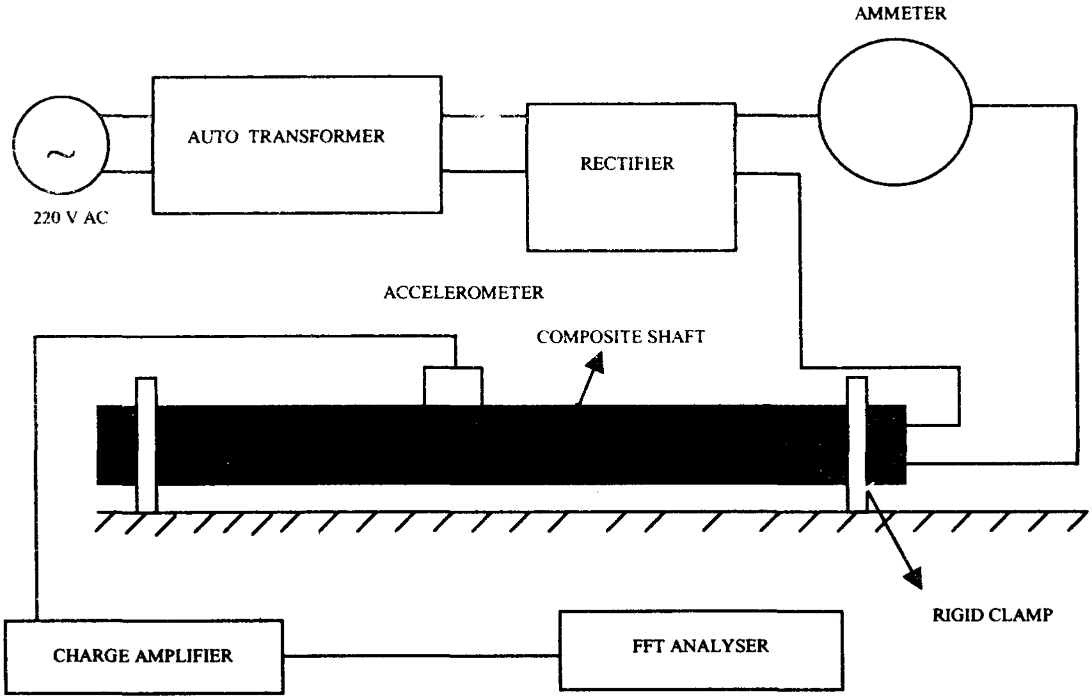

Figure 4. Setup with instrumentation for estimation of natural frequency

The natural frequency for a simply supported shaft is given by

$$p^2 = \pi^4 E_{sh} I \left(1 + r_t / \pi^2\right) / \left(m_{sh} L^4\right) \qquad (2)$$

here

$r_t = TL^2 / E_{sh} I$,

where

T Total tension in the shaft due to recovery stresses of nitinol wires

m_{sh} Mass per unit length for the shaft

L Length of the shaft

I Second area moment of shaft cross-section.

For nitinol, $E_n \approx 25$ GPa in unactivated state and has a higher value of about 80 GPa in activated state. For the present glass fibre composite shaft, Young's modulus (E_c) is estimated to be 28.3 GPa following the procedure described by Gupta[6]. Also the volume fraction of nitinol (V_n) works out to 0.0174. With these values in Eqn (1), the modulus of the shaft (E_{sh}) in unactivated and activated states of nitinol wires works out to 28.23 GPa and 29.2 GPa, respectively.

To compare the increase in natural frequency observed experimentally due to activation of wires, the effective tension in the shaft for an assumed 50 per cent recovered strain is given by $T = A_n E_n * 0.5 * 0.01$. It may be noted that initial strain applied on the wire is 0.01. The tension works out to 8.1 kN. The percentage increase in natural frequency due to combined effect of the increased shaft modulus and the tension in the shaft (assuming 50 % recovery) can be obtained from Eqn (2) and it works out to 3 per cent. The increase in the natural frequency measured from the experiment is 1.16 per cent, which is smaller compared to the theoretical value of 3 per cent. A plausible reason for this may be that the recovery in nitinol wires may be more compared to the assumed 50 per cent, resulting in smaller recovery stresses.

4. CONCLUSION

Switching of rotor stiffness value to alter the natural frequency of the rotor bearing system, to avoid resonance-related failures during rotor coast up and coast down operations is a feasible alternative. To demonstrate the use of smart materials, such as SMA in altering the shaft stiffness properties, an experimental setup to embed pre-strained SMA wires in the fibre-reinforced composite shaft is designed. The composite shaft with embedded SMA wires is fabricated and tested for change in the natural frequency due to activation and deactivation of SMA wires using electric resistance heating. In principle, the changes in the shaft stiffness properties, as evident through experimental investigations reported here, seem feasible. There is a noticeable increase in the natural frequency of the composite shaft due to activation of SMA wires, and the strategy has a potential for rotor vibration control provided higher initial strains could be induced in the wires.

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