Design and Manufacturing Concepts of Nanoparticle-reinforced Aerospace Materials

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ABSTRACT

Nanoparticle-based vibration damping shows the effect that molecule-level mechanism can have on the damping and that nanoparticles/fibres/tubes-reinforced composite materials can provide enhanced strength and vibration damping properties over the broader operational conditions. It is particularly worth noting that carbon nanotubes can act as a simple nanoscale spring. The mechanisms involved in such materials need to be understood and the relevance to damping identified. The focus in this paper is directed toward the development of the next generation of vibration damping systems, providing a road map to manufacturing technology and design solutions. The research work concentrates on an investigation related to nanoparticle-reinforced materials extensive dynamic characterization and modelling of their fundamental phenomena that control relationships between design and damping properties across the length scales.

Keywords: nanoparticle, damping, fan blade, design

1 INTRODUCTION

Vibrations and noise exist in almost every aspect of our life and are usually undesirable in engineering structures [1]. Vibrations are of concern in large structures such as civil (airbus A 380) or Rolls-Royce powered military aircrafts [2, 3], as well as small structures such as electronics [4]. Manufacturers have stated that for the next generation of transportation we need light-weight, cost-effective and reliable vibration-absorbing materials [5, 6].

Recent breakthroughs in automotive, maritime and aircraft design have resulted in the successful use of synthetic parts and novel designs in applications previously considered too demanding for non-traditional materials, comprising 20-25% of a typical car body weight [7]. Composites are also, besides aluminium, the most important materials for aerospace applications. Due to the opportunities they present for weight saving, their share has reached more than 15 % of the structural weight of civil aircraft, and more than 50% of the structural weight of helicopters and military aircrafts [8]. In addition to their high mass specific stiffness and strength, the high potential of composites for additional functionality is another reason for their success. Defined anisotropic behaviour, the possibility to integrate sensors or actuators, high structural damping, and superior fatigue performance are typical advantages. Motivation to the research work could be outlined as follows:

1. Nanoparticle/tube/fibre-reinforced composite material is a relatively new vibration damping technology entailing placement of numerous nanoparticles inside vibrating material structure that has wide applications in areas of transportation (aerospace, auto, rail, maritime) and electronics. Carbon nanotubes are particularly cost-decreasing material for potential large scale industrial applications.
2. Manufacturers such as Rolls-Royce, Boeing, Airbus require in a long term 10 time stronger and 2 time lighter components and materials as well as their 3 to 5 year goal is 30-40% enhancement of these operational parameters that can be achieved by advanced design and manufacturing based on about 50% nanotechnology content.
3. The CNT-reinforced material damping technology and related energy dissipation phenomenon is complex because of the variety of mechanisms involved and there is the gap between engineering applications/structures and nanotechnology leading to the next generation engineering.

It is now accepted that nanotechnology may considerably enhance strength/damping behaviour and reduce noise of engineering structures through the utilisation of nanomaterials that dissipate a substantial fraction of the vibration energy that they receive [7]. Carbon nanotubes are particularly promising cost-decreasing reinforcement material [8, 13]. Boron nitride or silicon carbide nanotubes are another possible candidate for aerospace material reinforcement [2, 9]. The benefits that may be achieved by both carbon nanotubes in lower temperature damping applications and boron-nitride/silicon carbide nanotubes in high temperature aerospace applications may be very significant. The present paper will outline some preliminary efforts made by the institutions in this direction under EU programmes. The key goal of this communication is to provide a route map in the future research and outline a project concentrated on the next generation industry-oriented nanotechnology-based solutions for enhanced vibration damping/dynamics performance.

2 DESIGN CONCEPTS

2.1 Damping nanomaterials

Selection of engineering material for the future nanoparticle-reinforced composite material is available from three types of solids that are metals, polymers and some ceramics. Selected matrix will mostly determine mechanism of energy dissipation [10, 11]; however, small CNT volume (1-5%) may greatly affect material's behaviour due to extreme nanotube properties over traditional materials [5-12].

Nanotube-metal matrix composite materials are still rarely studied [6, 13]. Most used metallic alloys are hard or soft materials such as titanium/nickel and aluminium/bronze respectively. While titanium is stiff, light-weight and good for high temperature applications such as turbine fan blades, car panels are made of light-weight and cheaper aluminium and its alloys. Produced metal foams have excellent energy absorbing/damping properties over bulk material [14] and most likely are used for the next generation engineering. The CNT-reinforced metal materials are generally prepared by standard powder metallurgy melting [16] or ultrasonic liquid infiltration method [15], but good mixing and dispersion of the nanotubes should be achieved. In this respect it would be worth producing CNT-reinforced metallic foam composites and investigate their damping/dynamics performance.

Carbon nanotube-reinforced ceramic-matrix composite materials are a bit more frequently studied [17]; most successful efforts were made to obtain tougher ceramics (SiC, Al_2O_3, etc.) [37]. The composites can be processed by 1) mechanically mixed nanotubes with the matrix and then sintering [13, 37], melting [20] or spraying [18] of the particle mixture; 2) CVD deposited CNT-based thin films on SiC substrate (up to 50 μm) [19]; and 3) electrochemical processing such as micro-arc oxidizing of metal substrate in an liquid electrolyte with added nanoparticles [21]. Some ceramic coatings are successfully used to enhance damping of titanium fan blades [18] and therefore, would be recommended as a candidate matrix material, but dispersion and orientation of nanotubes in the matrix is yet out of some control. Bulk properties other than mechanical are also worth being investigated.

Nanotube-polymer composites are now intensively studied [22-29], notably epoxy- and polymethylmethacrylate (PMMA)-matrix composites [25]; however, their damping behaviour is rather contradictory result than plausible information (see table 1). The ability of the polymer molecular chains to form large-diameter helices around individual nanotubes favours the formation of a strong bond with the matrix [36]. Selection of related manufacturing technologies is available from some well-known in the aircraft industry that are 1) manually or ultrasonically melt mixing and extrusion of nanotubes and polymer-layered silicate [12, 22], 2) CNT-reinforced resin by using so-called calandering technique [23, 24], 3) polymerization of carbon fibre by interfacial polymerization [26, 27].

2.2 Design of nanoscale-reinforced fan blade

Advanced damping material and fan blade design concepts could be introduced as follows:

1) Particle micro-balloons are currently being used for enhanced damping performance of fan blade over bulk material core or rigid stiffeners in a hollow blade [18]. Nanoparticle-reinforced micro-balloons may be added separately or used to create syntactic foam (a two-part epoxy adhesive filled with balloons) such that the density of the foam is about 1000 kg/m^3 (Fig. 1).

Motivation: Volume and weight of filler material should be minimized. In large civil engines, the blades are hollow and usually have stiff rib-like metallic structures in order to increase the rigidity and maintain cross-sectional profile of the blade. The filled fan concept is to replace this metal structure with CNT-reinforced foam simultaneously acting as a strengthener and a damping element.

2) CNT-reinforced damping coatings: both single layer and multi-layered sandwich structure.

Motivation: Coating has considerable adhesion and adds significant damping to titanium fan blades. Ceramic coating is desirable in high temperature applications, but its damping level is lower than that of polymeric ones. Another problem is fracture and fatigue of hard coatings on dynamic blade.

Syntactic foam fillers are frequently used to stiffen hollow fan on large civil aircraft engines. These typically comprise a two-part epoxy compound filled with glass micro-balloons such that the density of the foam is well below 1000 kg/m^3 and the concept of the cavity-filled fan blade has been introduced [8-10]. Hollow fan blades currently enclose a strong, stiff metallic structure to maintain the cross-sectional profile of the blade when subjected to the large static and dynamic forces experienced in normal operation. In the cavity-fill fan concept, the polymeric core replaces this metal structure simultaneously acting as both strengtheners and damping elements – an example is shown in Figure 1. It would be expected that incorporating CNT may affect not only the damping performance, but also the integrity under static, impact and fatigue loads. While hard balloons are desirable for maximising stiffness and damping, CNT-reinforced polymeric ones may be better for the damping and integrity.

Further improvements can be made to both the materials and to the blade design. In its simplest form, the CNT reinforcement concept is simply a fan blade coated or filled with a suitably selected damping material. Hollow fan blade may be filled with CNT-reinforced material and coated with CNT-reinforced layer on the top [12]. The blades are composed of a titanium sheet and composite internal / external manifolds with nanoparticle reinforcement.

Due to the complex whole structure and advanced design, these blades should have low natural frequencies and bending-torsion coupled mode shapes that could potentially lead to aeroelastic instabilities. Increasing the damping levels in these blades will improve the fatigue life and reduce aeroelastic instability concerns. The vibratory modes of interest include the first and second bending modes as well as first torsion mode. Due to the geometric constraints of the blade shape and large internal manifolds very little room is available for damping treatment placement; however, it is expected that large volume-to-surface ratio of carbon nanotubes may overcome the problems. Some possible outcomes would be also extending the temperature range over which some polymeric damping materials is present and finding ways to increase the modulus without sacrificing density and integrity. It is anticipated that significant weight, thickness and manufacturing cost reductions could be achieved in this way.

3 EXPERIMENTS

SWNT-reinforced polymeric matrix composites are prepared using an extrusion procedure. The polymer is made of polymethylmethacrylate polymer samples. SWNT particles produced by Dynamic Enterprises, UK (2 nm in diameter and 80-90 vol% sample purity) are added in concentrations of 10% by weight (including impurities) along with a surfactant (polyoxyethylene) to aid in dispersion. The mixture is put into a mold and subjected to a vacuum for 25 min and curing. Scanning electron microscope (SEM) is used to evaluate the nanotube dispersion and orientation in the polymeric matrix. CNT orientation was controlled by pressure rates at extrusion.

Hollow titanium alloy (6%W, 4%V) samples were then sandwiched with the composite material and glued by an adhesive epoxy resin. Resonance frequencies, the mode shape and damping at each mode were determined by laser vibrometry at standard vibration shaker tests. Heating of clamped sample was provided by two 1000W electrical “Philips” bulbs. The clamping block is fixed so that friction losses and extraneous damping is minimized. The data acquisition and control of the electro-dynamic system is based on Computer Measurement System. The deformation rates were 200 rad/s for shaker. The vibrometry procedure yields not only the resonance frequency, but also the mode shape.

Material	Young modulus at 25°C, GPa	Loss factor at 25°C
Epoxy resin	3.1-3.4 [12, 19]	0.01 [12]*
Polyurethane at 850Hz	0.3 [19]	0.58 [19]**
Epoxy adhesive filler	3 and 0.00275 at 850Hz [19, 34]	0.4 [19]
1-5 wt% CNT-matrix	3.2-3.6 [23, 24],	0.08 [12] (* - 8 times increase)
50-60 wt% CNT-matrix	7.1-7.5 [35]	
MWNT-reinforced thin SiC ceramic film (no matrix) at 850Hz	284 [19] Bending stiffness + 30% [19, 34]	0.3 [19] (** - 2 times decrease) +200% [34]

Table 1: Damping properties of CNT-reinforced polymeric materials.

In this paper, the concepts of CNT-reinforced titanium alloy sandwich have been introduced and CNT-reinforced composites were applied so as to investigate their applicability to aerospace components (fan blade). Modal strain energy numerical methods [18] for predicting damping was validated experimentally under non-rotating conditions. Loss factor exceeding η=1 have been demonstrated on fan blades under non-rotating conditions showing the design potential of the concept. CNT-reinforced composites affect not only the damping performance/strength, but also the integrity under static and cyclic loading. While CNT-reinforced ceramic material may be desirable for stiffening, polymeric ones were better for damping and integrity. The results (fig. 1) clearly show that the analytical methods used are reliable and that significant levels of damping can be achieved in fan blades using the cavity fill concept.

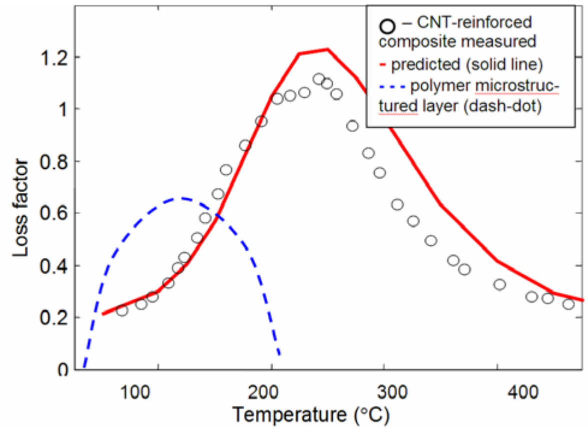

Figure 1: Comparison between measured and predicted modal properties under non-rotating conditions, showing a very close correlation.

Size of reinforcement nanoparticles may vary from 1 to 100 nm in diameter and length. The number of CNT walls and their size affect on stress concentration in the composite [29] and thus short and even round particles are the strongest ones (diamonds etc.), but longer fibres are flexible and may be worth for damping while CNT may particularly act as a simple nanoscale spring and a crack trapping nanomaterial blocking the holes in the composites [30, 31]. Such a damping phenomenon could be multiplied by a factor of billions when CNTs are dispersed in a material.

Orientation and geometry (waviness) of CNT particles may affect mechanisms of energy dissipation/fracture mechanics and maximum stiffness is achievable at 90^0 longitudinal CNT orientations [25, 29]. Notably those open-end CNTs do not collapse/failure/buckle due to higher stress concentrations while many authors [12, 22-31] have used closed-end CNT-reinforced composites. Thus isolated single-walled open-end nanotubes (SWNT) may be desirable for the future damping applications due to significant load-bearing ability in the case of CNT-matrix interactions. Defects of carbon particles limit the performance [23-27].

CNT dispersion should be optimized for damping at 1-5% volume content because of carbon fibre conglomeration at higher volumes [32, 35], but 60 wt% CNT concentration in polymer was modelled [35]. The main disadvantage of CNT dispersion is that it involves a large uncertainty to desired damping effect due to nanoparticles.

4 CONCLUSION

At some preliminary point it was validated that a concept of using CNT as vibration damping oscillators where CNT acts like a nano-shock-absorber and loss factor exceeding η=1 have been demonstrated on clamped specimens simulating fan blades under non-rotating conditions showing the design potential of the concept; however, a proof of manufacturing concept is required.

Future work should be concentrated on improvements to both the filler materials and the blade design. Efforts should be focused on ecology-oriented manufacturing & design, assessment of life cycle, durability, utilization and repair possibilities, comprising several steps for tailoring the nanoparticle-matrix interface, dispersion and orientation for specific application. It is anticipated that significant weight, thickness and manufacturing cost reductions could be achieved in this way. Selection of nanoparticles just lightly depends on its price, but application outcomes.

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