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Mechanical behaviour of tangled metal wire devices

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ABSTRACT

Tangled metal wire (TMW) devices can be used as damping elements in extreme environments where traditional materials such as viscoelastic polymers deteriorate or become ineffective. Dynamic properties of TMW devices are highly nonlinear because the microstructure consists of coiled metal wires that are compressed together. This paper examines the sensitivity of their dynamic stiffness and damping to loading conditions, in particular, pre-compression, dynamic amplitude and frequency of excitation. Using displacement-controlled experiments, it is shown that properties depend strongly on pre-compression and dynamic amplitude as would be expected in a structure comprising many frictional contact points. Frequency dependence is shown to be negligible over a broad frequency range that encompasses the region of interest for typical machine applications. This work identifies slow dynamic effects, with timescales of the order of around 10 s, which show that quasi-static testing, which is sometimes used for these materials, will not provide accurate estimates of dynamic properties.

1. Introduction

Tangled metal wire (TMW) devices are made by weaving together helically coiled wires and compressing them in a mould to produce a desired shape [1–3]. There is growing interest in employing them as passive vibration control elements because their performance does not degrade in extreme environments. This has led them to be used in spacecraft [4,5], turbomachinery [6,7] and cryogenic [8] applications. TMW devices have been produced using several materials including steel [8], titanium [9], and nickel based superalloys [10]. Remarkably, TMW devices have also been manufactured using shape memory alloys [11].

The vibration behaviour of TMW devices is comparable to equivalent ones made from rubbery polymers and, consequently, they are sometimes referred to as “metal rubber” devices. Their properties are affected by the type of wire used [12] and the microstructure that is created during manufacture. This microstructure is heterogeneous: X-ray scans reveal that it is formed of closely packed, interwoven coils whose distribution and orientation are somewhat inconsistent throughout the volume [13,14].

As with any dampers used to tackle vibration problems, the mechanical properties of TMW devices rely on their geometrical dimensions. Researchers have found that if the size of the device is large compared to its microstructure, it is reasonable to assume homogeneity [14]. Therefore, stiffness can be obtained directly from the nominal elastic modulus, and the loss factor can be assumed to be constant. However, due to the nonlinear strain dependence, unusual geometries that result in non-uniform strain could provide unexpected behaviour.

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Quasi-static, uniaxial load–deflection tests, conducted by many different teams of researchers, show that stiffness increases with compression level and that the load–deflection hysteresis loop is not symmetric. As Poisson's ratio is typically low [13], uniaxial compression results in increased density. It is commonly concluded that compression increases the number of wire-to-wire contacts.

As there are currently no reliable models that can predict dynamic performance based on device construction, successful selection and design of an TMW device for a particular application relies on previous experience, and a certain amount of trial and error. Much of the current research effort in this field is therefore focused on developing understanding of the mechanisms that govern behaviour, and their relationships to the microstructure. Complicating factors that delay consensus are that performance depends on the characteristics of the dynamic load and that there is inherent variability of the microstructure even for nominally identical specimens. Thus, the explanations provided by different research teams for particular behaviour can appear to be in conflict.

One area where uncertainty remains is the explanation of the way in which energy dissipation is affected by loading. In operation, TMW devices are usually subjected to pre-compression to ensure that they avoid tensile loads that can cause them to disintegrate. Most researchers accept that dynamic behaviour depends on the relative importance of three possible contact conditions between adjacent wire segments: open, sliding and sticking [15]. At very low compression levels, behaviour is dominated by open contacts (i.e. no contact) with deformation occurring in the wires in a linear elastic manner, and therefore energy dissipation is negligible. At very high compression levels, on the other hand, slip at most contacts is eliminated. Loads can exceed plastic limits, causing permanent bending of wires and local deformation at wire-to-wire contacts. Operation is this stage is generally avoided [16]. When the compression level lies in between these extreme conditions, slip can occur at contacts between adjacent coils.

The nature of the sliding contact has been discussed extensively. It is generally accepted that the stiffness reduces somewhat as the dynamic amplitude is increased and that this is caused by slippage at previously sticking contacts. There is less agreement, however, regarding the mechanism by which energy is dissipated. Experimental results showing that the addition of oil to an TMW device reduced the damping negligibly has led some to suggest that the damping may not be Coulombic in nature [17], and should be represented using a hysteretic model [18]. However, a typical hysteresis loop for an TMW device has sharp corners at the extreme displacements indicating that a classical hysteretic model is not appropriate [19]. While models employing combined Coulomb friction and viscous behaviour have been proposed [19,20], there is no clear experimental evidence to show that they are any more than convenient phenomenological models that fit specific data sets.

One of the main arguments for including damping of any kind other than Coulomb friction has been to explain frequency dependence evident in some published results. While most published data refers to quasi-static tests, a number of researchers have conducted dynamic tests at different excitation frequencies [16,19,21,10,22]. Hou et al. noted a reduction in damping with increasing frequency over the range 1–10 Hz [19]. When studying TMW bearing supports subjected to random vibration loading, Ma et al. noted that as frequency increased, the stiffness increased and the damping increased to a maximum before decreasing [21]. Zhang et al. tested TMW specimens over a frequency range of 1 to 200 Hz and noted that with increasing frequency stiffness increased significantly while damping reduced only slightly [10]. Zhang, K. et al., however, from evaluating TMW isolators at frequencies up to 3 Hz, stated that frequency did not affect damping behaviour [22].

The lack of agreement regarding performance is significant, as the differing viewpoints cast doubt on any model that is used to represent TMW. Successful models so far have typically been fitted models (for example, see the work by Zhang, B. et al. [20]) for particular specimens and input amplitudes. These are limited in value since the parameters in the fitted models, in general, cannot be extended to other TMW devices. The aims of this paper therefore are to investigate the effects of pre-compression, dynamic amplitude and excitation frequency on a set of test specimens and to relate these findings to conclusions made previously.

It should be noted that an extensive study involving these parameters has previously been performed by Zhang et al. [10]. In that work, a dynamic mechanical analysis (DMA) machine was used to take measurements. While the results from that study are valuable, particularly because they used a large number of nominally identical specimens to give statistical information such as the standard deviation in properties, a particular limitation was the type of loading that the equipment could deliver. Tests were conducted under a form of load control, where the actuator provided nominally sinusoidal forcing and the peak amplitude was adjusted to meet set levels. The key difference in the work described here is that closed loop waveform control is applied to the displacement signal. The advantage of this approach is that it allows like-for-like comparisons to be made as the frequency and amplitude of the loading is altered.

2. Methodology

TMW devices are typically designed to have a particular relative density. The relative density, $\tilde{\rho}$ is a measure of ratio of the mass of the specimen divided by the volume of the wires within the microstructure relative to the mass of a solid block of same geometry to its volume. As Zhang et al. demonstrated, specimen variability for TMW devices are considerable, with mechanical properties varying as much as 10% [10]. Whilst the results by Zhang et al. [10] bears significance, the main objective of this paper is to understand the underlying principles that dictate the mechanical behaviour of TMW devices. To achieve this, displacement controlled quasi-static, low frequency dynamics, and high frequency dynamics tests are carried