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Feasibility study on the use of Tangled Metal Wire particles as the adjustable elements in Tuned Mass dampers

N. Tang[1,*], J.A. Rongong

Abstract

Tangled metal wire particles are a recent innovation that could provide an alternative to traditional damping materials. As they have low mass and are relatively insensitive to temperature, they are suitable for use in harsh environments. The present contribution demonstrates that these particles can be used as working elements for an adjustable Tuned Mass Damper. It is shown that the dynamic properties of a collection of tangled metal wire particles can be characterised with a reasonable accuracy, to provide the basis for a practical adjustable damper. The effectiveness of the new damper is demonstrated on two different vibration modes of a typical engineering structure. Finally, the new damper is shown to be much lighter than an equivalent tuned mass damper that was constructed more traditionally using polymeric O-rings.

Keywords: Tangled Metal Wire, nonlinear, adjustable tuning, Tuned Mass Damper

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1. Introduction

A tuned mass damper (TMD) is a damped oscillator that is attached to a host structure to suppress vibration over a narrow frequency band. Adjustable and semi-active TMDs have been developed so that a single device can target different resonances of the host structure. A common design feature in TMDs is a polymeric element that connects the TMD mass to the host structure and provides the required stiffness and damping for the oscillator. This element can be made adjustable by altering its geometry [1, 2]. The main drawback in using a polymeric element is that it may only be effective over a narrow temperature range and can be degraded in harsh environments. This paper evaluates the suitability of tangled metal wire (TMW) particles as a replacement for the polymeric element of an adjustable TMD because they do not suffer from the same environmental limitations.

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The aim of this work is to evaluate the adjustability and effectiveness of a collection of TMW particles that form the stiffness and damping element for an adjustable TMD. In order to form this type of device, the dynamic properties (stiffness and damping) should be predictable and time-invariant. Additionally, a simple way to alter the stiffness needs to be developed to achieve the adjustable tuning.

The paper is arranged as a series of studies. Section 2 provides a brief review of the background knowledge relating to TMW particles. The variability in dynamic properties observed in a set of nominally identical particles is examined in Section 3. The reduction in this variability when a collection of particles is employed is then considered in Section 4. Section 5 reports the design and characterisation of a damper based on TMW while its adjustability is investigated in Section 6. Its effectiveness in suppressing the vibration of a test structure is then investigated in Section 7. Final conclusions are drawn in Section 8.

2. Tangled metal wire particles

Tangled metal wire (TMW), which is also known as metal mesh or metal rubber, is a porous material that is formed by compressing helical wires together in a mould [3, 4]. The microstructure of this material is in some ways similar, albeit on a much larger scale, to that of an elastomeric polymer and as a result, it displays similar stiffness and damping behaviour when subjected to vibration [5–8]. As it is constructed entirely from metal, it can be used in extreme temperature, pressure and radiation environments where a polymer would not survive and is therefore of interest for gas turbine and spacecraft applications [9, 10].

The TMW particle is a recent innovation [11]. It is formed in a similar way to bulk TMW [12] except that the final compression moulding stage is omitted. This significantly reduces the resulting density and stiffness but also increases the inconsistency in properties, as particles are irregular in shape and microstructure as can be seen in Figure 1. The interest in investigating their use in TMD applications arises because they are highly compressible with void fractions well above 0.9. As stiffness is closely related to the density for TMW materials, this indicates that stiffness can be controlled by adjusting the compression level [12]. As repeatability is important to allow optimisation, minimising the variability in properties is important. One way to achieve this is to use collections of particles rather than individual ones so that averaging occurs.

In previous work, collections of particles have been evaluated in terms of their damping under compressive loads [12], or in particle damper and cavity fill applications [13]. Under compressive loading, the inherent damping of the particles is similar to that of the bulk material, with loss factors reported in the range 0.18 to 0.4 [13]. When deployed in a discrete particle damper however, they were shown to be ineffective as their low density resulted in low-force impacts that dissipated little energy. When used as a cavity filler instead, impressive vibration suppression was achieved as shown in Figure 2.

Figure 1: Tangled wire metal particles

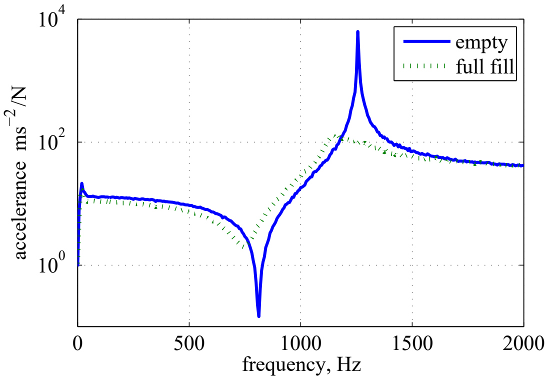

Figure 2: Effect of the TMW structural fillers for box beam [13]

The result shown in Figure 2 was achieved on a box-section aluminium beam, suspended from light springs and excited using an instrumented hammer. The external dimensions of the beam were 260 × 25 × 12.5 mm while the wall thickness was 1.6 mm. The cavity was completely filled with TMW particles which had a total mass that was approximately 20% that of the beam. The reason for the high damping achieved was thought to arise from the presence of wave modes within the particle medium acting perpendicular to the beam, in a way similar to multiple TMDs [13]. This can be verified by considering the modulus and density of a typical TMW particle collection [12], which indicates that the bulk wave speed within the medium was below 40 m/s and hence at the frequencies of interest the quarter-wavelength was less than the depth of the cavity making such damping likely [14]. While the filler application is somewhat different to the TMDs proposed in this paper, the important point is that the filler application provides clear evidence of effective deployment of TMW particles in damping structural vibrations.

3. Stiffness and damping of individual particles

An important requirement for designing an adjustable damper made from TMW particles, is the ability to predict dynamic properties (stiffness and damping). In this section, some important parameters including loading history, static compression and repeatability for the same type of particle are investigated.

3.1. Experimental configurations

Stiffness and damping of the TMW particles were measured using a dynamic mechanical analyser (Metravib VA2000). Individual particles were pre-compressed between parallel plates and load-deflection behaviour measured under low-frequency sinusoidal forcing. For the tests described here, this pre-compression was 0.3 mm, the dynamic displacement was 0.05 mm while the excitation frequency was 2.5 Hz (due to the limitation of test machine). In each test, a single TMW particle was subjected to 40 sinusoidal displacement oscillations, and the ensemble average of the resulting force-displacement hysteresis loops were used to identify the mid-point stiffness and damping for the particles. A typical hysteresis loop produced in this way is shown in Figure 3. In this figure, the force and displacement measurements are relative to the equilibrium condition reached after the pre-compression was applied with further compression being in the positive direction.

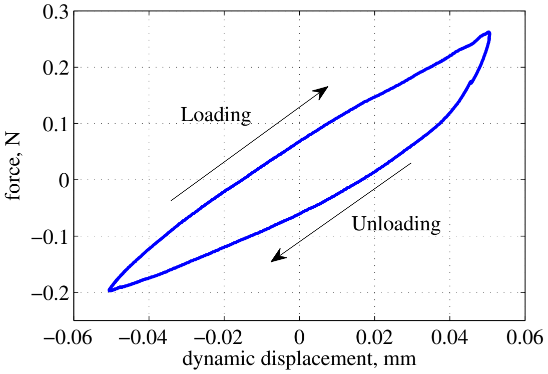

Figure 3: Typical hysteresis loop for TMW particle

From the time-domain test data, the resulting force-displacement hysteresis loops were used to estimate nominal stiffness and loss factor.

3.2. Sample preparation

Often, a TMW device is conditioned before use to stabilise its properties. This conditioning involves subjecting the device to cyclic loading that induces deformations greater than those that are expected in practice. Stability in values for Young's modulus and damping is usually achieved after a few cycles as the microstructure, comprising wire coils and contacts, adjusts to the loading applied. With TMW particles, conditioning of this kind cannot be defined easily as the particle can be loaded in many different ways. However, to provide some comparison with standard behaviour, a particle was subjected to uniaxial sinusoidal loading, the results of which are shown in Figures 4 and 5.

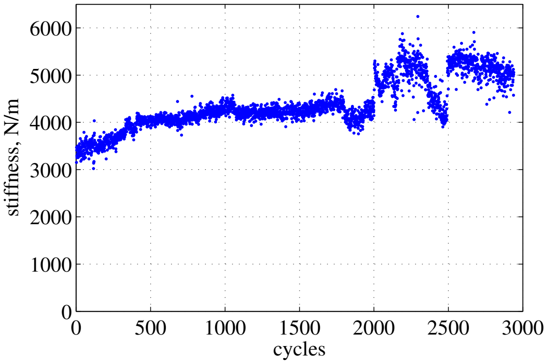

Figure 4: Effect of load cycle on the stiffness of a TMW particle

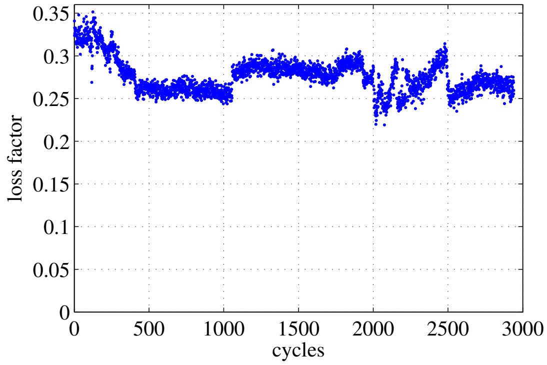

Figure 5: Effect of load cycle on the damping of a TMW particle

The results reveal two important phenomena. First, there is considerable variation in both properties. This happens on a cycle-to-cycle basis, where the effects of individual contacts opening, closing and sliding are unlikely to be repeatable at a microstructural level. Sudden jumps are also noticeable around 1100, 2000 and 2500 cycles which are attributed to rotation of the particle between the loading plates that results in a sudden change in load paths within the particle. The second phenomenon is that the underlying properties change gradually throughout the loading process, with stiffness increasing and loss factor reducing as the number of cycles increases. This change is most significant over the first 500 cycles and are thought to relate to irreversible density change in the particle caused by the compressive loading.

3.3. Static compression-dependent properties

Previous work [15, 16] has shown that dynamic properties are highly dependent on static pre-compression. Using the same test conditions as before, sensitivity to pre-compression was measured for a specific particle. Results are summarised in Table 1.

	Static compression, mm				
	0.03	0.07	0.11	0.14	0.17
Stiffness, N/mm	5.7	16.2	18.98	22.9	46.3
Loss factor	0.16	0.21	0.25	0.23	0.23

Table 1: Effect of the static compression on single TMW particle

The results clearly show a high level of nonlinearity in both stiffness and loss factor. As compression level increases, the stiffness increases dramatically and the loss factor first rises to a maximum and the reduces somewhat. This behaviour is typical for a system dominated by dry friction contacts. However, the level of nonlinearity appears to be more severe for the particle than for the bulk material [**?**]. This is likely to be because the open structure of the particle allows more change in density, and the number of wire-to-wire contacts that occur.

3.4. Variation in properties between different particles

Each tangled metal wire (TMW) particle is approximately spherical in shape. However, as it is formed from coiled metal wire, there is no obvious outer surface and the void ratio exceeds 0.9. In addition to this, the forming process does not produce identical particles significant variation is noticeable from a simple visual inspection. Because of these facts, it is not surprising that stiffness and damping vary depending on loading direction and from one particle to another. In previous work [13], the loss factors of individual particles were found to be in the range 0.18 to 0.40 but as only a small number of particles were studied, the significance was uncertain. In this work therefore, the dynamic properties (stiffness and loss factor), were measured for 50 different particles with nominally identical properties. The ranges in important dimensions are provided in Table 2.

Variable	Unit	Value
estimated nominal diameter	mm	4.07-6.70
wire diameter	mm	0.12
mass	g	0.03-0.055
material	-	stainless steel

Table 2: mechanical properties of individual TMW particles

Results, in the form of frequency histograms, are presented in Figures 6 and 7.

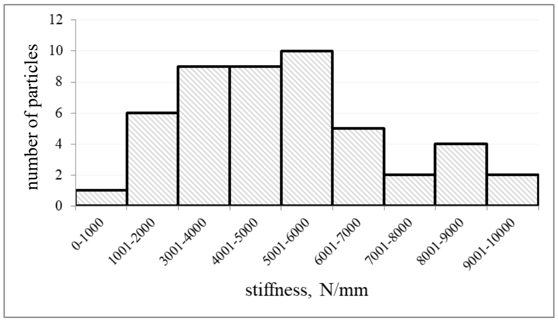

Figure 6: Stiffness for fifty different TMW particles

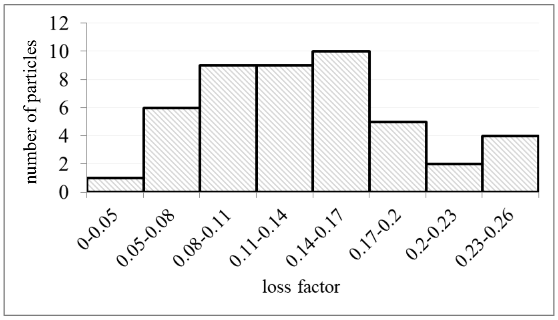

Figure 7: Damping for fifty different TMW particles

It can be seen that there is a considerable variation between the different particles in terms of both stiffness and loss factor, and there is no significant correlation between stiffness and loss factor.

Unlike normal TMW devices, TMW particles are not subjected to a compression moulding stage. This gives them a much more open microstructure and potentially very different behaviour. Testing on single particles was carried out to ascertain, in a qualitative manner, whether stiffness and damping were sensitive to loading in a broadly similar way to that seen in TMW devices subjected to compression moulding.

From the studies carried out in this section, it is evident that because of the variability of properties from particle to particle and their high sensitivity to loading, attempting to predict behaviour in a quantitative manner is not a practical approach. However, design of a tuned damper requires an ability to estimate properties of the key elements. The next step in the study therefore, was to consider collections of particles, where spatial averaging effects might be expected to simplify behaviour.

4. Stiffness and damping for a collection of TMW particles

While the properties of individual particles can vary significantly, their combined effect, as part of a large collection, should be more consistent. This section reports measurements of stiffness and damping that were made for a collection of approximately 100 particles, constrained within a cylindrical cavity and subjected to piston-like loading.

The container for holding the particles was made from a transparent polymeric material (PMMA) to allow visual observation. The cavity diameter was 38 mm and, to minimise possible stretching under load, its walls were 6 mm in thickness. Particles were placed within the cavity, layer by layer, to a depth of three particles. Due to the variability in size and shape of the particles and the tendency of the coils in adjacent particles to overlap, structured arrangements of particles were not attempted. The free height after initial placement was approximately 14 mm. For comparison, if 100 hard spheres, with diameters uniformly distributed over the range stated for the particles (see Table 2), were placed randomly within the container, the theoretical value for the free height would lie in the range 13-15 mm. The container was attached to the lower loading column on the test machine, directly connecting to the load cell. A circular plate was attached to the upper loading column to provide consistent deflection over the free surface of particles. A sketch of the test set-up is provided in Figure 8. An initial deflection condition was specified by lowering this plate 0.05 mm below the point at which the force sensor first recorded contact. Subsequent testing involved applying a further static deflection of 0.5 mm followed by sinusoidal loading with a frequency of 2.5 Hz.

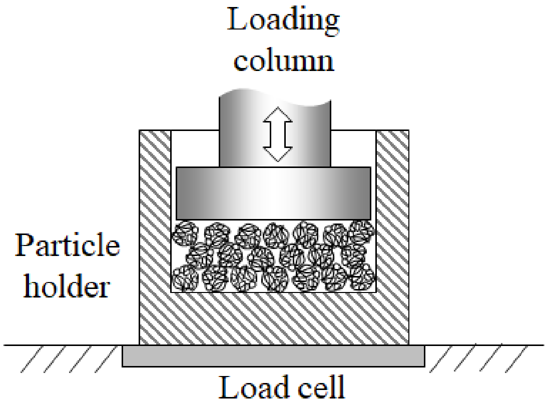

Figure 8: Sketch of the test set-up

The consistency of properties was first tested at a dynamic amplitude of 0.025 mm. Repeatability was checked by emptying the particles out of the cavity, refilling and re-testing. Results for stiffness and loss factor are presented in Figures 9 and 10 respectively. Note that the mass of particles was slightly lower when the cavity was refilled because it took fewer particles to complete the 3 layers.

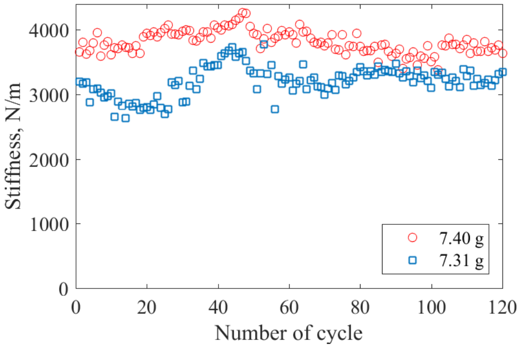

Figure 9: Repeatability of three layers of TMW particles: stiffness

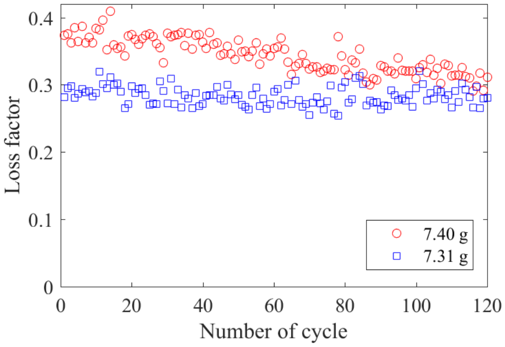

Figure 10: Repeatability of three layers of TMW particles: damping

The figures show that properties do still vary somewhat from cycle to cycle and from one fill to another. However, as expected, the magnitude of this variation is much less than was observed for individual particles. It is also noticeable that the gradual increase in stiffness with cycle number that was observed for the single particle does not occur. The most probable reason for this is that individual particles in the collection were subjected to smaller deformations and therefore individual wires underwent much less plastic deformation: for reference, the three-layer bed of particles was subjected to dynamic deformation amplitudes of 0.025 mm while the single particle test amplitude was 0.05 mm. Additionally, the loose structure meant that adjacent particles tended to penetrate each other rather than deform within their own original space, resulting in an even lower likelihood of exceeding plastic load limits in individual wires.

Interlocking of this kind was evident when TMD cavity was emptied and the particles were observed to have formed loosely agglomerated clumps. Overall, the improved reproducibility and stability of properties indicate that a collection of particles might be suitable for a practical device.

The nonlinear nature of the load-deflection behaviour was investigated by repeating testing at six different static compressions - 0.5 mm, 0.9 mm, 1.3 mm, 1.7 mm, 2.1 mm and 2.5 mm. A comparison of typical hysteresis loops at different loading levels is provided in Figure 11. Here the force is normalised to highlight the similarity in the shape of the loops. Also, the axes are shifted such that the origin for both force and displacement are set to values directly before dynamic testing was conducted, that is, static pre-compressive loads are ignored.

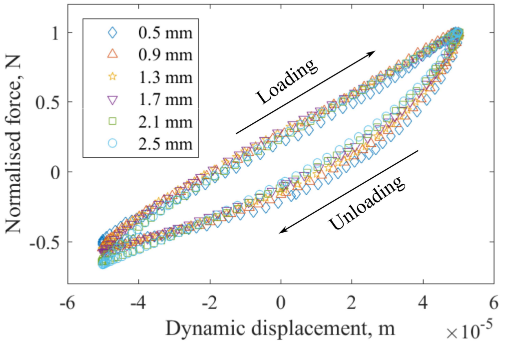

Figure 11: Normalised hysteresis loop for three layers of TMW particles

The actual values for stiffness and loss factor are presented in Figure 12 and 13.

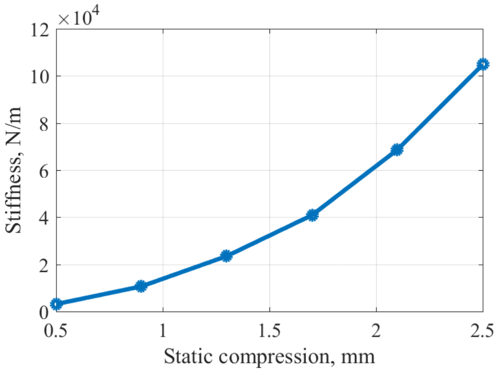

Figure 12: Nonlinear stiffness of three layers of TMW particles subject to different static compressions

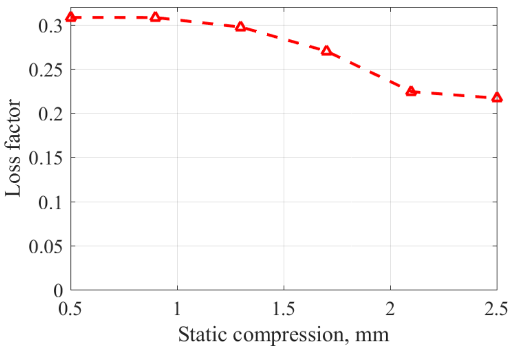

Figure 13: Nonlinear damping of three layers of TMW particles subject to different static compressions

It can be seen that stiffness increases with static compression by a factor of 30 over the range 0.5 to 2.5 mm while the loss factor does not change dramatically, dropping gradually from 0.3 towards 0.2.

These results show that the TMW particles are much more suitable to form a TMD when they are considered as a collection rather than as individual particles. The stiffness is easily adjusted through compression equivalent to bulk strains of up to 20% while the damping changes only slightly.

5. Feasibility of Tuned Mass Damper using TMW particles

TMW particles have been shown to be particularly effective when filling a cavity in a hollow structure if standing waves are generated within the particle medium [17] as this motion instigates significant deformation of the particles. Because of the low density of the particle medium, standing waves are only generated at relatively high frequencies for most cavity geometries. In this work, the onset of standing waves was reduced to lower frequencies by introducing within the medium, a high density element in the form of a solid steel plate. The lowest frequency standing waves involve significant motion of this plate within the restraints provided by the particle medium and the cavity walls.

A sketch of the damper used for this study is presented in Figure 14 along with the important dimensions for the casing and cap. The damper was designed to operate in the axial direction at frequencies where standing waves within the particle medium involved significant axial motion.

The threaded cap allowed the cavity depth to be set at any value between 0 and 45 mm. In this way, the damper contents could be pre-compressed in a repeatable manner. Once the cavity depth was set, the position of the lid was maintained by an additional locking ring. The casing was made from PMMA to allow visual observation of its contents and the design ensured that the first casing resonance was high enough (> 1000 Hz) to avoid overlap with the expected operating range.

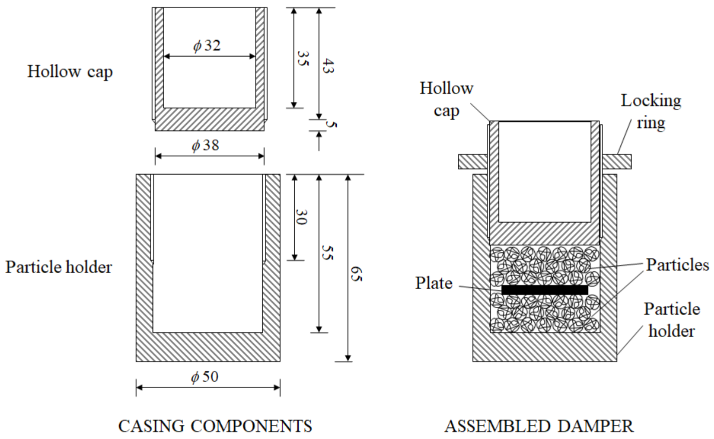

Figure 14: Sketch of damper casing (unit: mm)

Within the damper, particles were placed in a layer-by-layer manner. The steel plate, 30 mm in diameter and 2.5 mm in thickness, was placed centrally between particle layers in order to maximise its motion for the lowest frequency standing waves. It was assumed that the principal mode of interest would involve the steel plate translating axially within the cavity. However, slight misalignment or asymmetry could also excite modes involving rotation about an axis perpendicular to the damper axis.

A TMD exhibits at least one internal vibration mode that can be matched with the targeted resonance of the host structure. Measurement of the vibration response of a TMD itself therefore provides important information about its performance in controlling vibration. Consequently, in this study, the transmissibility between the steel plate and the casing was measured in order to characterise the TMD. A 10 mV/g miniature accelerometer was attached to the disc and a 6 mm hole drilled in its centre to accommodate the associated cable. The combined mass of the plate and accelerometer was 22 grams. Three layers of the particles were placed in each side of the plate with a total particle mass of 12.32 grams.

The damper was mounted directly onto the platform of a permanent magnet shaker with 480N peak sine force capacity. A second accelerometer was attached to the shaker table. A schematic diagram of the test configuration is shown in Figure 15.

The work presented in Section 4 showed that the properties of a collection of particles can change when subjected to vibration loading. The effects of this behaviour on the transmissibility of the TMD was investigated using stepped-sine testing where the magnitude of the shaker table acceleration was controlled to within 3% of the target value. At each excitation frequency, the response level evaluated using 10 averages and tracking filter of 50 Hz bandwidth was used to remove background noise from the signal. A typical set of results from

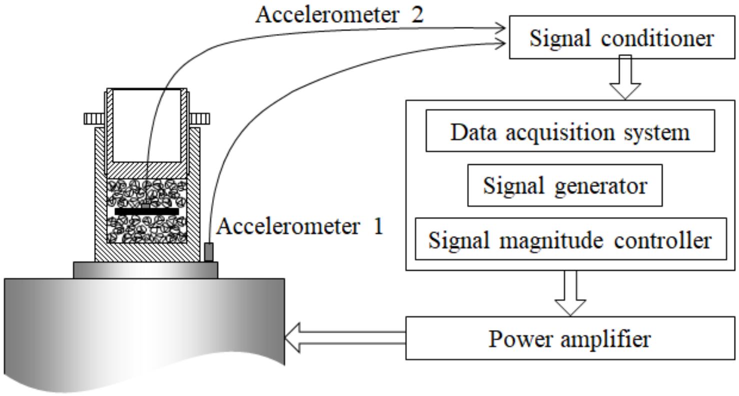

Figure 15: Sketch of set-up for tests for the damper by itself

this testing is shown in Figure 16.

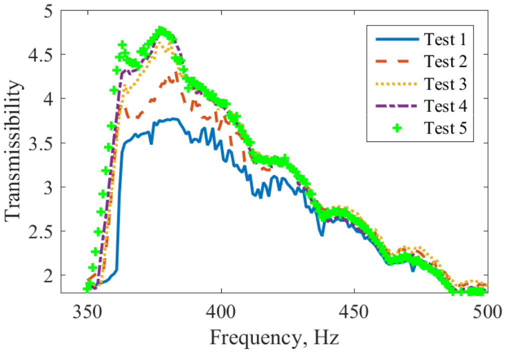

Figure 16: Repeatability of the transmissibility curves for selected configurations of TMW TMD (static compression of particles in each side is 0.45 mm)

In Figure 16, Test 1 to Test 5 refer to five repeated tests with same loading profiles. In this case, the dynamic acceleration amplitude was approximately 30 ms^{-2} and a pre-compression of 0.45 mm (i.e. approximately 1.5%) was applied to the particles. Note that the frequency range for each compression level was set, based on an initial low-amplitude, broadband response measurement which, for the sake of conciseness, are not shown here.

The figure shows that the transmissibility around first main resonance varies somewhat with repeated testing although these changes reduce with the number of repeated tests. This behaviour is in line with observations made in Section 4. Additionally, the curves are not smooth but contain fluctuations. The smaller point-to-point fluctuations are thought to be caused by local changes that take place within the particle medium during the test and the tolerance of the controller attempting to maintain constant vibration amplitude. During the test, the change in frequency after each step may alter the local deformation pattern enough to adjust the location of materials. The larger and more consistent fluctuations (near 360, 380, 400, 425, 450 and 475 Hz) are thought to be caused by standing waves within the particle medium. Similar behaviour has been observed elsewhere in vibrated granular systems [18].

Figure 16 also shows that significant levels of damping are present. The principle damping mechanism is thought to be inter-wire friction caused by deformation of the particles. The presence of the disc-shaped mass, results in much higher levels of deformation in the particles than when it is not present, which results in a significant increase in damping. A comparison of the approximate damping levels with and without the mass is given in Table 3. Note that the damping level in Table 3 was estimated from the transmissibility data shown in Figure 16 using a circle-fitting procedure on the Nyquist plot. This ignored the small fluctuations seen in the response curve.

Item	Fraction of critical damping
Without proof mass [13]	0.0075
With proof mass	0.2035

Table 3: Effect of the proof mass on damping of TMW particles

In summary, this section demonstrates that TMW paricles can construct a damped oscillator with reasonably repeatable properties.

6. Evaluation of adjustable tuning capability of TMW TMDs

The adjustability of the new TMD was evaluated using both random and sinusoidal excitation using the same test setup as reported in Section 4. Testing was carried out with different pre-compression levels (up to 9%) applied to the particles in the damper cavity. Note that the quoted compression levels should be treated with some caution, particularly for the low compression cases, because the irregularity of the particles made the zero compression condition hard to define precisely.

For the random test, the input signal was passed through an analogue filter, set to pass frequencies in the range 10 to 1000 Hz, before reaching the shaker amplifier. This was done in order to protect the equipment by eliminating large-displacement motion at low frequencies. Transmissibility curves, showing the motion of the disc-shaped with reference to the casing, are shown in Figure 17. It can be seen that increased compression can raise the resonance frequency considerably.

Close observation of Figure 17 reveals that there is a minor resonance peak at a slightly lower frequency than the main one. An explanation for this lies in the fact that a configuration such as this one (i.e. a rigid plate held between two flexible elements) has several low-frequency modes that relate to the translation and rotation of the rigid plate [1]. As the accelerometer is located near the

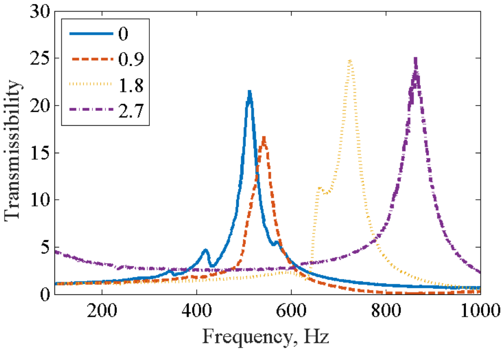

Figure 17: Effect of static compressions when subjected to different static compressions (RMS base accelerations are in a range from 0.17 to 0.51 ms^{-2})

centre of the disc, the modes associated with rocking motions would give a lower amplitude response than those associated with translation.

Stepped-sine tests of the same kind as described in Section 5 were next performed on the damper. The results for a base acceleration of 30 ms^{-2} are presented in Figure 18.

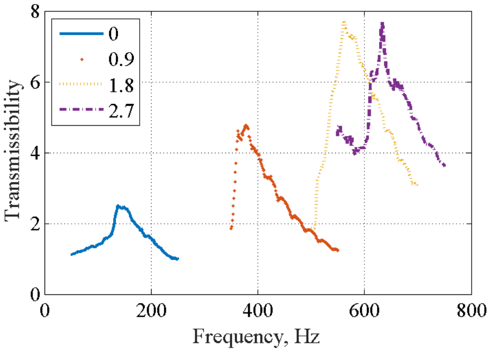

Figure 18: Effect of static compressions: stepped sinusoidal base excitations

The excitation levels in this test were significantly higher than those in the random test and as a result greater deformation was imparted to the particles. This caused the resonances to move lower frequencies and show increased damping levels. These are summarised in Table 4.

Since the TMW particles are sensitive to imposed deformation, the effect of dynamic amplitude on the damper was investigated. A static compression of 0.9 mm was applied to the particles and stepped sine testing was repeated at different excitation levels. Results are presented in Table 5 where it can be seen that increased dynamic amplitude causes the resonance peak to shift towards lower frequencies.

	Static compression - whole TMD, mm			
	0	0.9	1.8	2.7
Resonance frequency, Hz	142	371	565	634
Stiffness, N/mm	17.6	120	278	349
Average fraction of critical damping	0.19	0.09	0.06	0.07

Table 4: Static compression-dependent dynamic characteristics (a) stiffness (b) damping

Dynamic properties at each different excitation level (expressed as an estimated deformation magnitude) are summarised in Table 5. It can be seen that damping stops changing significantly when the amplitude is higher than 6 μm whereas stiffness continues to reduce with increasing amplitude.

	peak-to-peak dynamic displacement, μm			
	2	6	10	14
Resonance frequency, Hz	433	340	296	283
Stiffness, N/mm	163	100	76	70
Average fraction of critical damping	0.11	0.19	0.18	0.19

Table 5: Dynamic characteristics of this damper subject to different dynamic amplitudes

This study therefore shows that while the resonance frequency of the TMD can be adjusted over a wide range using the pre-compression level, the results are also sensitive to vibration amplitude. This uncertainty must therefore be taken into consideration when selecting such a TMD for a practical application.

7. Case study

This section reports a test case where the same adjustable damper discussed in previous sections was used to damp the response of a host structure with more than one vibration mode.

The structure selected for this study was a 500 × 38 × 19 mm aluminium box-section beam that was clamped at both ends. Excitation was applied using a shaker attached 185 mm from one end while the damper was attached as a point 185 mm from the other end. This was the same structure used by the authors in previous work [1] when studying the performance of an elastomeric damper. A sketch of the set-up is provided in Figure 19.

The TMW damper used in this work was pre-conditioned to minimise the drift in properties before it was fixed to the structure. This was achieved by exposing the damper to five repeated stepped sine tests at an amplitude of approximately 30 ms-2 over the frequency range 350 to 500 Hz. The total time that the damper was exposed to this vibration was approximately 5 minutes.

An initial test was carried out using band-limited random excitation over the range 0 - 1000 Hz which encompassed the first two flexural modes of the beam. Results showing the driving point response of the structure before the damper

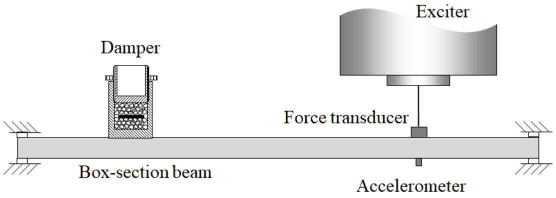

Figure 19: A sketch of test set-up: box beam with damper

was attached and with the damper set at two different compression levels are presented in Figure 20.

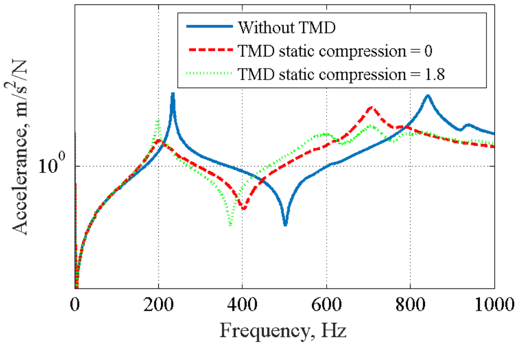

Figure 20: Effect of the adjustable TMD using TMW particles subject to different static compressions

It can be seen that the presence of the damper reduced vibration levels for both modes. The zero-compression condition had greatest effect on the lower mode around 210 Hz while the 1.8 mm compression condition was more effective for the higher mode. This provides clear evidence that the TMD can be adjusted to target different modes of a structure.

The performance of this novel TMD is next compared with a tuneable TMD consisting of a disc-shaped mass and elastomeric O-rings studied previously [1]. In terms of adjustability, the TMW particle damper is more sensitive to static compression than the O-ring damper, allowing a greater range to be addressed. Also, because the TMW layers are generally thicker than O-rings, set values are easier to achieve in practice. Comparative testing was carried out using amplitude-controlled, stepped sine testing. The FRFs of the beam are shown in Figures 21 and 22.

It can be seen that that the performance of the new adjustable TMD is similar to that of the elastomeric O-ring TMD in terms of reducing the peak vibration levels. This is highly satisfactory as the overall mass of the TMW damper is around a quarter of the mass of the O-ring damper (see Table 6)

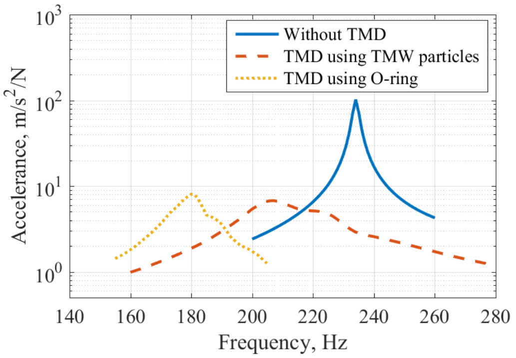

Figure 21: Effect of adjustable TMD on the rubber-ended beam: 1st mode (dynamic acceleration is 30 ms^{-2})

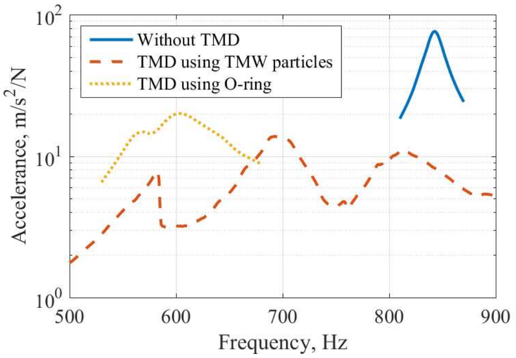

Figure 22: Effect of adjustable TMD on the rubber-ended beam: 2nd mode (dynamic acceleration is 30 ms^{-2})

yet, because its active elements are made from metal, it is suitable for extreme environments.

	O-rings	TMW particles
Mass of the TMD	320g [1]	78g

Table 6: Mass of the TMD

It is interesting to observe that addition of the TMW damper to the host structure changes the higher frequency resonance from a single peak to several signicantly lower ones. Classical TMD theory, involving the addition of a single-mode resonator, indicates that a single peak is split into two by the addition of a TMD. In this case, the presence of more than two peaks is explained by the fact that the TMW damper itself has at least two internal vibration modes that are close to the frequency of the host structure resonance. One of these internal modes involves the steel plate moving axially within the cavity while the other involves its rotation about an axis perpendicular to the damper axis [1]. Note that damper-only tests carried out earlier involved excitation in line with the damper axis and therefore will have primarily activated the axial mode. In this case, where the damper is attached to a beam, it is subjected to linear and rotational motion, depending on attachment location, as the beam undergoes flexural deformations. This combined linear-rotational motion applied to the damper activates both internal resonances discussed, resulting the multiplicity of peaks.

8. Conclusion

This paper describes a feasibility study into the use of Tangled Metal Wire particles as the stiffness and damping elements of a tuneable damper. TMW particles are attractive as they can provide consistent performance in extreme temperature environments.

The work has shown that while repeatability in the dynamic properties cannot be achieved for individual particles, the stiffness and damping of a collection of particles can be, to a large extent, stabilised after exposure to vibration.. These properties still remain sensitive to static and dynamic strains.

A tuned mass damper (TMD) was constructed in the form a cylindrical container within which the movement of disc-shaped mass is restrained by the presence of TMW particles. Adjustment of this device was achieved by altering the size of the cavity and hence the compression of the TMW particles. A number of vibration tests were carried out to show how the resonant behaviour was affected by compression level and also by vibration amplitude.

The new TMW particle TMD was demonstrated in a test case where it was attached to a host structure. It was shown that this damper could be adjusted to target particular modes of the host structure, although significant reductions were achieved without the need for fine-tuning. This was thought to be due to the damper having several internal resonances close to each other in frequency. The new damper was also compared with an equivalent TMD constructed from polymeric O-rings. The new damper was found to be significantly more weight-efficient than the more traditional one.

The fragmented and inhomogeneous nature of the particle medium results in some variability in performance and it is likely that a slight drift in properties will occur after prolonged use. However, the presence of multiple internal resonances within the damper makes it relatively insensitive to detuning. Additionally, as the range available for tuning is much broader than the potential property change, re-adjustment to achieve optimal performance is possible for critical applications.

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