DEVELOPMENT AND TESTING OF A TUNEABLE DAMPED SPRING SYSTEM FOR TREADMILL VIBRATION ISOLATION

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Abstract

Effective isolation of vibration generated by treadmill usage is a challenge due to the frequencies at which footfall typically occurs. Vibration theory suggests that an effective isolation system should have a fundamental frequency significantly lower than that of the excitation; however in practice this approach would require springs of very high static deflection, resulting in a tall, heavy and potentially unstable running platform. One solution is to use an isolation system with a fundamental frequency above the footfall frequency, but below the fundamental frequency of the structural floor. In this scenario, the isolators will reduce vibration transmitted at and above the fundamental frequency of the structural floor, but may amplify vibration at lower frequencies. Introducing damping to the isolation system can assist in moderating this amplification; however, too much damping may compromise isolation efficiency at higher frequencies. In a particular case where a treadmill platform was installed on a gym floor slab with a fundamental frequency of 11 Hz, computer modelling indicated that a damping ratio of approximately 0.2 would be optimal. To test this result, a damped spring system was developed by Embelton, in which the amount of damping could be varied. This paper presents an overview of the computer modelling and subsequent testing of the damped spring system, with reference to the above case study.

1. Introduction

Commercial and private gymnasiums are commonly located in buildings where there are apartments, offices, or other uses which may be sensitive to noise and vibration from gym activities. When adequate vibration isolation has not been provided, structure-borne noise and vibration from treadmills located above grade is often observed as a source of annoyance to other occupied spaces.

A vibration isolated treadmill must not only provide vibration isolation across a wide range of driving frequencies extending below 3 Hz, but it must also be sufficiently stable to maintain useability under the impulsive loads subjected by footfall. A stable running platform provides the runner with a firm base, transferring most of the energy from each stride to forward motion in relation to the conveyor belt. If the platform is too mobile (i.e. it bounces, rocks or moves in some other manner in response to load), it may noticeably sap energy from each stride, ruining the ‘feel’ of the treadmill for the user. It may also affect the balance of the user, making running or walking more difficult, and it can be visually perceived as unstable.

In many cases, attenuation of vibration at audio frequencies is sufficient to control structure-borne noise and vibration issues from treadmills. In these instances, satisfactory isolation of treadmills can be achieved using low deflection moulded rubber isolators installed beneath a plinth on which the treadmill is mounted. However, in some cases attenuation of audio frequencies alone is not sufficient if the structure is of low stiffness and resultantly conducive to the transmission of vibration at lower frequencies. In these cases isolation is required at frequencies below those at which rubber mounts are typically effective and the use of an isolator designed to provide more deflection is necessary.

To provide more deflection the isolators must be less stiff, and when in the form of steel springs typically used for high deflection isolators, there is none of the inherent damping that is present in moulded rubber isolators to assist in stabilising the treadmill. As such, a treadmill platform mounted on high deflection springs has the potential to bounce, rock, or move more than is desirable in response to the impulsive loading associated with footfall on the treadmill. This would be exacerbated by resonance effects if the footfall frequency is close to the fundamental frequency of the system. Introducing mass and damping to a spring isolation system can however assist in controlling this movement.

In response to a project where rubber isolators were determined not to be sufficient, Embelton commenced design of a tuneable damped spring isolator specifically for treadmills. This paper describes the particular scenario for which the design was developed, outlines the key design considerations and theory, and presents an overview of the modelling, development and testing process.

2. Case Study Description

The project which triggered this investigation involved a commercial gym located on the ground and first floor level of a residential apartment building. The treadmills in the gym were located on a nominally 10 metre by 3 metre vibration isolated plinth on the first floor level. The plinth was mounted on low deflection moulded rubber isolators, and the structural concrete floor has a fundamental frequency of approximately 11 Hz.

Initially, the plinth held three treadmills, two spin bikes, and two adaptive motion trainers. In this configuration, satisfactory attenuation of structure-borne noise and vibration was achieved. However, when a further three treadmills were later added to the plinth, an apartment located two floors higher up began to complain about vibration.

The higher forces imparted to the structure due to the greater number of treadmills operating on the platform, in combination with a slight change in the fundamental frequency of the plinth due to the added mass, were resulting in the structure being excited sufficiently for vibration from the treadmills to become noticeable at certain locations in the building.

Investigation into the issues by an acoustic consultant identified that the dominant frequencies of vibration in the affected apartment were between 20 and 25 Hz. An analysis conducted by the acoustic consultant suggested that isolators with a fundamental frequency between 4.5 Hz and 5 Hz would be effective in controlling the vibration observed in the complainant's apartment.

To achieve this fundamental frequency, an isolator with a static deflection of approximately 10 to 12 mm was determined to be required. The use of an isolator with this level of static deflection would require relatively soft springs, meaning the plinth could potentially move around excessively under footfall loads if not designed correctly. To make such a system useable, Embelton determined that a degree of damping would need to be added to the system. The system was therefore modelled using finite element analysis (FEA) to determine optimum level of damping.

3. Vibration Theory and Modelling

Isolating a source of vibration from a connected structure requires knowledge of the type of driving force, the stiffness and damping of the isolation material, and the mass of the components to be isolated. Where there is a known forcing frequency, isolation performance is often described in terms of transmissibility i.e. the ratio of the magnitude of force transmitted through the connection to the structure to force applied by the vibration source [1]. If the vibration source is modelled as a spring-mass-damper system connected to a fixed base, the transmissibility ratio can be derived mathematically, giving the results presented in Figure 1.

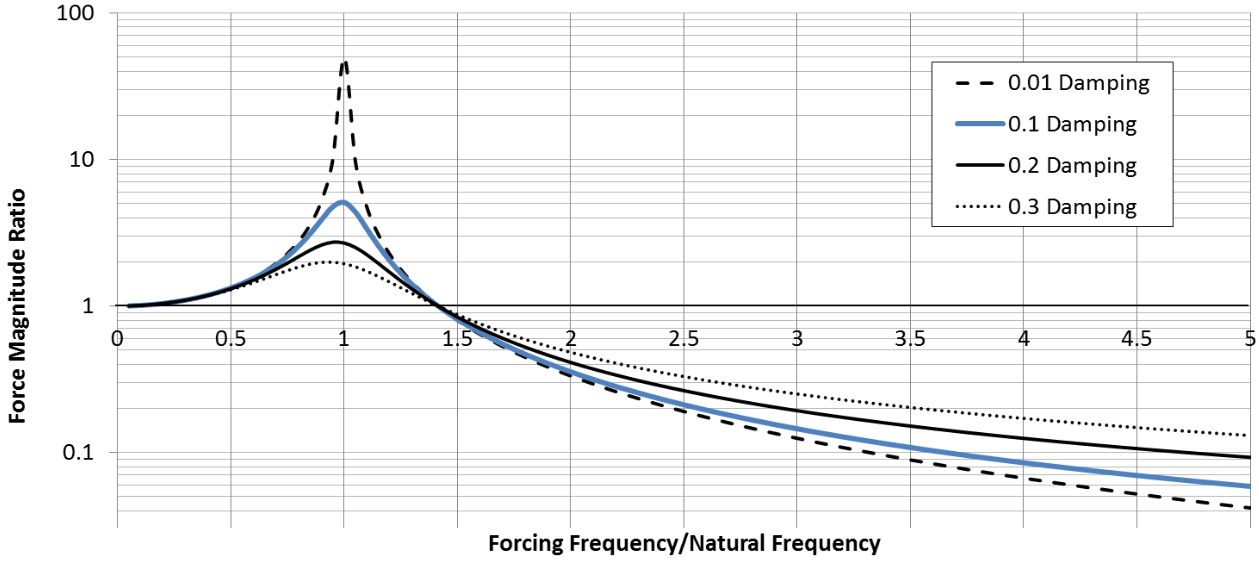


Figure 1. Force transmissibility ratios of spring-mass-damper systems

In Figure 1, it is shown that attenuation occurs for ratios of forcing frequency to fundamental frequency above the square root of two. At a frequency ratio of one, resonance occurs. Below a frequency ratio of one, amplification reduces but attenuation is never achieved.

Table 1 presents the typical footfall frequencies associated with walking and running activities.

Table 1. Typical footfall frequencies associated with walking and running [2]

	Pacing Frequency f (Hz)	Forward Speed V (m/s)	Stride Length L (m)	Vertical fundamental frequency F_{vert} (Hz)	Horizontal fundamental frequency F_{lat} (Hz)
Slow walk	1.7	1.1	0.60	1.7	0.85
Normal walk	2.0	1.5	0.75	2.0	1.0
Fast walk	2.3	2.2	1.00	2.3	1.15
Slow running (jogging)	2.5	3.3	1.3	2.5	1.25
Fast running (sprinting)	>3.2	5.5	1.75	>3.2	>1.6

The required static deflection for a helical compression spring to provide isolation from jogging frequencies is greater than 80 mm. If such an isolator was used in this application, its height and the amount of mass required in the system to keep the amplitude of vibration low enough to be usable would result in economical and likely structural issues.

Thus far, according to theory it would appear that achieving effective isolation of a treadmill from a structure is not a feasible task. However, Cross' study [3] of the response of a force plate subject to the force of a runner demonstrates that the input approximates a series of half-sine impacts, rather than a constant sinusoidal excitation, as shown in Figure 2. A half sine profile produces an infinite number of higher order harmonics compared with a pure sinusoidal excitation.

For an isolator with very low inherent damping such as a spring, oscillation following the initial impact will take a substantial period of time to settle. Successive impacts before the oscillation has settled result in amplification of the response as shown in Figure 3a.

However, if a level of damping is introduced such that the response amplitude reduces sufficiently before the next impact, the cushioning properties of an isolator would decrease the rate of change of momentum and hence the force transferred to the structure, reducing the overall acceleration (Figure 3b).

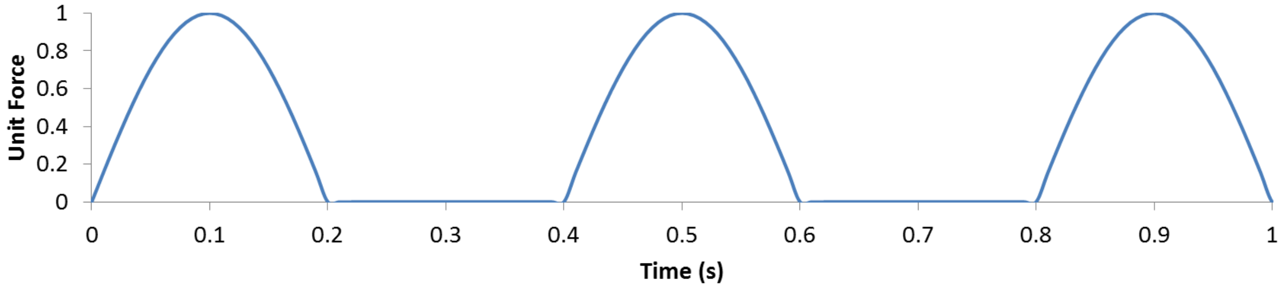
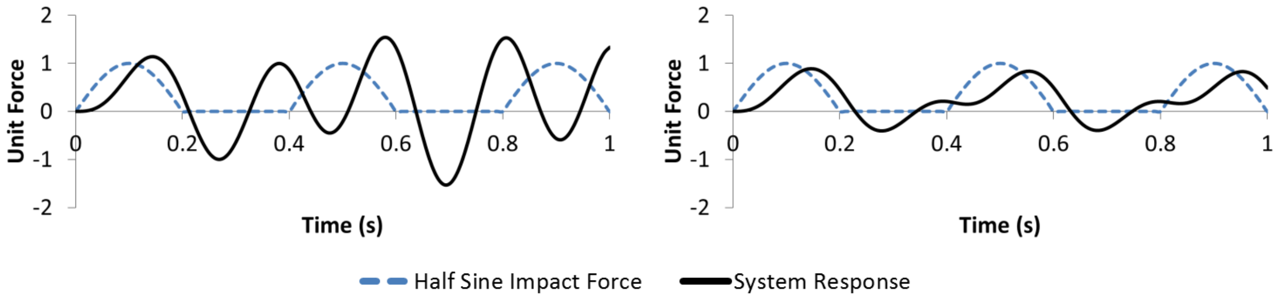


Figure 2. Approximated half sine force profile of footfall



(a) (b)

Figure 3. Approximated half sine force profile of footfall with superimposed plinth response for (a) damping ratio of 0.01 and (b) damping ratio of 0.2

Fundamental frequency of an isolation system is still very important, and the ideal frequency is dictated by several conditions: a lower fundamental frequency improves the cushioning properties by slowing the change in momentum of the system from impact, but it must be high enough to avoid resonance from the repeated impacts. Another drawback is that with the damping kept constant, a lower fundamental frequency increases the period and the settling time to rest.

FEA modelling of the response of a two degree-of-freedom system subject to a half sine series input was conducted, varying the damping and fundamental frequency of the isolation system. The system modelled was a 1.2 metre by 3.2 metre platform isolated with eight linear stiffness isolators placed centrally on an 11 Hz structural concrete slab. The magnitude of the input was taken from [3] which yielded 2.0 kN for an 80 kg runner at jogging speeds. A linear transient dynamic analysis was run for a period of 4 seconds to allow steady state values to be reached. Both jogging and running frequencies from Table 1 were simulated.

Isolation system fundamental frequencies ranging from 4.0 Hz to 5.5 Hz were modelled. The lower end of this range was selected to be sufficiently above the highest expected footfall frequency (~3.2 Hz) to avoid footfall forces driving the plinth into resonance. The upper end of this range was selected so that the forces transmitted from the plinth to the slab would be attenuated for slab fundamental frequencies down to approximately 8 Hz – a common fundamental frequency for floor slabs in modern multistorey dwellings.

In the modelling, Rayleigh damping ratios were varied from 0.05 to a maximum 0.20. With reference to Figure 1, transmissibility of higher frequency noise increases unfavourably at higher damping ratios. Structural damping of the slab was 0.05.

Vibration isolation performance was measured against a system with no isolators i.e. treating the system as a treadmill rigidly fixed to the 11 Hz slab. The results are displayed in Table 2, with all values shown as relative to the steady state peak of the un-isolated system. The interest in this paper was to reduce the continuous vibration levels, so transient peaks from start-up were not analysed.

For an input of 2.5 Hz (jogging), the steady state acceleration levels showed significant improvement at 4.0 and 4.5 Hz isolation system fundamental frequency with further incremental improvements as the damping ratio was increased. The 4.0 Hz isolator showed a superior response to the 4.5 Hz isolator at lower levels of damping, which would indicate that settling time outside of resonance is not as important as the cushioning properties of the mount. The 5.5 Hz system amplified the acceleration when the damping ratio was 0.06, with improvement only achieved at higher damping ratios.

When the input frequency was increased to 3.2 Hz to simulate fast running, acceleration performance was less favourable for the lower frequency isolators. Notably, the 4.0 Hz system showed very minimal improvement over the 4.5 Hz acceleration until the damping reached 0.2, suggesting that the proximity of the input frequency was influencing performance.

Table 2. Normalised FEA results of isolated treadmill platform with probe on structural slab. Acceleration values are relative to results modelled with no isolation from the 11 Hz slab.

Plinth Fundamental Frequency	Damping ratio	2.5 Hz Footfall Frequency		3.2 Hz Footfall Frequency	
		Relative Steady State Acceleration	Acceleration Attenuation (dB)	Relative Steady State Acceleration	Acceleration Attenuation (dB)
11Hz (No isolation)	-	1.00	-	1.00	-
4.0Hz	0.06	0.40	7.9	0.68	3.3
	0.1	0.38	8.4	0.58	4.7
	0.15	0.36	8.8	0.50	6.0
	0.2	0.33	9.5	0.43	7.3
4.5Hz	0.06	0.67	3.5	0.65	3.7
	0.1	0.61	4.3	0.60	4.4
	0.15	0.51	5.9	0.54	5.4
	0.2	0.44	7.1	0.49	6.2
5.5 Hz	0.06	1.20	-1.6	1.04	-0.3
	0.1	0.79	2.1	0.93	0.6
	0.15	0.67	3.4	0.81	1.8
	0.2	0.63	4.0	0.78	2.1

The modelling results were promising in terms of the numbers and the correlation with theory. To avoid any issues that could occur with higher running frequencies than those simulated if a 4.0 Hz isolator were to be used, it was decided to proceed with the design of a prototype isolator, targeting 4.5 Hz to 5 Hz fundamental frequency and a damping ratio of 0.15 to 0.20.

4. Practical Design Considerations

In addition to the technical design constraints concerning vibration isolation and stability, there were a number of practical factors that needed to be considered in the development of a solution, including that:

- The solution had to be easily installed;
- Cost had to be minimised;
- The solution had to perform for a minimum of 10 years in a commercial gym environment;
- The solution would ideally have adjustable damping and spring rate so that it could be tuned and/or applied to other situations with differing requirements.

5. Spring Element Selection

There are various types of vibration isolators that could economically be used as the spring element under an isolated treadmill plinth. These include:

- Vibration isolating rubber pads;

- Moulded rubber mounts;

- Steel spring mounts;

Rubber pads and moulded mounts provide a low cost option for isolation. They offer inherent damping and low deflection under load, which aids stability of the platform.

Moulded rubber mounts are commonly used under treadmill plinths, and are effective in isolating higher frequencies, above about 20 to 25 Hz. However, in some scenarios (as in the case study discussed in this paper) vibration at lower frequencies is problematic and must also be attenuated. Rubber mounts are therefore unsuitable in these scenarios.

Steel springs offer higher deflections than rubber mounts, and are therefore better for isolating lower frequencies and reducing force transmission from footfall. However, the higher deflection of the spring mounts comes at the expense of stability, as the spring is effectively 'softer' resulting in more movement of the plinth, particularly if the fundamental frequency of the isolation system is close to or above the footfall frequency. Damping of the spring can alleviate the stability issue, but, as shown by the modelling, a fairly high level of damping is required to be effective.

Given the above factors, damped steel spring isolators are considered to be the best option for vibration isolation of treadmills where low frequency vibration is an issue.

6. Damping

Damping works by dissipating the kinetic energy of the moving plinth as heat. Practical damping methods for a spring-isolated treadmill plinth include coulomb (friction) dampers and viscous dampers. A coulomb damper utilises the friction between two sliding surfaces to convert kinetic energy to heat. A viscous damper works by forcing a liquid, usually oil, through a small orifice.

Viscous dampers provide a wider range of adjustability and operate more smoothly than coulomb dampers. For small input forces, coulomb dampers can stick and prevent the isolator from moving as a result of the static coefficient of friction being higher than the dynamic coefficient of friction. However, for applications in gym floors and gym equipment bases, the input forces are generally high in proportion to the static friction force, and coulomb dampers offer a number of advantages over viscous dampers. In particular:

- The cost of a coulomb damper is considerably lower due to fewer parts and less precise manufacturing tolerances.

- Coulomb dampers are typically shorter in length than equivalent off-the-shelf viscous dampers. A shorter length allows a lower build-up height for the floor or base. Build-up height is often an important consideration for floors or gym equipment bases as the National Construction Code prescribes specific height requirements for steps, ceilings and door frames measured from the finished floor level.

- Viscous dampers require sealing to contain the damping fluid. Over time, there is a risk that the seals may deteriorate and damping fluid may leak, resulting in loss of damping and possible damage to other surfaces from leaked fluid. Whilst a coulomb damper will also wear and lose some damping capacity, it has no fluid to leak.

Given the above, coloumb dampers provide a more attractive option for damping of the isolated treadmill plinth than viscous dampers.

7. Damped Spring Concept Design

Embelton's existing product range includes a damped spring isolator with a simple coulomb damper. The existing product is called the NXS gym floor spring. The NXS spring uses the friction between a precisely sized rubber element and the inner surface of the spring coil to provide coulomb damping. However, the NXS spring was developed for weights areas, rather than treadmill isolation. In weights areas the damping requirements are lower, since the floor is subject to discrete impacts rather than a continuous driving force. The NXS spring achieves a damping ratio of 0.06, which is not sufficient to provide a highly stable base for treadmills.

To create an isolator suitable for treadmill bases, it was decided to utilise Embelton's existing NXS spring technology, but increase damping and provide adjustability by redesigning the coulomb damper. A concept design was developed which achieved the above requirements, and prototype isolators were manufactured to test the concept.

8. Vibration Performance Testing

8.1 Damping and Fundamental Frequency Test

The first set of vibration performance tests that were carried out were to check the fundamental frequency of the prototype mounts and the range of damping ratios that were able to be achieved with the adjustable coulomb dampers.

In order to achieve the specified 4.5 to 5 Hz fundamental frequency, weights were added to the top of the prototype damped spring mounts until the spring deflected by nominally 12 mm under the load. An impulse force was then applied to the loaded spring and the acceleration was measured while the spring oscillated to rest. The fundamental frequency was checked using an FFT of the measured acceleration of the oscillating spring, and the damping ratio was obtained from the rate of decay of the acceleration.

Tests were conducted with various settings of the coulomb dampers. Each setting was defined by the number of turns applied to the damping adjusters, from the minimum damping setting. An undamped spring and an ordinary Embelton NXS damped spring of the same stiffness were also tested for comparison. Table 3 below presents the measured fundamental frequencies and damping ratios of each test.

Table 3. Measured fundamental frequencies and damping ratios

Test	Measured Fundamental Frequency (Hz)	Damping Ratio
Undamped spring	4.8	0.01
Embelton NXS spring	4.8	0.06
Prototype damped spring, minimum damping setting	4.8	0.06
Prototype damped spring, 1 turn on damping adjuster	4.8	0.07
Prototype damped spring, 2 turns on damping adjuster	4.8	0.11
Prototype damped spring, 3 turns on damping adjuster	4.8	0.14
Prototype damped spring, 3.5 turns on damping adjuster	4.8	0.16

It was found that a maximum damping ratio of 0.16 was the practical limit able to be provided by the prototype damped spring. Above a damping ratio of 0.16 the damper was found to bind due to static friction and not return properly to its original equilibrium position.

8.2 Vibration Attenuation Test

To quantify the attenuation of vibration achieved by prototype damped springs, the treadmill was installed on a mock plinth (nominally 1 metre wide by 2 metres long) which was mounted on the prototype damped springs. The plinth was installed on top of a concrete slab on grade, so as to minimise influence of the fundamental frequency of the slab on the measurements.

For the testing, the dampers were set to achieve a damping ratio of approximately 0.14, and the springs were loaded to achieve the specified 4.5 to 5 Hz fundamental frequency. The acceleration of the slab due to operation of the treadmill was measured at several points around the treadmill, at a distance of 0.5m from the treadmill. This procedure was then repeated with the treadmill installed directly onto the slab without the isolated plinth, to establish the baseline condition. For comparison, a treadmill plinth mounted on Embelton NR1 moulded rubber isolators was also tested. All testing was conducted using the same 65 kg person running at 12 km/h. This speed was chosen as a typical speed at which a treadmill would operate. At this speed, the footfall frequency of the test runner was approximately 2.7 Hz. Figure 4 below presents a comparison of the average slab acceleration measured in each test.

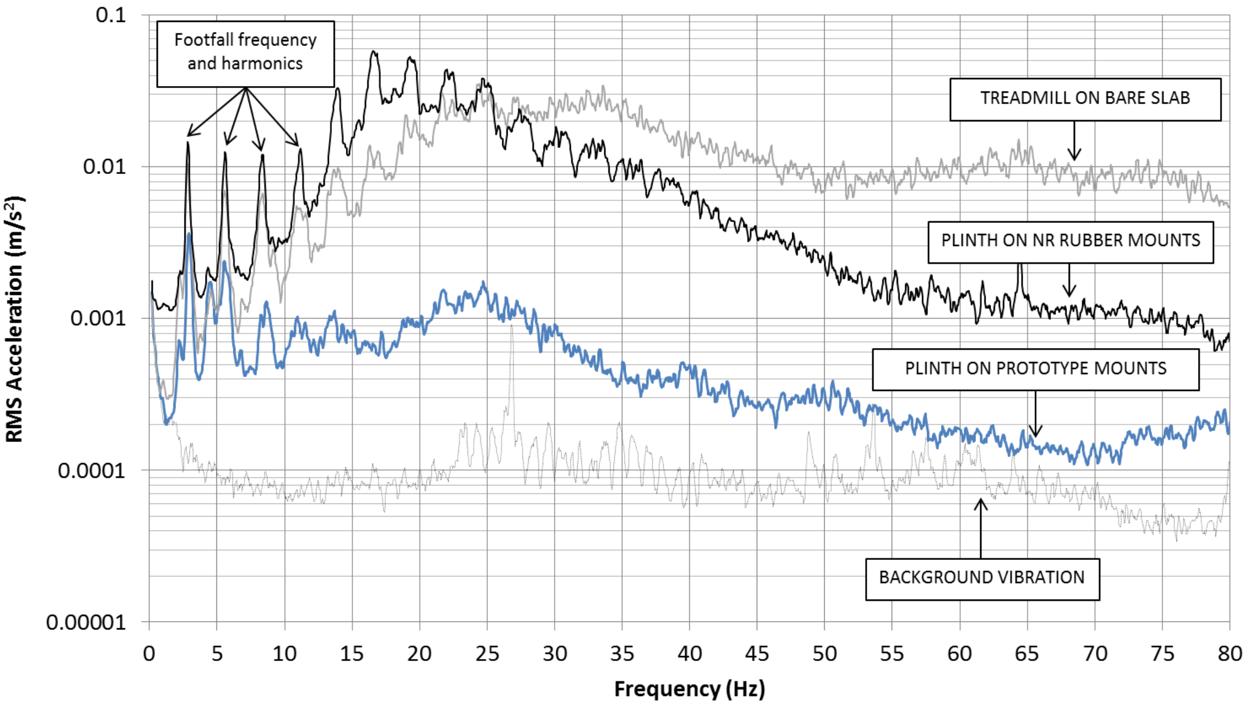


Figure 4. Average slab acceleration at 0.5m due to treadmill with 65 kg runner at 12 km/h

The results showed that the prototype damped spring consistently attenuated the treadmill vibration at frequencies above approximately 7 Hz. Below 7 Hz a reduction was achieved at some frequencies, most notably the footfall harmonics, but at other frequencies no reduction or slight amplification of the vibration occurred.

For comparison, the plinth mounted on the Embelton NR1 moulded rubber isolators was only lightly loaded for the test and had a resulting fundamental frequency of approximately 20 Hz. The NR1 plinth was only found to produce a consistent reduction in vibration above about 28 Hz. Below 28 Hz, the vibration was amplified, consistent with what would be expected from theoretical calculations, given the light loading and resulting fundamental frequency.

9. Acoustic Performance Testing

To determine the acoustic performance of the prototype damped spring system, the treadmill and plinth were installed on a suspended 150mm thick concrete slab (19 Hz fundamental frequency) on the first floor of a building. The L_{eq} Sound Pressure Levels due to operation of the treadmill were then measured in the room below. Each measurement was performed with the treadmill at a steady speed over a period of nominally 30 seconds. The measurements were repeated at three different locations in the middle of the receiving room and the results were arithmetically averaged. As for the vibration tests, the acoustic tests were repeated with the treadmill installed directly onto the slab without the isolated plinth, and using a plinth mounted on Embelton NR1 moulded rubber isolators for comparison.

Testing was again conducted using a 65 kg person running at 12 km/h, with a footfall frequency of approximately 2.7 Hz. Figure 5 below presents the measured L_{eq} Sound Pressure Levels.

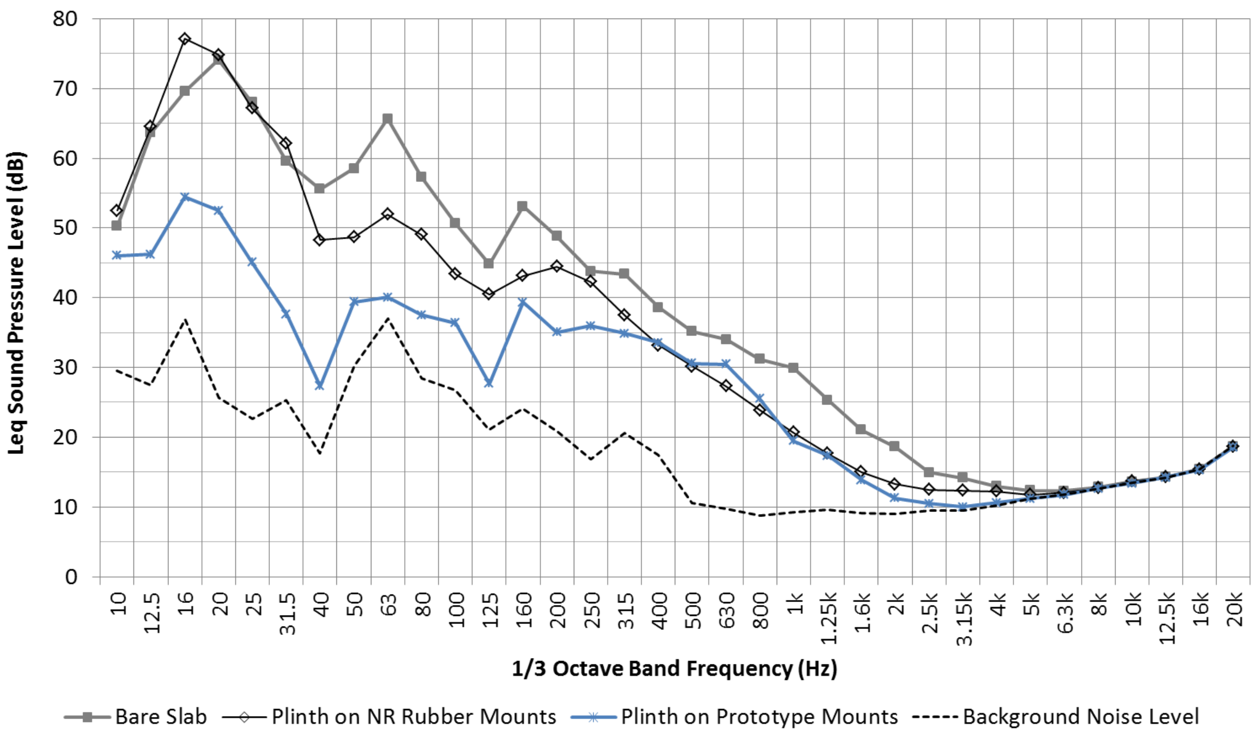


Figure 5. Measured L_{eq} sound pressure levels in room below with 65 kg runner at 12 km/h

The noise measurement results show that the prototype damped spring attenuated structure-borne noise from the treadmill across the frequency range from 10 Hz to 5 kHz. The largest reductions, up to 28 dB, occurred in the 20 to 80 Hz frequency range; however even as low as 10 Hz, a reduction of 4 dB was achieved.

In comparison, the moulded rubber isolators only provided attenuation of structure-borne noise at about 40 Hz and above. At frequencies below 40 Hz, slight amplification of the sound was generally observed. Both of these results are consistent with what was expected given the findings of the vibration attenuation test.

At some frequencies, particularly those above approximately 2 kHz, the noise levels due to the treadmill were too low to be measured without influence from background noise in the receiving room. The peak that can be seen in the spectrum for the bare slab at approximately 20 Hz is likely to be due to resonance effects associated with the 19 Hz fundamental frequency of the test floor slab. The peaks at approximately 63 Hz and 160 Hz and are thought to be due to strong room modes close to those frequencies in the receiving room (the receiving room dimensions were approximately 5.5 metres long x 5.0m wide x 3.2m high).

10. Useability Testing

The general stability and ‘useability’ of the plinth was assessed qualitatively based on the perception of onlookers and treadmill users.

When initial testing was conducted using a small test plinth of approximately the same footprint as an individual treadmill (1 metre by 2 metres), the spring mounts were found to result in an unacceptable amount of movement in the running platform. The small test plinth was less stable than a larger plinth would be due to its smaller footprint and lower mass relative to the forces imparted by individual runners. This was an unrealistic representation since a much larger plinth would be installed in most commercial gym scenarios. Outriggers were therefore added to the test plinth to increase its footprint by approximately a metre on each side. With the outriggers installed, a degree of movement was still detectable, but general useability was greatly improved. This provided confidence that when installed at the full scale required for the case study gym (10 metre by 3 metre plinth), the stability would be satisfactory.

11. Ongoing Work

At the time of writing, the tuneable damped spring system has not yet been installed in the gym for which the system was developed. It is intended that further testing will be undertaken once the system has been installed to verify in-situ performance.

Prior to verifying the performance in-situ, further work will need to be undertaken to establish the longevity of the damper. Further consideration is also being given to the design of the damper so that in-situ adjustment of the damper could be performed if necessary, to compensate for wear or allow for further tuning after installation.

12. Summary

A prototype tuneable damped spring vibration isolator for treadmills has been developed and tested. Conventional vibration theory suggests that a fundamental frequency of less than the footfall frequency would be required in order to provide good isolation of the treadmill without resonant amplification at low frequencies. To achieve fundamental frequencies less than the typical footfall frequency of a runner, high deflection springs would be required. The use of such springs beneath a treadmill would affect the useability of the treadmill due to the amount of movement that would occur in response to running loads. However, treating each foot impact as a discrete force impulse and introducing damping to the spring system allows an isolation system with a fundamental frequency higher than the footfall frequency to be used.

Laboratory testing of a prototype damped isolator showed that good isolation of structure-borne noise and vibration was achieved at frequencies above approximately 7 Hz. From approximately 10 Hz upwards, the acceleration of the test slab was more than halved, and the structure-borne noise levels were reduced by between 4 and 28 dB, compared with the case with no isolation.

Stability of the treadmill when installed on the isolators was found to be satisfactory provided that the isolated plinth had a larger footprint than the treadmill. In a typical commercial gym where multiple treadmills are mounted on the same plinth, it is expected that stability would be acceptable.

In-situ performance testing on a full scale treadmill plinth is yet to be conducted.

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