DESIGN OF A TUNEABLE DAMPED SPRING SYSTEM FOR GYM TREADMILL ISOLATION

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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.
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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 for 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 general vibration control applications, when seeking to control frequencies below 20Hz and higher than 7Hz, 25mm deflection steel springs are a cost effective solution. But such a spring suspension system would not offer the inherent damping desirable for stability of the treadmill that a system using moulded rubber isolators would provide. That is, a treadmill platform mounted on 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 assist in controlling this movement.

In response to a project where a rubber mount isolated plinth was causing complaints, Embelton studied possible design solutions based on a tuneable damped isolator specifically for treadmills. This paper describes the background to the scenario for which the design was developed, outlines the key design considerations and theory, and presents an overview of the modelling, development, testing process and analysis.

2. Case Study Description

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

From vibration data measured in the apartment it was identified that the dominant frequencies of vibration in the affected apartment were between 20 and 25 Hz.

3. Vibration Theory and Modelling

Isolation performance is often described in terms of transmissibility, beingthe ratio of the magnitude of force transmitted through 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 rigid base, the theoretical transmissibility ratio can be derived mathematically, giving the graph presented in Fig. 1.

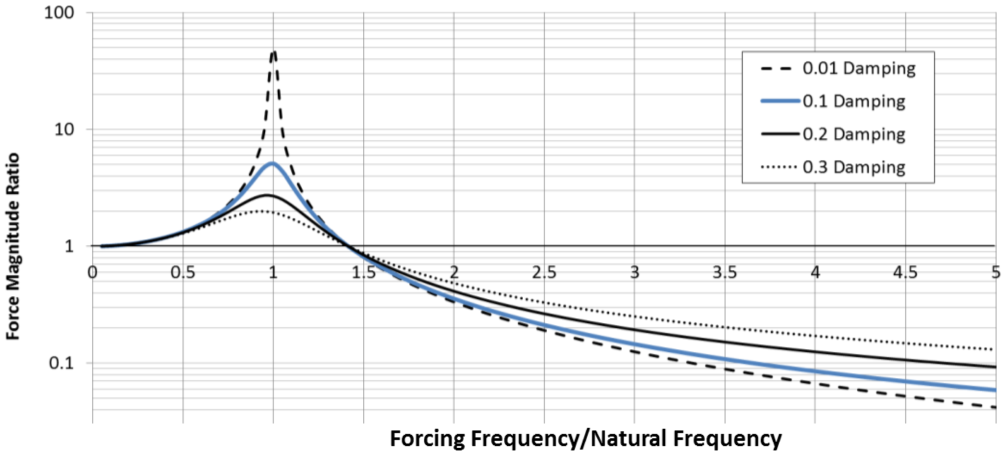


Figure 1: Force transmissibility ratios of spring-mass-damper systems

Typical footfall frequencies associated with walking and running vary from 1.7Hz for a slow walk to 2.5Hz for jogging and greater than 3.2Hz for sprinting [2].

From Fig. 1 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 likely result in adverse economical and possible structural issues.

The force amplitude profile over time from running foot impacts does not have the characteristic of a pure sinusoid. 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. From Fig. 2, a half sine profile produces an infinite number of higher order harmonics compared with a pure sinusoidal excitation. These higher order harmonics, which can align with the buildings structural modes to cause resonance, will be more effectively attenuated with a 5Hz isolator than with the original stiffer mount, with a trade-off loss of performance at frequencies 5Hz and below.

Additionally, 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 decayed sufficiently can result in amplification of the response as shown in Fig. 3a.

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 (Fig. 3b). The problem can then be treated in part as impact cushioning rather than isolation of a pure harmonic input. Refer Fig. 3.

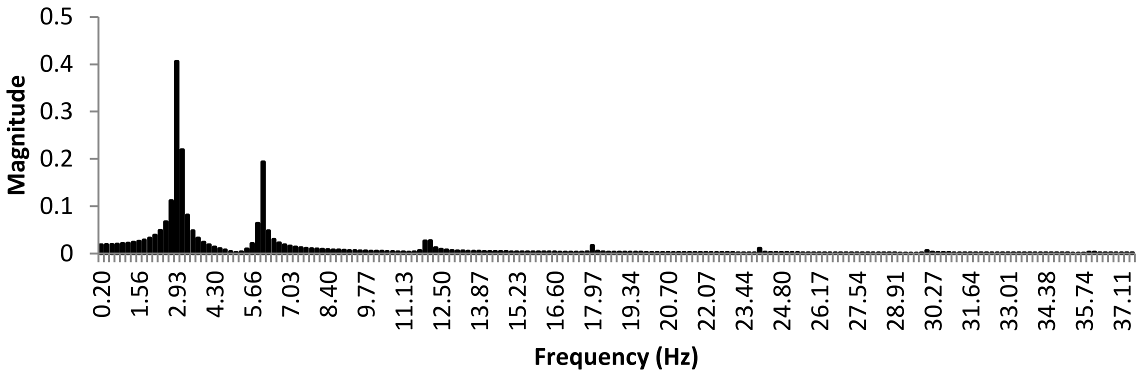
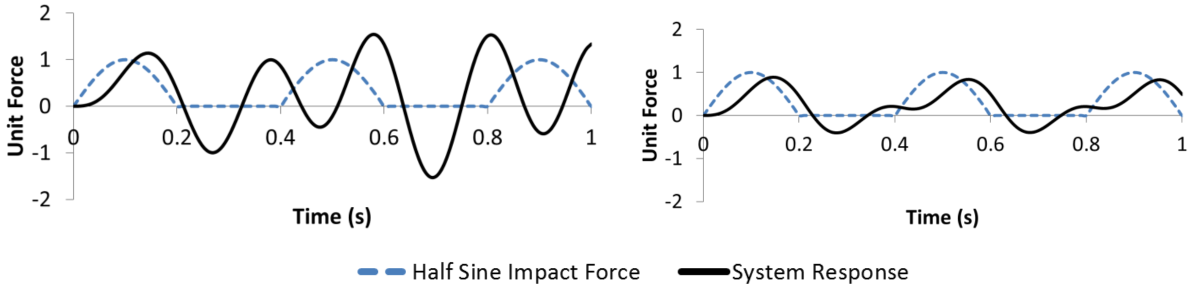


Figure 2: Fast Fourier Transform of 3Hz half sine input



(a) (b)

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

FEA modelling 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 2.0 kN representing an 80 kg runner at jogging speeds [3]. 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 were simulated [2].

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, isolator damping ratios were varied from 0.05 to a maximum 0.20. With reference to Fig. 1, transmissibility of higher frequency noise increases unfavourably at higher damping ratios. Structural damping of the slab was taken as 0.05, a typical upper limit for open plan offices to reflect the effect of the non-structural masses present in a typical gym environment [4].

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. Continuous vibration levels were the source of annoyance for the case study, so transient peaks from start-up were not analysed.

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

While the reductions of modelled vibration levels were not of a magnitude likely to resolve a severe annoyance, the modelling correlated with theory. It was decided to proceed with the design of a prototype isolator, targeting a 4.5 Hz to 5 Hz fundamental frequency and a damping ratio of 0.15 to 0.20 in order to avoid any issues that could occur with higher running frequencies than 3.2Hz.

4. Damped Spring Concept Design

Practical damping methods for a spring-isolated treadmill plinth include coulomb (friction) dampers and viscous dampers. Coulomb dampers offer a number of advantages over viscous dampers such as cost, shorter height and lack of any working fluid to potentially leak over time.

Embelton's existing product range includes an NXS damped spring isolator with a simple coulomb damper. 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 achieves a damping ratio of 0.06, which from Table 2 is not sufficient to provide attenuation.

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.

5. Vibration Performance Testing

5.1 Damping and Fundamental Frequency Test

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.

Tests were conducted with various settings of the coulomb dampers. 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
Embelton NXS spring	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

For damping ratios greater than 0.16, the damper was found to bind due to static friction and not return properly to its original equilibrium position.

5.2 Laboratory Vibration Attenuation Test

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. 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.

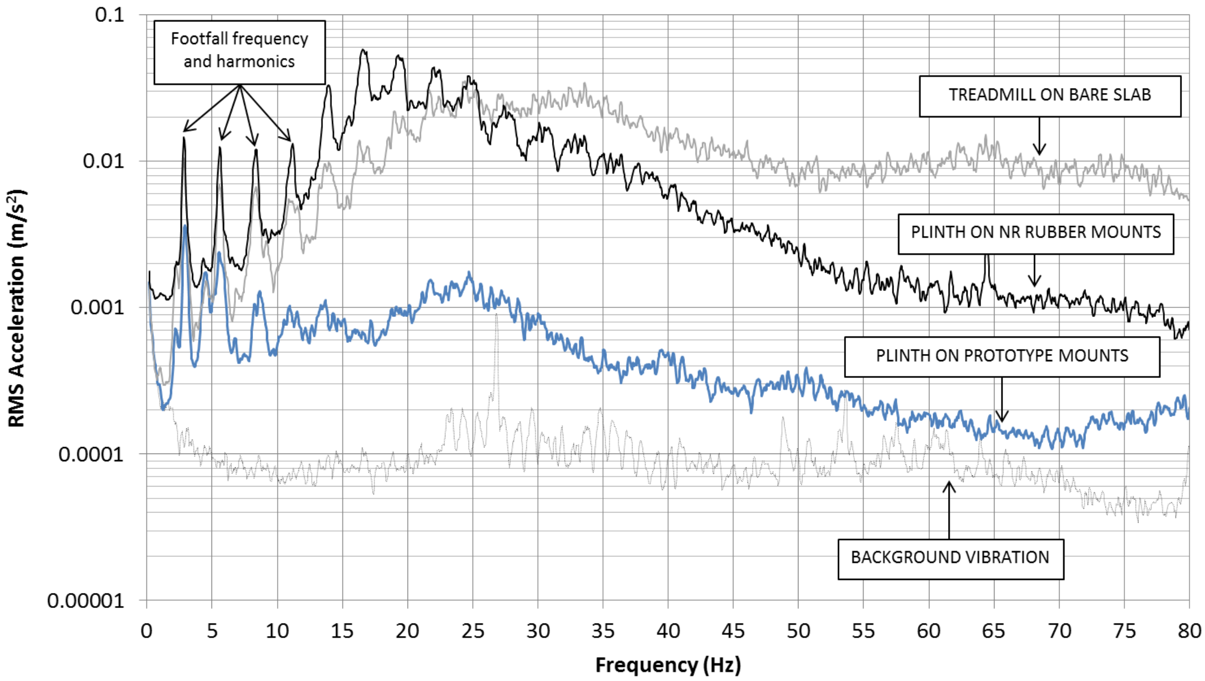


Figure 4: Average slab acceleration at 0.5m due to treadmill with 65 kg runner at 12 km/h

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. It can be concluded that replicating the NR1 setup on the case study slab would see unfavourable amplification at the 11Hz fundamental frequency relative to a rigid fixing.

6. Laboratory Acoustic Performance Testing

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. The tests were repeated with the same three plinth arrangements as the vibration tests, again using a 65 kg person running at 12 km/h, with a footfall frequency of approximately 2.7 Hz. Fig. 5 below presents the measured L_{eq} Sound Pressure Levels.

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.

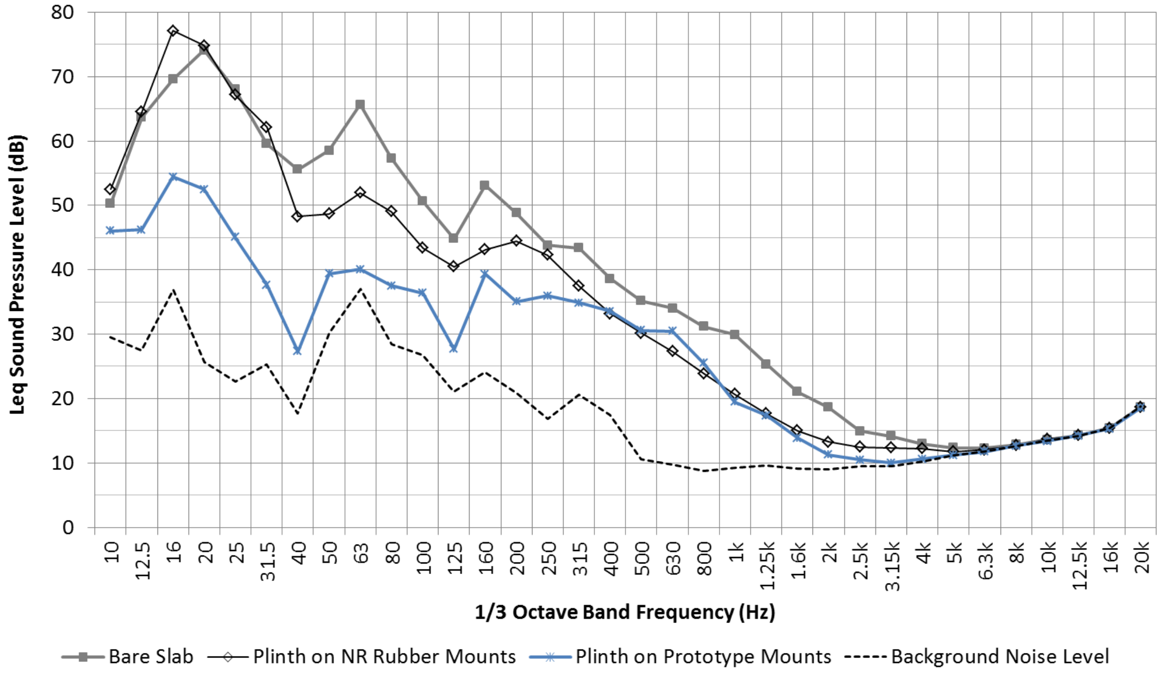


Figure 5: Measured L_{eq} sound pressure levels in room below with 65 kg runner at 12 km/h

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).

7. In-situ Performance

The developed product was installed to support a large plinth of 8.8x2.7m capable of carrying 6 treadmills. The floor build-up consisted of timber joists supporting 3 layers of 18mm compressed fibre cement sheet (density 1700kg/m^3) screwed together to provide the necessary mass to achieve the 4.5-5Hz isolator frequency. It was believed that by having all treadmills on a common platform, the combined mass and stiffness of the compressed fibre cement would eliminate any instability caused by the spring supports.

Although complaints of vibration ceased following installation, treadmills were experiencing roll from running activity which was rocking other treadmills on the platform up to 2 metres away. This was caused by foot impact flexing the cement sheets and placing a bending moment through the joists. The joists had been installed in an alignment to minimise pitch rotation, butit was apparent that bracing battens should have also been installed to stiffen the floor in the roll direction. The movement was generally not excessive enough to impact the running experience of the person using the treadmill; however, there was sufficient movement to disconcert onlookers and users that were stationary or walking slowly on the adjacent treadmills. It was therefore decided to divide the entire floor into individual plinths. Extra spring mounts were necessary to provide support at each division, which raised each loaded plinth mount frequency up to 5.5-6.0Hz. A revised prototype platform of the same construction that was installed in the gym was built in the laboratory and tested to determine if the reduced platform width that was proposed would be sufficient to provide plinth stability. This was found to be the case and the revised platform design, using 5 individual plinths, was implemented in the gym.

Figure 6: The initially installed platform's build-up.

The revised platform arrangement was confirmed to successfully address both the stability issues and vibration attenuation when installed in the gym. The compromise in performance from raising the mount frequency did not result in any fresh annoyance to the original complainant. The extra springs lessened the roll amplitude and the treadmills were unaffected by excitation due to runners on adjacent plinths. At the time of writing this paper, the system had been in place for one year.

8. 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. 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.

In-house stability testing 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-situ performance on the full scale treadmill platform was a success in terms vibration attenuation, however the plinth's construction proved flexible enough that the use of a treadmill would affect those adjacent to it. The platform was subdivided into individual plinths in order to resolve useability issues whilst keeping below vibration annoyance thresholds.

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