Chapter 6
Power Requirements for Active Control of Floor Vibrations

M.J. Hudson, P. Reynolds, and D.S. Nyawako

Abstract Recent research has made significant developments towards improved Active Vibration Control (AVC) technology for the mitigation of annoying vibrations in floor structures. However, there are very few examples of permanent AVC installations in floor structures; this is in part due to the requirement of a continuous power supply and the ensuing electricity costs. This paper investigates potential improvements to AVC from the perspective of the choice of control algorithm. Firstly, the use of model-based controllers as opposed to the direct output feedback controllers that have been used in most prior research effort is considered. For a model-based (MB) controller, because the controller can be designed to target modes within a specific frequency band of interest, it is possible that control effort is used more effectively for a given reduction in response. Secondly, the potential benefits of using a switching-off rule to reduce the actuator effort during periods of low structural response is investigated. Future actuators and amplifiers could incorporate a switching-off rule similar to this in order to minimise the overhead costs associated with running the amplifier. The changes in potential electricity consumption for the previously declared control laws are experimentally determined through direct measurement of the power drawn by the actuator. The results from these analyses are compared and conclusions drawn.

Keywords Active vibration control power experimental

6.1 Introduction

There have been numerous papers in recent years examining the use of Active Vibration Control (AVC) for the mitigation of annoying vibrations in floor structures [1–4]. These have been shown to be very effective at reducing the vibration responses of the floors. However, when real floor structures are observed to require vibration mitigation, it is generally only passive technologies such as Tuned Mass Dampers (TMDs) that are utilised; very rarely is AVC considered as it is still at a relatively new stage for this application.

Whilst AVC is a fairly well developed technology in other fields, e.g. aeronautics, space and marine, its use for the mitigation of floor vibrations is still emerging. This is one of the reasons why the hardware associated with it is typically expensive. In addition to this, AVC has on-going costs associated with running the active devices. Over the life of a building this could amount to substantial electricity costs. The research in this paper investigates the issue of on-going electricity costs from the perspective of controller design.

Much research into AVC for floors has focussed on the use of direct output feedback controllers. For example, Direct Velocity Feedback (DVF) has been the basis of much research [1, 5, 6]. Here, the structural acceleration from the accelerometers is integrated and a constant gain applied to the resulting velocity. In the absence of actuator dynamics this results in a predominanty augments the structural damping. However, actuator dynamics have a destabilising effect for high feedback gains. Developments from DVF have included: Response Dependent Velocity Feedback (RDVF) [7]; Compensated

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Acceleration Feedback (CAF) [3]; DVF with a feedthrough term [4] and On-Off nonlinear control [8]. These developments all utilise the key benefit of DVF, namely that the structural damping is effectively enhanced, but offer some improvement. For example, RDVF effectively employs an automatic gain selection for DVF, whilst CAF and DVF with a feedthrough term deal with some of the instability issues brought about through the dynamics of the actuators. The On-Off nonlinear control aims to eliminate stability issues that can arise through non-optimal feedback gain choice when using DVF.

Alongside these developments, model-based controllers are being investigated for this application; research in this field for the application of floor vibrations is on-going however presently available literature is much less common. For example, an LQR controller was examined by Nyawako [2] which used the threshold of human perception of vibrations and output constrained control for the optimisation procedure. Further to this, Independent Modal Space Control (IMSC) and Pole-Placement technologies have been investigated by [9] to isolate individual problematic modes in an attempt to reduce spillover instability and improve robust performance.

There are two aspects from the currently developed control laws that have potential to facilitate savings in power requirements for AVC of floor vibrations. Firstly, there is the possibility of using a model-based controller that utilises known structural dynamics in order to control specific modes of vibration. For example, IMSC provides a framework through which one can control low frequency modes that are more likely to be problematic whilst leaving higher frequency modes uncontrolled. In theory, this could allow the controller to reduce the energy used for control purposes whilst still achieving vibration mitigation performance for critical structural modes of vibration. Secondly, the use of a switching-off rule as used in the on-off control could be utilised. This would allow the actuator to become inactive during periods of low structural response and only be active when the response exceeded a particular threshold. This paper investigates these two ideas through experimental research performed on a laboratory slab structure. A specially developed power meter is used to measure the RMS real power drawn at the mains socket while the actuator is operating. Measuring at this point accounts for all losses within the amplifier and actuator circuit and is indicative of the amount of electricity the user would be charged.

The structural system and walking force applied to the structure are described in Section 6.2. The development of the control algorithms is discussed in Section 6.3. Following from this, the results from the experimental tests are provided in Section 6.4. Finally, conclusions are drawn in Section 6.5.

6.2 System Description

6.2.1 Modal Properties (EMA)

The structure used for this testing is a laboratory slab strip at the University of Sheffield. This is a 11.2m × 2.0m × 0.275m reinforced concrete slab spanning 10.8m between knife edge supports. The modal properties of this structure were determined through a forced vibration test using one APS dynamics model 400 shaker located 2.7m from the support and 0.2m from the long edge of the slab, and 21 Honeywell QA accelerometers located on 3 × 7 grid throughout the structure. The data were processed in ME'Scope and modal parameters identified using global curve fitting with the Ortho Polynomial method. The resulting mode shapes are shown in Fig. 6.1 and modal parameters in Table 6.1.

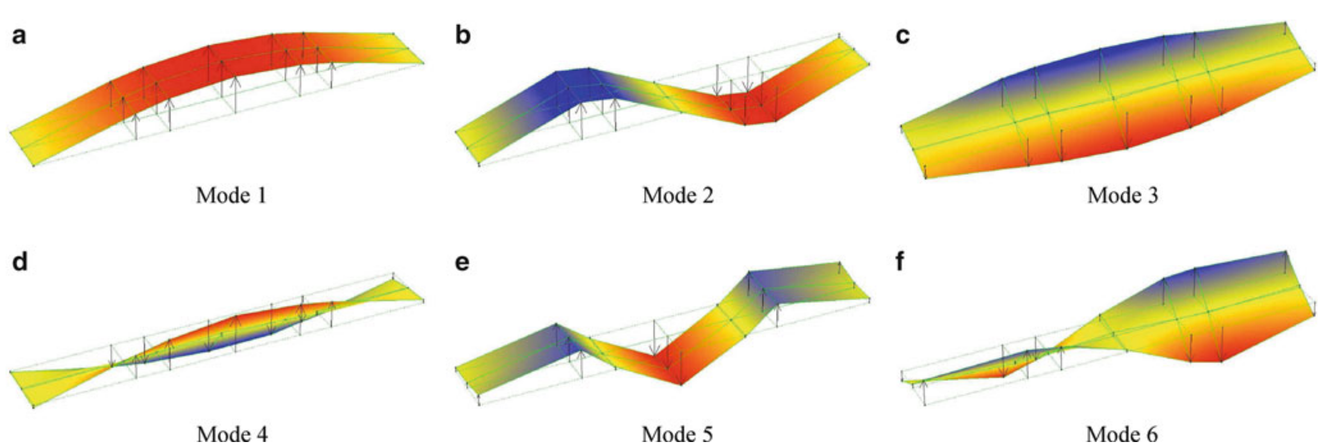

Fig. 6.1 First six modes of vibration of slab strip

Table 6.1 Modal properties for first six modes of vibration of slab strip

Mode number	Natural frequency/Hz	Damping ratio/%	Modal mass/kg
1	4.6	2.2	6010
2	16.8	0.5	6010
3	26.1	1.2	3540
4	28.7	1.1	21250
5	37.7	1.2	7310
6	51.4	2.3	2600

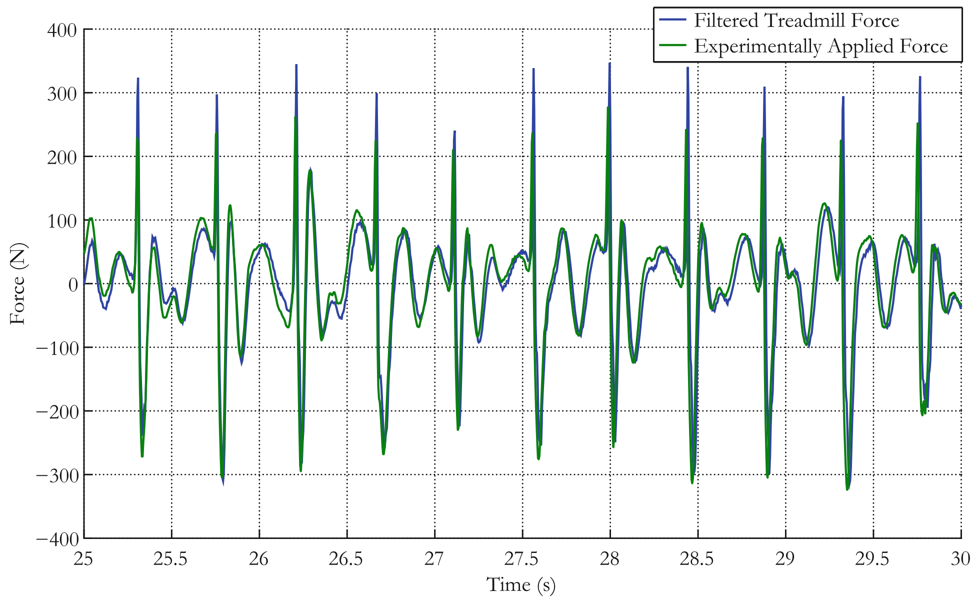

Fig. 6.2 Measured and theoretical walking time history

6.2.2 *Walking Force*

The aim of this paper is to determine and compare the typical power demand from the active control system due to walking excitation. However, in order that comparisons may be accurately made, the excitation must be repeatable which human walking is not: there is both intra- and inter-person variability with walking excitation [10]. Therefore, it was decided that the excitation would be provided by another inertial mass actuator generating a force representative of walking. This is done by converting a walking force time history into a command voltage such that when this is used to drive the actuator a force representative of walking is generated.

The force time history for a pedestrian walking at around 2.2Hz to 2.3Hz was measured using an instrumented treadmill [11]. This frequency of walking has a second harmonic that will excite the first structural mode of vibration. However, it is very difficult to generate the 2.3Hz component of this walking because of the stroke limits of the inertial mass actuator. As this frequency component is not actually exciting the structure in any way, it was deemed justifiable to remove this component from the time history through the use of an 8th order high-pass Butterworth filter at 3Hz. It is worth noting that a high order filter, such as this, significantly modifies the phase of the signal. However, it has been shown that the phases between walking harmonics are random [10] so this additional phase contribution is not a problem.

The inverse of the actuator dynamics were modified with the use of a 2nd order high-pass Butterworth filter at 0.5Hz to avoid magnification of low frequency components. The result of this filtering is shown in Fig. 6.2. Here, the measured force time history after filtering at 3Hz is shown along with the force measured from the actuator when simulating this force time history. A close correlation is observed between the experimental force and the filtered treadmill data, with the exception that the amplitude of the sharp peaks are slightly reduced for the experimental force. This is not a problem as these peaks correspond with excitation at 2.25Hz, i.e. the component that we have tried to filter out because they do not contribute to excitation of the structure. Therefore this difference does not preclude the actuators from generating an effective walking force.

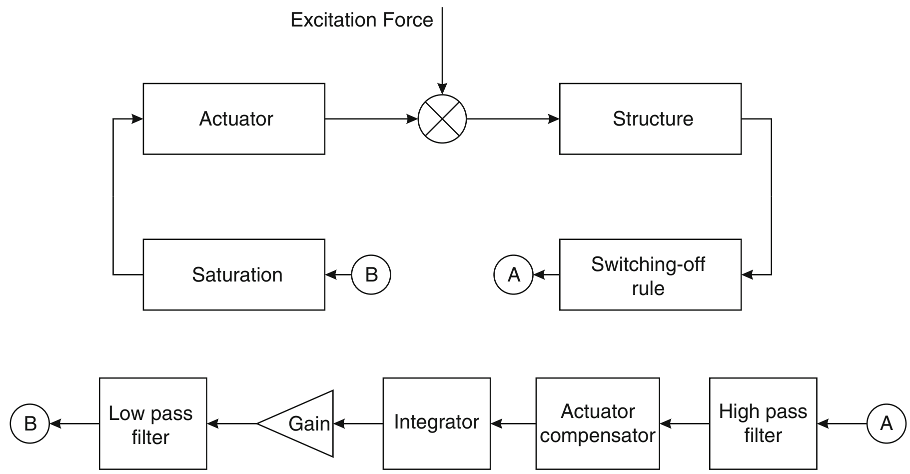

Fig. 6.3 Control architecture for the DVF controller

6.3 Active Controllers

6.3.1 DOFB

The direct output feedback controller used in this study is a modified form of Direct Velocity Feedback (DVF). Here, the acceleration signal from the accelerometer is passed through a 2nd order high-pass filter at 1Hz to remove low frequency components before being integrated to yield a velocity signal. A 1st order low-pass filter is also included at 50Hz to avoid the actuator attempting to control very high frequency modes and noise. Finally, an actuator compensator is included to artificially reduce the natural frequency and increase the damping ratio of the actuator. The feedback gain is chosen such that a gain margin of 2 and a phase margin of 30° are achieved. A saturation non-linearity at 2V is included in the command signal in order to reduce the chance of stroke saturation occurring at low frequencies and to avoid force saturation. In addition to this, for some of the tests a switching-off rule has been incorporated to deactivate the actuator when the RMS of a previous block of data is below a threshold value. The schematic for this controller is shown in Fig. 6.3.

6.3.2 MB

The model based controller used in this study is an Independent Modal Space Control (IMSC) design, as described by Nyawako et al. [9]. The active control configuration is very similar to that described in this study. It was demonstrated that one actuator and two accelerometers can control the first mode of vibration whilst leaving the second mode un-attenuated. Here, the simple dynamics of the structure are utilised to simplify the design process. The structural mode shapes' orthogonality condition is utilised, resulting in the actuator being located at one third span and the two accelerometers at third and two-third spans respectively. In this way, the accelerometers and actuators are located at nodal points for modes 3–6, as shown in Fig. 6.1 and the phase of the second mode differs by exactly 180° between the two accelerometers. This means that the acceleration signal from each accelerometer can be combined and the resultant signal will only feedback to control the first mode of vibration. The controller schematic is shown in Fig. 6.4.

6.4 Experimental Results

The power demand of the actuator and amplifier was measured through the use of a custom built power meter. This device samples the mains voltage and current supply at 2.8kHz to calculate the average power over 5 mains cycles (0.1 seconds). The power meter was used to monitor the APS Electrodynamics model 124 EP extended power amplifier when this was used to drive the APS Electrodynamics model 400 shakers with attached reaction masses. Monitoring the power at this point accounts for all losses within the amplifier and actuator circuit and therefore is indicative of the amount of electricity the device is drawing from the grid.

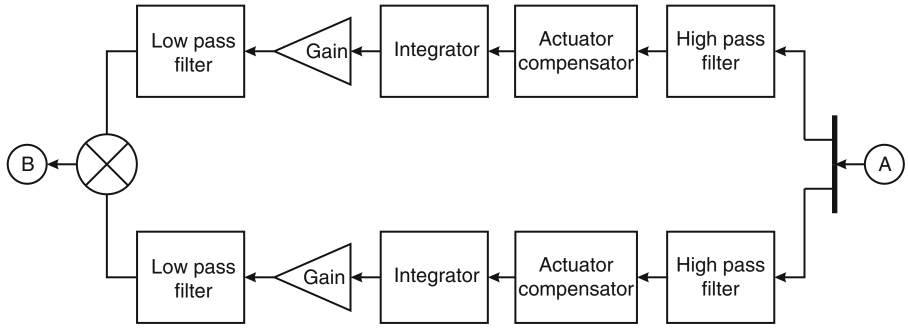

Fig. 6.4 Controller design for IMSC

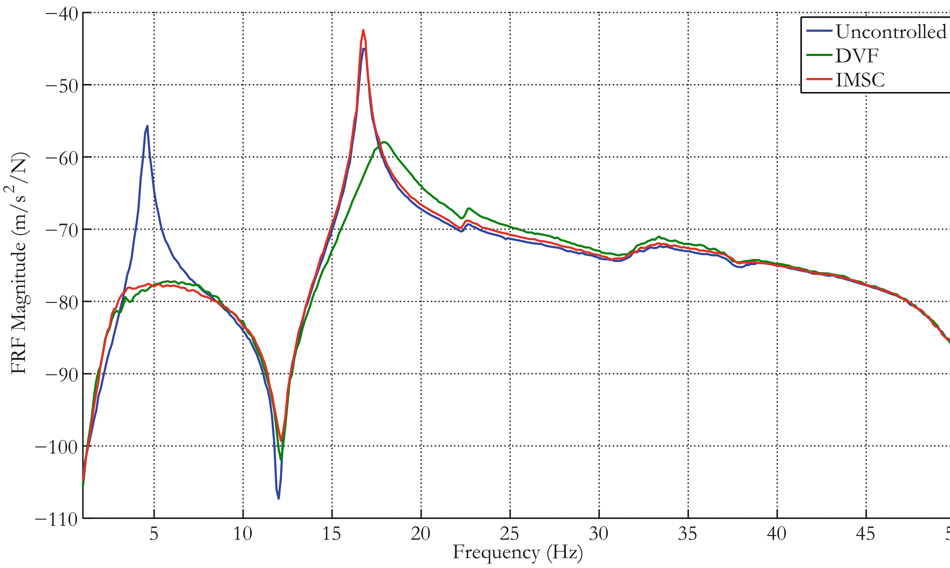

Fig. 6.5 FRFs for DVF and IMSC controllers

Both controller types were configured on the laboratory slab structure as described in Section 6.3, and FRF measurements were taken to validate the controllers were performing as expected. The results of this are shown in Fig. 6.5. Here it is observed that DVF successfully reduces the magnitude of response for both modes, whilst IMSC reduces the response for mode 1, but does not reduce the response of mode 2. In fact, a slight increase in the response is noted for mode 2. It is believed that this is due to the assumption that the shape function at the location of both accelerometers is exactly equal and opposite for mode 2. However, slight differences could be expected in reality which may result in the slight deterioration in response at this frequency.

As previously discussed, the aim of this paper is to investigate the power demand of AVC for human-induced floor vibrations. Therefore, two different walking time histories were synthesised using the actuator: one at around 2.25Hz in order to achieve resonance with the first mode of vibration through the second harmonic of the walking force, and one at 2.5Hz in order to impart as much energy into the system at higher frequencies as is realistic. The idea behind this second time history is that the impulses due to each footfall will significantly excite the second mode of vibration and so the difference between DVF and the IMSC controller (which controls the first mode but does not control the second mode) should become apparent. In addition to these forces, real walking was conducted on the slab strip for comparative purposes. This set of walking types was applied to the structure with 1) no control, 2) control using DVF controller, and 3) control using IMSC controller. Note that the gain for both DVF and IMSC had to be reduced to 80% of the original value for the case of the real walking excitation in order to avoid stroke saturation from the quasi-static structural response to the 2.25Hz component of the force.

Typical time histories for the acceleration response and the power demand are shown in Fig. 6.6, whilst the maximum response measured and average power for each of the experiments is shown in Fig. 6.7. The maximum response is characterised by the R factor which is the maximum of the running one second RMS of the W_b frequency weighted acceleration signal, normalised by $0.005 m/s^2$ which is taken as the perceived limit of human perception of vibrations.

These results show that both controllers reduce the maximum R factor recorded for all walking excitation types, as should be expected. However, it is particularly interesting to note the results for the 2.25Hz excitation which aimed to target the first

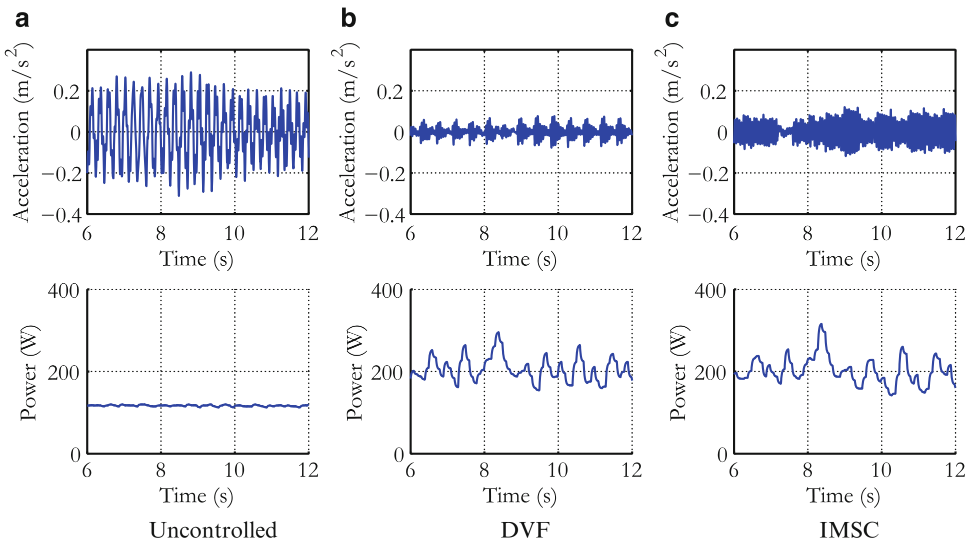

Fig. 6.6 Acceleration and average power measured for 2.25Hz synthesised walking excitation

mode of vibration. Here, IMSC does not reduce the response of the structure as much as DVF despite the FRFs in Fig. 6.5 showing the magnitude of response for the first mode to be approximately equal for these two controllers. This is because this excitation also has significant higher frequency components that excited the second mode of vibration. Considering the power demand, it is important to note that the amplifiers were left running but had no command voltage applied to them for the uncontrolled case. This is the reason why all uncontrolled cases reported an average power of 114W - these are the overhead required for the amplifier to run itself. A marginal improvement in the power demand for IMSC over DVF was observed for all three excitation types. However, the response of the structure is significantly higher with IMSC.

6.4.1 Variations in DVF Feedback Gain

In order to explore this area further, the feedback gain of the DVF controller was systematically decreased and the experiment repeated. The resulting changes to the controlled structure's FRF are presented in Fig. 6.8, and the results for these controllers subject to the walking excitation are shown in Fig. 6.9

It is apparent that by varying the feedback gain for DVF we have arrived at a set of controllers that all lie closer to the utopian goal of zero response for zero power demand than the IMSC controller. This means that for this structure the DVF controller is the preferred choice and this is due to the significant contribution to the structural acceleration from the second mode of vibration. It is crucial to note that this does not mean that DVF is "better" than IMSC or other model-based controllers; it means that there is no benefit in designing a model-based controller to intentionally not control higher frequency modes (within a range excitable by human walking) with the idea of reducing power consumption because little power saving is made and the structural response can be significantly higher.

6.4.2 Use of a Switching Off Rule

The effect of using a switching-off rule is considered next. The idea here is to prevent the actuator from working when the response of the structure is below a threshold, such that power savings can be made whilst keeping the large responses low. The nature of the excitation/structural system in this study is such that high response levels are achieved and maintained for the entire test duration. This means that the switching-off rule must be set relatively high so that its effect can be seen. A range of different thresholds were chosen, namely from $R = 4$ to $R = 8$ (with frequency weights applied assuming the response is dominated by the first mode of vibration). In addition to this, a range of time periods used to calculate the RMS response were considered - 1s, 0.5s and 0.25s. A 2nd order low pass filter at 1Hz was used to remove low frequency components of the measured acceleration before the RMS block was calculated. The differences in both vibration response and average power are very small for the controllers tested. This means that the results are more strongly influenced by both

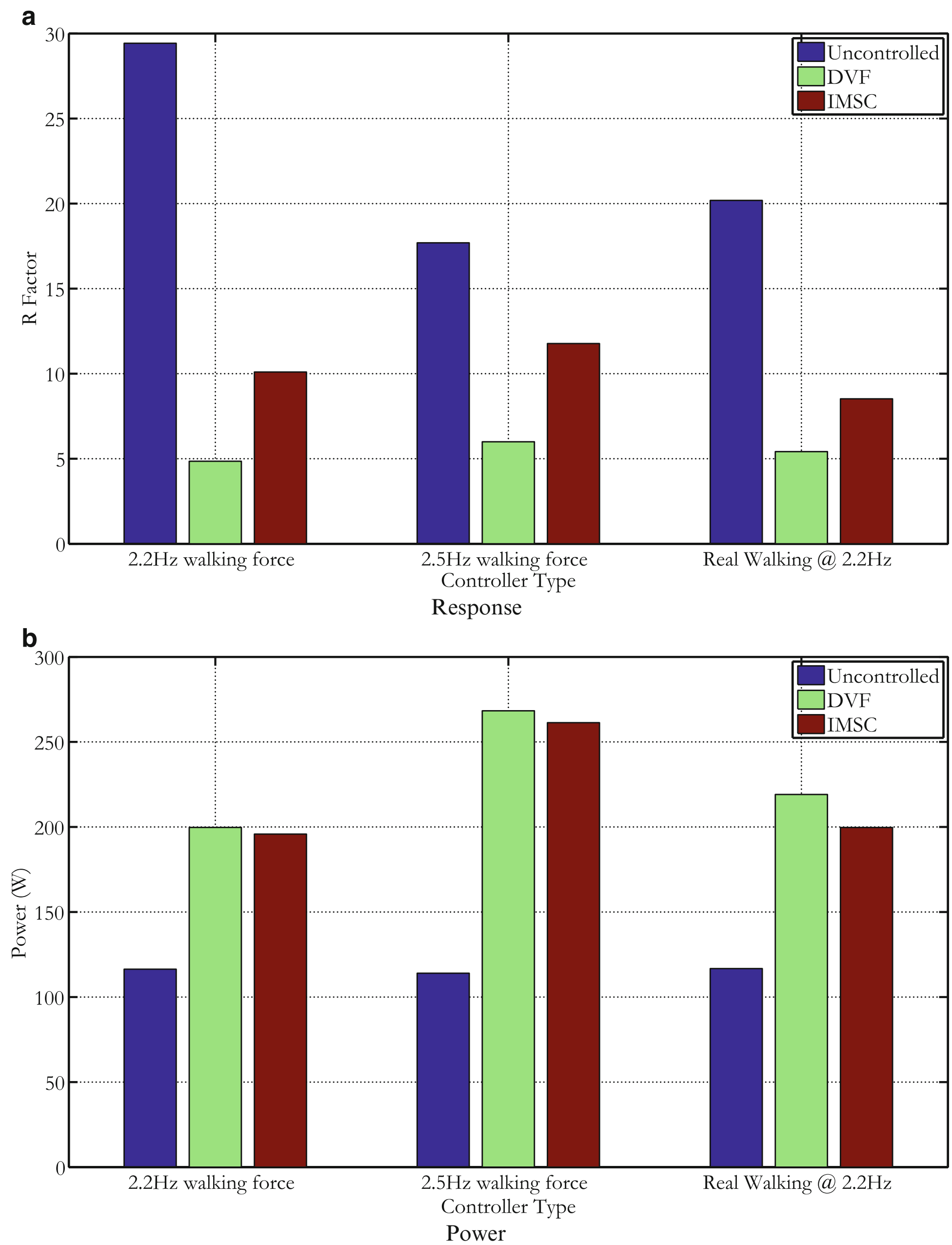

Fig. 6.7 Maximum response factor and average power measured for various types of excitation

external excitation and variance in the amplifier overhead. Therefore, in order to improve reliability of the experiments, each test was repeated several times and averages of the results were taken. These averaged results from all the tests with the switching-off rule for DVF are shown in Fig. 6.10 where they are compared with the results for varying the gain in DVF.

Here it is seen that by using a high threshold, i.e. a higher level of response is permitted before the actuator turns on, the maximum response is increased and the average power is decreased. This effect is observed for all RMS block sizes. However, when compared with a simple linear decrease in the gain for DVF it is seen that reducing the gain is a more effective solution for this situation; the average power required for a certain level of response is high when using a switching off rule. The reason for this can be found by examining the time history of the power demand and structural response, as shown in Fig. 6.11.

The threshold for the switching-off rule in the controller shown in Fig. 6.11 is at an RMS acceleration of $0.042 m/s^2$ which approximately equates to an R factor of 8. The power demand for the switching-off controller rises rapidly to a high level as soon as the threshold is exceeded. As the response reduces below the threshold the controller switches off. However the continuous excitation will cause an increase in the response. This means that at the instant in time when the response

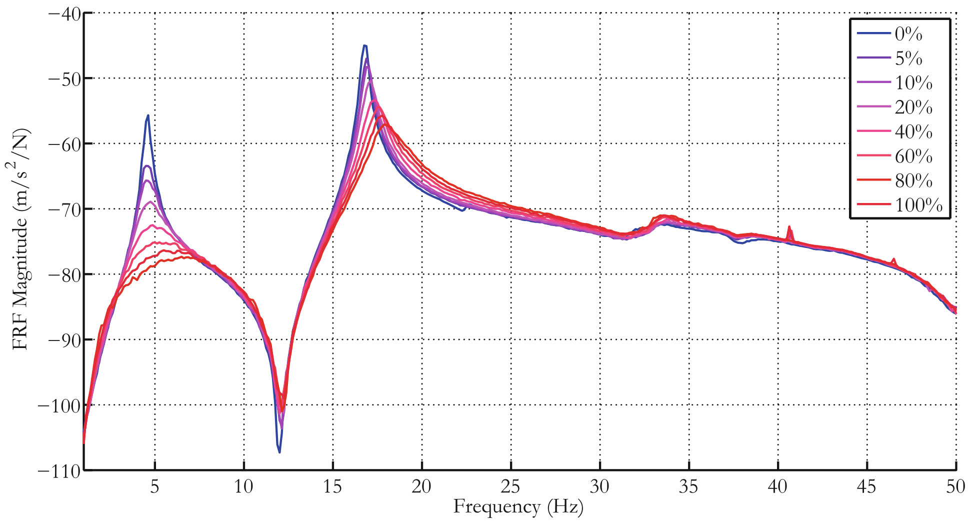

Fig. 6.8 FRFs for uncontrolled structure and DVF with gains varying from 5% to 100% of optimal

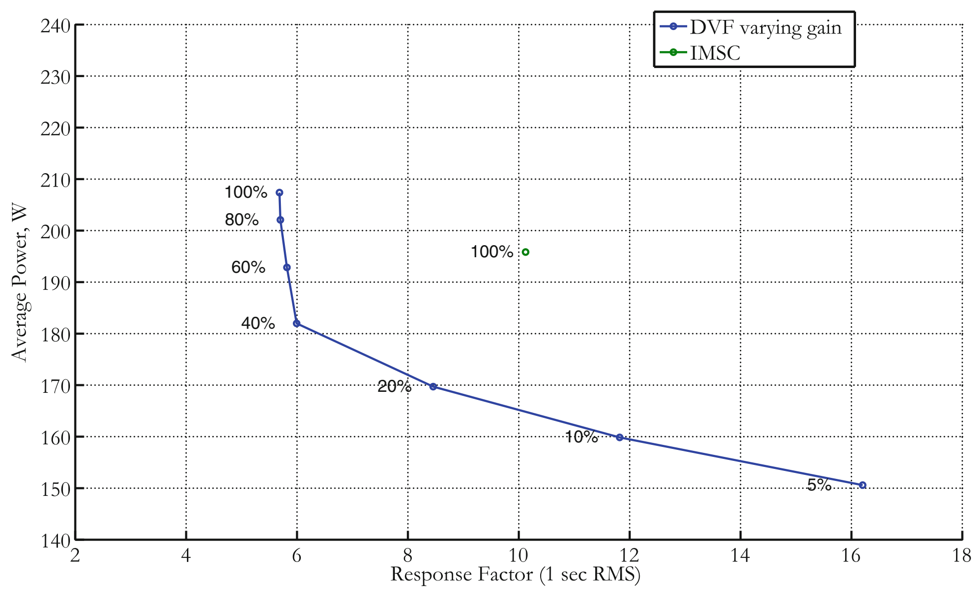

Fig. 6.9 Average power and maximum R factor for various feedback gains (as indicated by % of optimal) of DVF and IMSC

increases above the threshold again, the controller will have to work harder to reduce the response than if it had been working all the time. In addition to this, the delay introduced by having to wait one second to determine the RMS of the acceleration means that the response could actually be higher than the threshold. Evidence of this is seen in Fig. 6.11 where the same threshold values are used for each block size, but the response factor measured is lower for the smaller blocks. The continuous nature of the excitation used in these tests meant that the response alternated between being under and over the switching-off threshold relatively rapidly. This increases the proportion of power spikes relative to the total duration. As Fig. 6.11 shows, the power demand is low when the response is below threshold, high immediately after the response exceeds the threshold, and approximately the same as the controller without a switching-off rule once the response has exceeded the threshold for a short duration. Therefore, the effectiveness of using a switching-off controller is dependent on the ratio of low to high levels of response.

Finally, a relatively simple deadzone was considered. This is effectively a special case of the switching off rule where the block size for calculating the RMS of the acceleration is one sample. Thresholds varying from $R = 1$ to $R = 8$ were considered (with the same assumption of frequency weighting being for the first mode of vibration as in previous tests). The results of this are shown in Fig. 6.12.

Here, again the compromise between increase in response and reduction in power is observed as the deadzone threshold changes. However, all the solutions lie further from the utopian goal compared with simply changing the DVF gain.

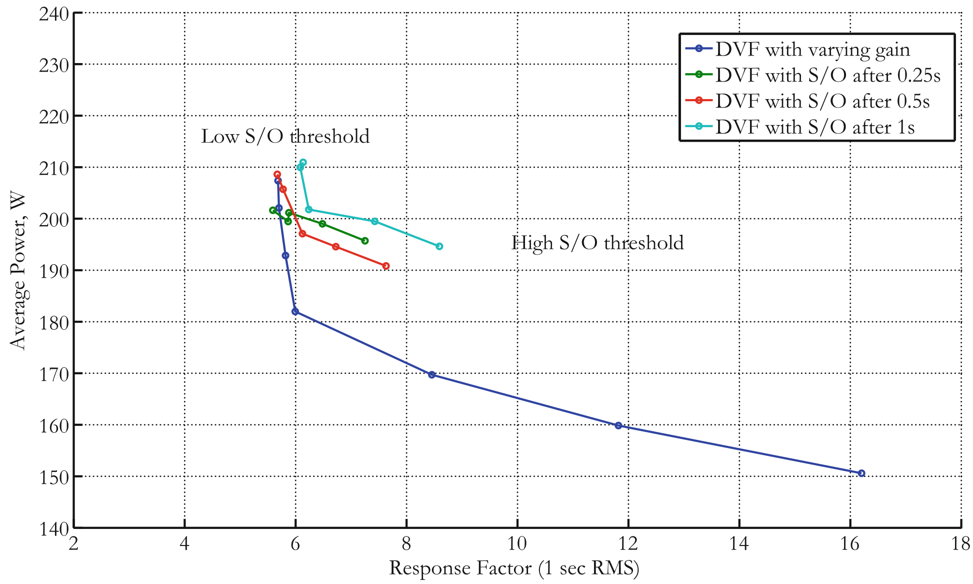

Fig. 6.10 Comparing effect on response and power of varying DVF gain with varying switching-off parameters

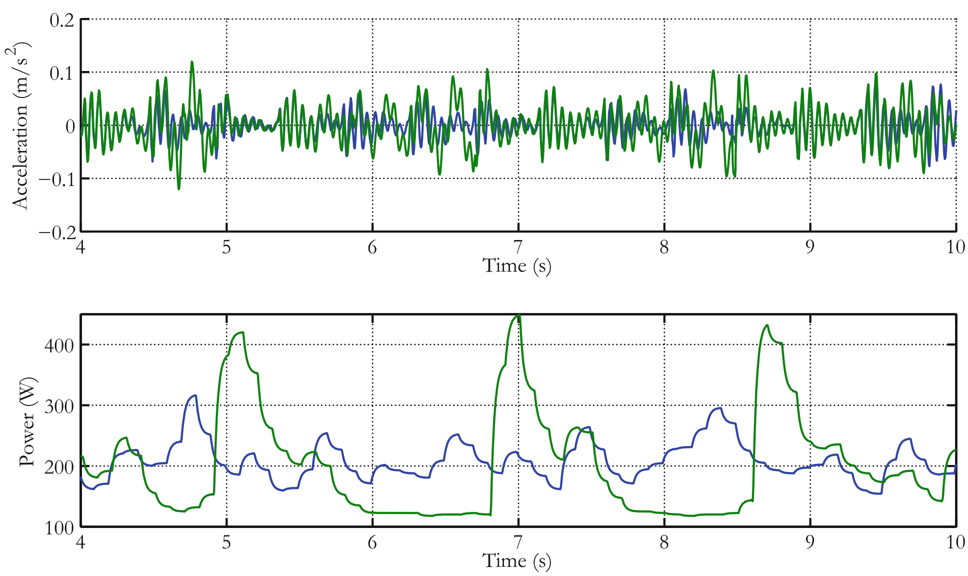

Fig. 6.11 Time history for AVC power demand and structural response without a switching-off rule and with

6.5 Conclusions

The power requirements of various active control configurations have been investigated. A repeatable walking force has been generated by inertial actuators and this facilitates direct comparisons between controller types for the same excitation input.

It immediately becomes apparent that there is a high power demand from these actuators when the force output from the actuator is zero. These overheads contribute a significant portion of the total average power demand from the shakers: the largest average power recorded was about 270W indicating that, for these tests, at *best* the overheads accounted for 40% of the total. Future work should certainly investigate the use of improved amplifiers that have much lower overheads. If it is possible to reduce, or even remove this overhead completely, possibly through the use of Class-D amplifiers, then very significant power savings can be realised.

With regards to specific controllers tested, it was observed that no significant power savings were made by using IMSC to intentionally not control the second vertical mode of vibration, when compared with a simple DVF controller. Indeed, the marginal power savings made are far outweighed by the increase in response despite the relatively high frequency of this mode.

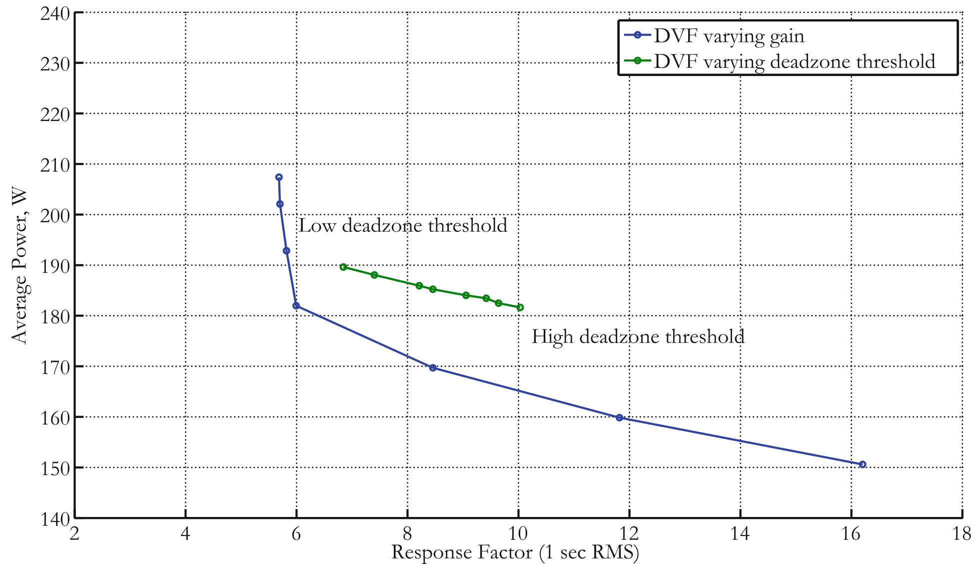

Fig. 6.12 Comparing effect on response and power of varying DVF gain with varying deadzone threshold

For this excitation type the most effective way to reduce the power requirements of the controller are to use a simple DVF controller with a reduced feedback gain. Although the use of a switching off rule did achieve power savings, the structural response was higher than DVF for any given average power requirement. However, other excitation types may not result in the same conclusion: the effectiveness of the switching off rule is dependent on the proportion of time the controller switches from inactive to active resulting in large transient increases in power demand. The use of a deadzone (i.e. a switching off rule with block size of one) was similarly not as effective as a simple reduction in feedback gain for DVF.

Future work should consider working towards predicting the power requirements of an AVC system based on the command signal without the need for a power monitor device. This would then allow predictions for typical power requirents of AVC due to in-service loading in real structures and thus enable predictions for how much electricity would be required for AVC during the building's operational life. In addition to this, there is the potential to achieve material savings through the design of AVC into new floors whose design is governed by vibration serviceability. The overall cost savings due to fewer materials being used in construction, both financial and environmental, should be calculated for these structures and compared with the ongoing costs associated with AVC to determine the cost effectiveness of this strategy.

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