Findings with AVC design for mitigation of human induced vibrations in office floors

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ABSTRACT

In recent years, there have been extensive active vibration control (AVC) studies for the mitigation of human induced vibrations in a series of office floors, in which such vibrations are deemed to be 'problematic' and have been found to affect only certain sections of the floors. These floors are predominantly open-plan in layout and comprise of different structural configurations for their respective bays and this influences their dynamic characteristics. Most of the AVC studies have comprised extensive analytical predictions and experimental implementations of different controller schemes. The primary measures of vibration mitigation performance have been by frequency response function (FRF) measurements, responses to controlled walking tests, and in-service monitoring, all tests with and without AVC.

This paper looks at AVC studies in three different office floor case studies in past field trials. Some of the estimated modal properties for each of these floors from experimental modal analysis (EMA) tests are shown as well as some selected mode shapes of fundamental modes of vibration. These reflect the variability in their dynamic characteristics by virtue of their different designs and thus the potential for their 'liveliness' under human induced excitation. An overview of some of the controller schemes pursued in the various field trials are mentioned as well as a brief insight being provided into some challenges encountered in their designs and the physical siting of the collocated sensor and actuator pairs used in the field trials. The measure for the vibration mitigation performances in this work is in the form of uncontrolled and controlled point accelerance FRFs which show attenuations in the target modes of vibration between 13-18 dB. These tests also show the variability in vibration mitigation performances between the various controllers.

Keyword: active vibration control, vibration mitigation, frequency response function, experimental modal analysis

INTRODUCTION

The liveliness in many contemporary floor structures under human induced loading is often the result of advancements in materials, design and construction technologies that lead to progressively longer, structurally more efficient and slender floors. They also tend to be more open plan and with fewer internal partitions [1,2], which in turn contributes to their low internal damping characteristics as well as low and closely spaced natural frequencies, sometimes falling within the range of frequencies produced by human activities.

Active vibration control (AVC) technologies are emerging as an attractive means of controlling human-induced vibrations in floors based on recent field trials. When compared with alternatives such as tuned mass dampers, AVC technologies make use of much smaller units, provide quicker and more efficient control, have the ability to adapt to changes in the structural dynamic properties and can tackle multiple modes simultaneously [3,4]. However, at present they suffer from initial high installation costs and the need for regular maintenance and a constant power supply.

Primary requirements for an AVC system for mitigation of human-induced vibrations in floors is that it should be simple, reliable and low-cost, which actually are typical requirements for AVC systems that are demanded for any application. Additional challenges imposed by modelling errors, control and observation spillover influences, time delay issues, changes in structural properties over time as well as control design errors must be addressed in order to achieve AVC systems that offer robustness with respect to the vibration mitigation performance and stability [4,5].

AVC studies for mitigation of human induced vibrations in floors have focused mainly on direct output feedback (DOFB) approaches in collocated sensor and actuator pairs and more recently the tendency is towards trials with model-based controllers. Typical controller schemes that have been investigated in both laboratory and field trials include direct velocity feedback (DVF), compensated acceleration feedback (CAF), response dependent velocity feedback (RDVF), on-off velocity and acceleration feedback schemes, integral resonant control, and pole-placement type schemes [3,6,7,8,9,10,11,12].

To date, there has been a fairly good understanding of the requirements for AVC systems needed for mitigation of human-induced vibrations in floors. The sensors used in past and on-going studies are piezoelectric accelerometers with integral signal conditioning, while the actuators are commercially available APS Dynamics models 113 and 400 electrodynamic shakers. This paper examines some selected past AVC field trials in a number of office floor structures which suffer from vibration serviceability problems under human induced dynamic loading. An overview of the office floor configurations in past field trials is provided as well as some results from experimental modal analysis (EMA) tests, being point accelerance frequency response function (FRF) measurements and some selected mode shapes from modal parameter estimates. Additionally, the controller schemes used in the field trials are outlined and uncontrolled and controlled FRF measurements from the field trials are presented. Finally, some conclusions are set out.

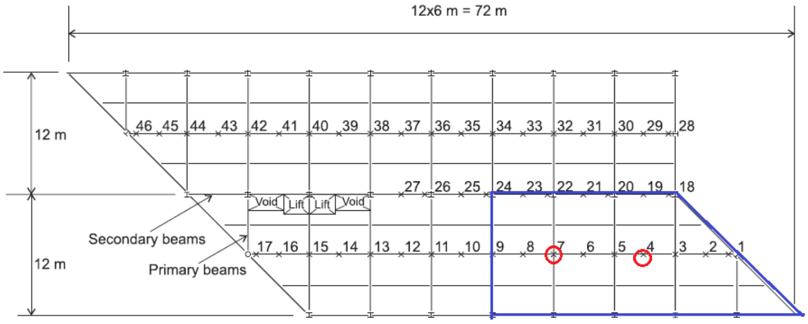
FLOOR CONFIGURATIONS TESTED

Three different floor configurations, for which AVC studies have been undertaken in past field trials are briefly described here. All these floors have sections or bays which are susceptible to human-induced vibrations or transmission problems from human-induced activities in upper floors. All these floors are fully fitted out with office furniture, partitions, suspended ceilings and false flooring. Floor 1, shown in Figure 1a, is a composite steel-concrete floor in a steel framed office building. The primary beams span approximately 12m between the column lines, the secondary beams span between the primary beams and the composite slab spans between the secondary beams. Columns are located along the two sides of the building as well as along the centreline. The point numbers, TP1 to TP46 are the locations that were selected for EMA tests. Four excitation points were used (TPs 04, 07, 31 and 36) and responses were measured at all TPs, resulting in 4 columns of the FRF matrix. Figure 2a shows the point accelerance FRFs.

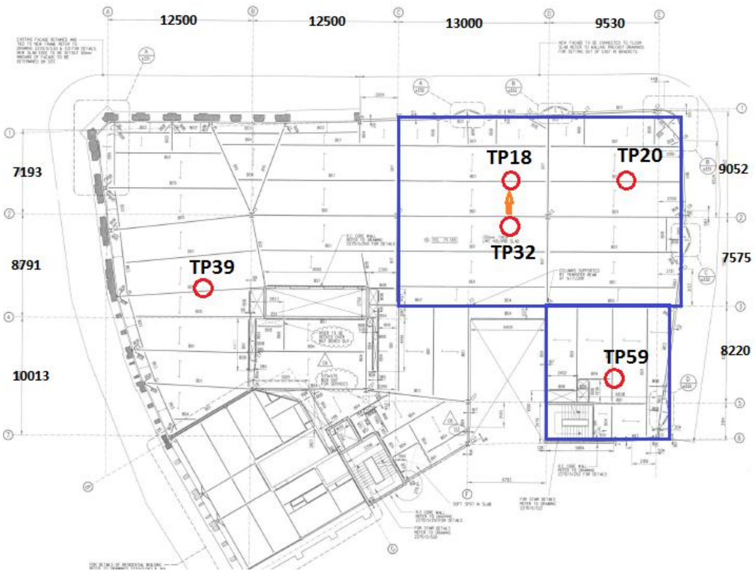
Floor 2 is also a composite steel-concrete floor in a steel framed office building. This structure is highly irregular by design with the primary beams varying from 7.193m to 10.013m in length and spanning between the column lines as shown in Figure 1b. The secondary beams also vary in length between 9.53m to 13.0m whilst spanning across the primary beams, and the composite slabs span one-way between these secondary beams. Columns are again located along the two sides of the building as well as along the centreline. The point numbers, TP1 to TP69 are the locations that were selected for the EMA tests. Four excitation points were used (TPs 20, 32, 39 and 59) and responses were measured at all TPs, again resulting in 4 columns of the FRF matrix. Figure 2b shows the point accelerance FRFs from the EMA.

The structure on which floor 3 is built on is a fairly regular steel-framed building that has been constructed on top of a reinforced concrete building. Figure 1c shows a plan view of this floor and with the numbered locations being the test points for the EMA tests. Within the steel-framed building, the primary floor beams, 6.0m in length, span between the column lines. The secondary beams, 9.8m in length, span between the primary beams and the composite slab spans between the secondary beams. The point numbers, TP1 to TP81 on the college floor are the locations that were selected for the EMA tests. TPs shown using the parenthesis indicate points both on the college floor and gym floor above. Four excitation points were used (TPs 29, 33, 49 and 53) and responses were measured at all TPs, also resulting in 4 columns of the FRF matrix. Figure 2c shows the point accelerance FRFs from EMA.

In the EMA tests, four APS Dynamics electrodynamic shakers were used (2x model 400 and 2x model 133) to excite the floors. They were driven with statistically uncorrelated random signals so that FRFs corresponding with individual shakers could be evaluated. The shaker forces were measured using Endevco 7754A-1000 accelerometers that were attached to the inertial masses. Responses were measured using arrays of 20-24 Honeywell QA750 servo accelerometers that were mounted on levelled Perspex base plates, and these were ‘roved’ over the entire floor areas. Data acquisition was carried out using a Data Physics Mobilyzer II digital spectrum analyser with 24 24-bit input channels and 4 output channels to supply drive signals to the shakers.



a) Floor 1

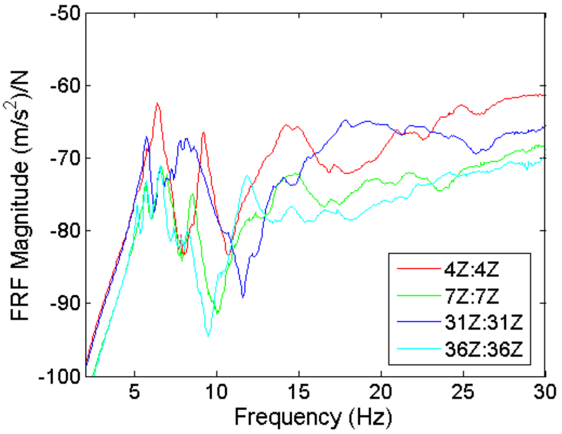


b) Floor 2

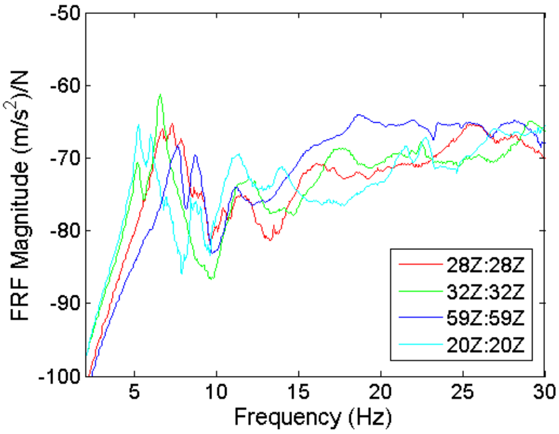
c) Floor 3

Figure 1. Floor plans for each of the floor configurations

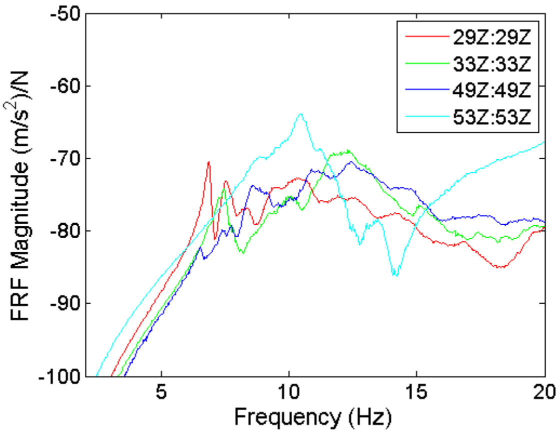
For all floors, the locations marked in blue were deemed to be the liveliest sections and for which the AVC studies were focused. Floors 1 and 2 are susceptible to human-induced vibrations from people walking within the office, whilst floor 3 suffers from transmission of vibrations from human activities in a gymnasium floor above. In all these floors, the EMA tests undertaken enabled their modal properties to be estimated, i.e. the natural frequencies, modal damping ratios, mode shapes and modal masses of the modes of interest. Figure 3 shows some selected mode shapes, identified from EMA tests, of some low modes of vibration in each of the floors. These are mode shapes from global modes identified from shakers at TPs 4 and 7 in floor 1, TPs 20 and 32 in floor 2, and TPs 29 and 33 in floor 3. Tables 1, 2, and 3 show the fundamental modes estimates from ME'scope software for each of the floors.



a) Floor 1

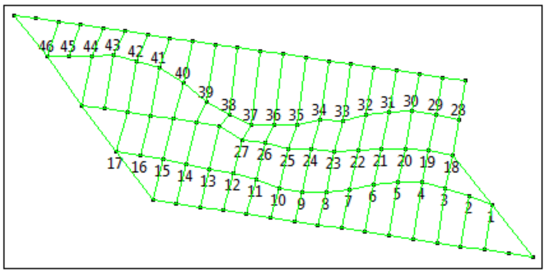
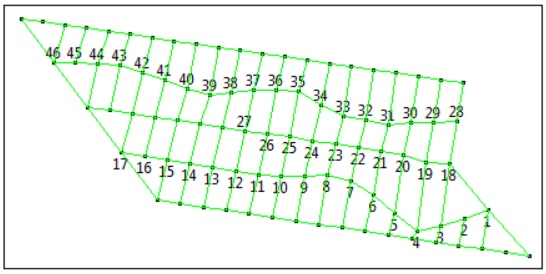


b) Floor 2

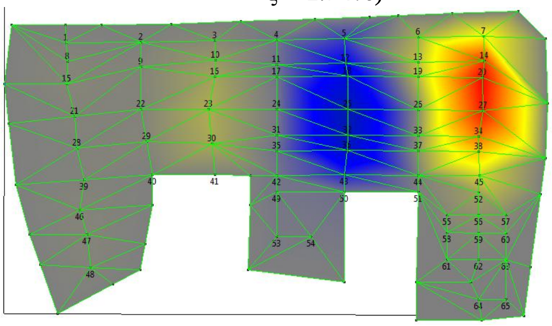
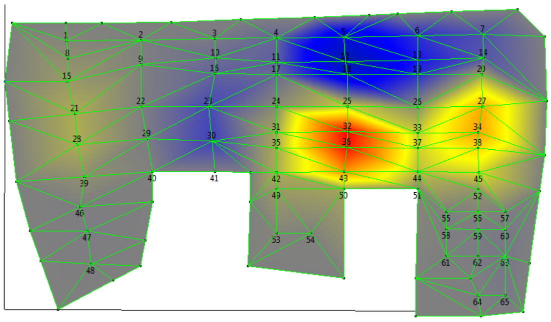


c) Floor 3

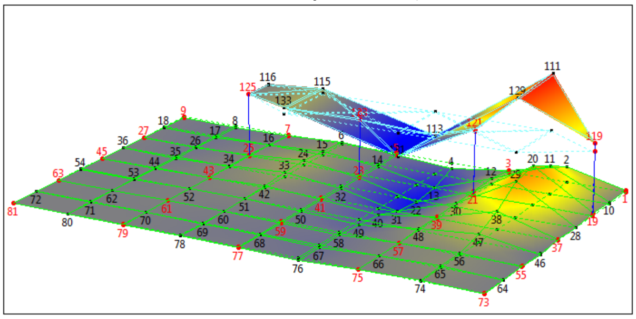
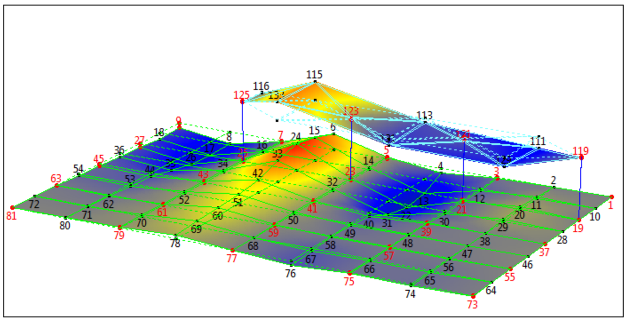
Figure 2. Point accelerance FRFs for each of the three floors

a) Floor 1 (Shaker at TP7) - Mode 1 (5.20Hz, ζ = 1.74%) Floor 1 (Shaker at TP4) - Mode 5 (6.36Hz, ζ = 2.93%)

b) Floor 2 (Shaker at TP20) – Mode 1 (5.24Hz, ζ = 4.15%) Floor 2 (Shaker at TP32) – Mode 3 (6.53Hz, ζ = 2.27%)

c) Floor 3 (Shaker at TP29) – Mode 2 (6.87Hz, ζ = 1.50%) Floor 3 (Shaker at TP33) – Mode 3 (7. 58Hz, ζ = 1.70%)

Figure 3. Typical mode shapes of vibration for selected modes

Table 1. Summary of estimated modal properties for first 5 modes for floors 1, 2 and 3

	Floor 1		Floor 2		Floor 3	
Mode	Natural Frequency [Hz]	Damping Ratio [%]	Natural Frequency [Hz]	Damping Ratio [%]	Natural Frequency [Hz]	Damping Ratio [%]
1	4.86	1.7	5.24	4.2	6.56	1.2
2	5.20	4.2	6.00	1.8	6.87	1.5
3	5.34	1.4	6.53	2.3	7.58	1.7
4	5.76	2.3	7.70	2.0	8.54	1.3
5	6.36	2.9	8.63	2.9	8.97	1.1

ACTIVE VIBRATION CONTROL DESIGNS AND FEASIBILITY

AVC controllers for each of the three floors are described comprised of collocated sensor and actuator pairs at pre-selected locations deemed to be most lively under human-induced loading as highlighted in Figure 1. These are TPs 4 and 7 on floor 1, TPs 18 and 20 on floor 2, and TPs 29 and 33 on floor 3. Typical installations of the actuator and sensor pairs in each of these floors are shown in Figures 4a, 4b and 4c. Note that TP 18 was selected in floor 2 as it was inconvenient to site the collocated actuator-sensor pair for in-service monitoring at TP32 due to obstruction from ‘services’ and desks. The global mode at TP32 was also observable and controllable at TP18 as can be seen in Figure 3. The actuators used in the AVC tests were two APS Dynamics model 400 electrodynamic shakers with four Endevco 7754A-100 accelerometers, where two accelerometers were used for providing the response/feedback signals and the other two being used to monitor the control forces. There is a limitation in this work on the number of actuators that can be deployed, which is a maximum of 2. All of the control schemes in the experimental study are implemented in dSPACE hardware (an Advanced Control Education Kit, ACE1103, consisting of a DS1103 PowerPC GX/1 GHz controller board and CLP1103 LED panel) and National Instruments Kits (2 NI cRIO-9081 chassis with 2 sets of NI9215 and NI9263 input and output modules).

Amongst the controller schemes investigated in these studies to mitigate human-induced vibrations have comprised of DOFB approaches, for example, DVF without and with compensation, RDVF, PI (proportional-integral, similar in principle to CAF), Integral Resonant controllers and model-based controllers, for example, pole-placement, LQG, IMSC types. Full details of these past controllers and associated designs can be seen in [8,9,10,7,11,12]. All the controllers used were designed with adequate stability margins and a typical DVF scheme with inner loop actuator compensation as is shown in Figure 5. Amongst the key challenges encountered in these designs included:

a) Limits being placed on the design feedback gains, particularly with DOFB approaches to prevent actuator stroke saturation instability as well as prevent high frequency instabilities, for example, with DVF.
b) Determination of suitable reduced order models (ROM) for reduced-order controller designs from EMA tests. EMA tests with the present actuators and for different floor structures are often limited to a narrow frequency bandwidth and good judgment of obtaining ROM is necessary for robust controller designs and predictions of closed-loop performances.

a) TP 4 – floor 1 b) TP 18 - floor 2 c) TP29 – floor 3

Figure 4. Typical collocated sensor and actuator pairs at TPs 4, 18 and 29 in floors 1, 2 and 3, respectively (note that the additional shaker here is used for uncontrolled and controlled FRF tests only)

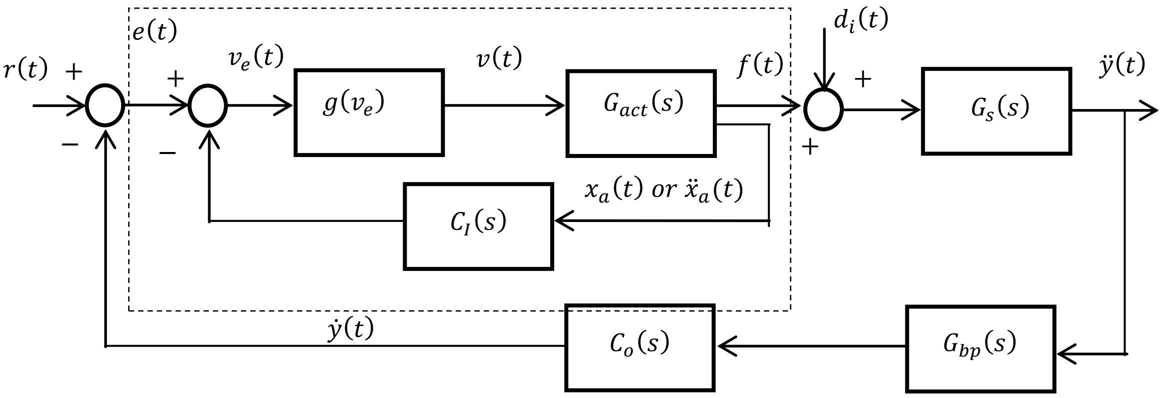


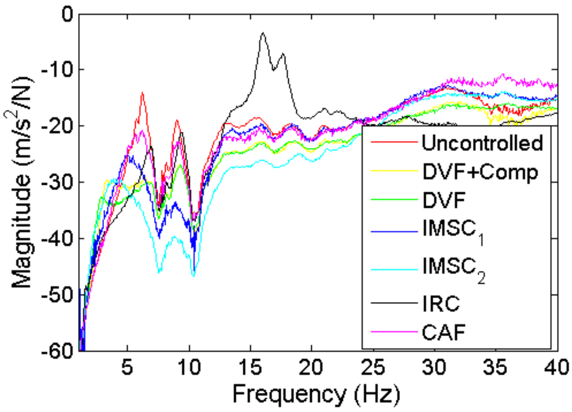
Figure 5. Direct velocity feedback with an inner loop actuator compensator

Where:

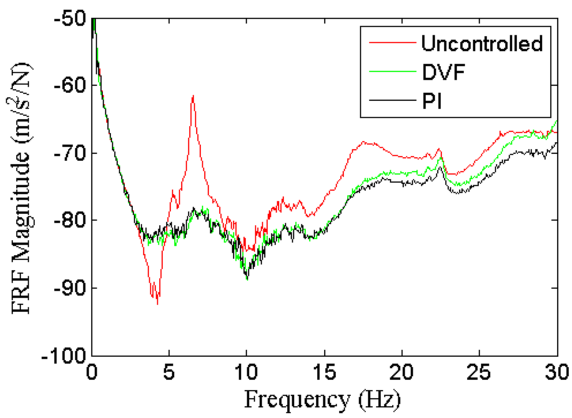
$G_s(s)$	Floor model	$\ddot{y}(t)$	Structural acceleration response
$G_{act}(s)$	Actuator model	$\dot{y}(t)$	Structural velocity response
$G_{bp}(s)$	Band pass filter (2^{nd} order Butterworth)	$f(t)$	Actuator force
$C_o(s)$	Transfer function of outer loop	$v(t)$	Final control voltage signal
$C_I(s)$	Transfer function of inner loop	$v_e(t)$	Initial control voltage signal
$x_a(t)$	Displacement of actuator moving mass	$d_i(t)$	Input disturbance
$\ddot{x}_a(t)$	Acceleration of actuator moving mass	$e(t)$	Error signal
$r(t)$	Reference signal	$g(v_e)$	Saturation nonlinearity

All field trials comprised of FRF tests, monitoring of responses to controlled walking tests and in-service monitoring studies with and without AVC. A variety of controller schemes were also investigated in each of the floors. This paper only shows findings from the point accelerance FRF tests at the pre-selected locations on each of the floor structures. Figure 6 shows the uncontrolled and controlled FRFs measured experimentally, which were found to be identical to the analytically predicted ones for the controller schemes selected in each floor scenario.

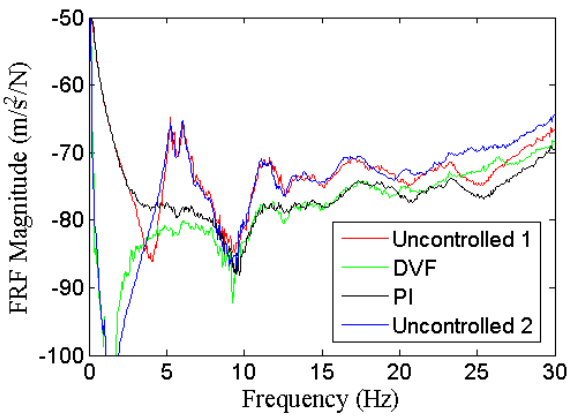
In each of the FRF tests in figure 6, there is considerable enhancement in damping characteristics for each of the floors with the AVC system in operation. Attenuations of between 13 – 18 dB in target vibration modes were realised. The noisy nature of the FRF measurements in figures 6c for TPs 29 and 33 associated with floor 3 were as a result of the on-going activities in the upper gymnasium floor when these tests were being undertaken.



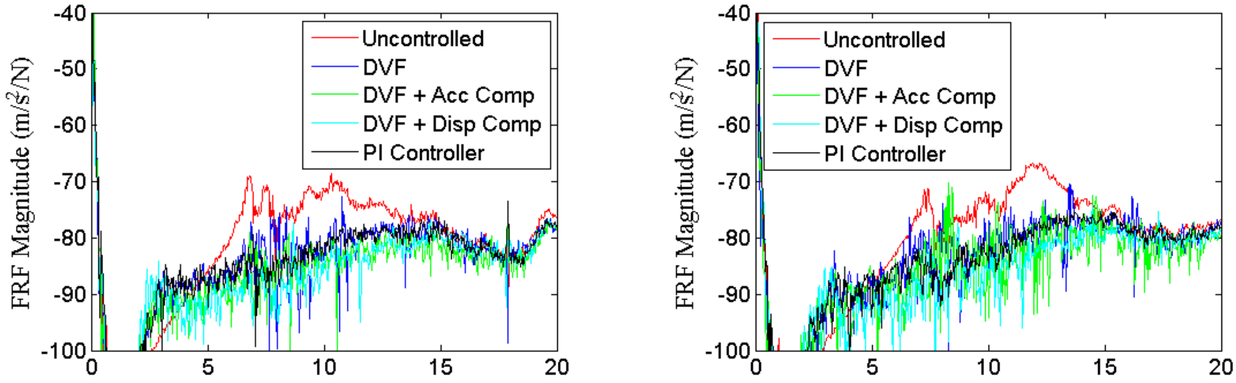
a) Floor 1 – TP4



b) Floor 2 – TP18



Floor 2 – TP20



c) Floor 3 – TP29 Floor 3 – TP33

Figure 6. Uncontrolled and controlled FRFs measured in field trials

(DVF+Comp – Direct velocity feedback with compensation, DVF+ Acc Comp – Direct velocity feedback with acceleration compensator, DVF+Disp Comp – Direct velocity feedback with displacement compensator)

A quick observation of some of the selected mode shapes in Figure 3 reflects their different characteristics. Some modes of vibration are quite localised whilst others engage several bays. These features influence their controllability and observability properties during AVC design, and as a result would dictate the feasible number of actuators and sensors needed to effectively control a given floor area. For example, considering figures 3c based on floor 3, a single actuator sited at TP29 would not be effective in controlling the dominant mode at TP33 and vice versa as the vibration modes are quite localised. Effective control of this floor would entail use of multiple combinations of actuator and sensor pairs. Considering figures 3b based on floor 2, some global vibration modes can be controlled either at TP20 or TP32 as they are observable in both locations. This floor can be controlled adequately to some extent using the two actuator-sensor pairs available. This is often an additional challenge with designing AVC systems for floor structures.

CONCLUSIONS

These field trials reveal AVC as a viable and potential technology for mitigation of human-induced vibrations in problem floors as can be seen in figure 6. There are challenges, however, that must be overcome before it can be fully realised, stemming from higher installation and maintenance costs. Additional challenges imposed by modelling errors, control and observation spillover influences, time delay issues, changes in structural properties over time as well as control design errors must be addressed in order to achieve AVC systems that offer robustness with respect to the vibration mitigation performance and stability. Comprises also have to be made with respect to location of services and hence inability to locate actuators at desired locations.

A further pertinent issue as pertains to the realisation of AVC schemes mainly arises from controllability and observability conditions which mainly arise from floor configuration, which is in turn influenced by its design. This governs how many actuators and sensors are feasible to control a given problem floor. As seen in this work, in some floors, e.g. floor 3, where the global vibration mode extends over several bays, it is possible to use a local point for control. In other floors, e.g. floor 2 where vibration modes are pretty much localised, there would be a need for multiple actuators to control all problematic modes. A judicious decision must therefore be made on the combinations of actuators and sensors needed to effectively control human-induced vibrations in a floor considered as being 'problematic' under human-induced vibrations.

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