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VIBRATION MODELLING AND PERFORMANCE EVALUATION OF SPECIALIST BUILDINGS: A DESIGNER'S APPROACH

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State-of-the-art experimental, research and development facilities often need to meet stringent low vibration limits. The accuracy of experimental work in sensitive laboratory areas requires as little influence as possible from sources of vibration, such as low-frequency footfall from people walking within the building, mechanical plant, transportation and so forth. Therefore, the dynamic performance of the building (floors, walls and all other structural elements) must be determined by, and suitable for, the processes/experiments that will take place in these sensitive laboratory areas. Numerical methods, such as Finite Element Analysis (FEA) modelling, is one of the tools for assessing and optimising the performance of a complex structure during the conceptual and design stage, prior to construction and commissioning. This paper presents the parameters that should be considered when producing an FEA model and presents the predicted vibration levels in a new science building based on typical expected sources of excitation. The measured data, following the construction of the building, also provides a unique insight into the accuracy of the assumptions and modelling uncertainties during the design stage.
Keywords: FEA, building design, vibration modelling.

1. Introduction

Specialist buildings often require a 'vibration-free' environment for housing highly sensitive processes. For instance, vibration-sensitive experimental work may involve the use of lasers, supercooled magnets, various analytical instruments, such as Scanning Tunnelling Microscopes (STMs) and Atomic Force Microscopes (AFMs). Most of these sensitive processes require a high-level of imaging resolution and normally are housed in areas which are as far away as possible from the influence of vibration.

Vibration sources may either originate from activities within the building, e.g. local footfall excitation from lab users, or people using circulation areas, such as corridors and staircases [1 and 2]. Mechanical sources housed within plant room areas can generate levels of vibration that may also have an influence on the operation of sensitive processes. Noise-induced vibration from HVAC systems may equally have an impact on the vibration performance of the labs: low-frequency noise may induce vibration in the slab of a sensitive laboratory. This is due to the fact that HVAC noise can easily manifest energy down to 10 Hz [3]. Other sources, which may induce vibration, relate to loading bay areas, e.g. daily loading/unloading of goods delivery, or scheduled activities associated with the general operation and maintenance of the building (weekly testing of sprinkler pumps in line with fire regulations, testing of emergency generators, or operation of heavy goods lifts). Additionally, there will be a multitude of vibration sources taking place outside the confines of the building, such as transportation sources (road and railway traffic to name a few), or construction vibration from nearby sites. Many of these sources are ‘uncontrolled’ by default and as such their statistical variation, and hence impact, is difficult to gauge in the medium to long term.

For building projects, it is often the case that specialist vibration design is sought to address particular requirements right from the early stages of the conceptual and design phase. However, it is not uncommon that vibration design is only sought once the design is frozen and there is little opportunity of addressing any necessary changes. Either way, traditional numerical modelling analysis methods can be used to address any potential design modifications. Finite Element Analysis (FEA) methods are now often used to model complete buildings in order to predict the dynamic behaviour of laboratory slabs. Typically, the starting point is a 3D CAD geometry of the building, supplied either by the architects, structural engineers or end client, which can then be used to develop the baseline model of the building, e.g. all structural components and foundation layout. The FEA model can then be used to assess the vibration response in sensitive laboratory environments under certain excitation conditions as mentioned earlier.

It is imperative to underline that FEA modelling of specialist buildings during the early stages of the project provides an invaluable feedback mechanism to other design members of the team and stakeholders. However, given the complex nature of modelling work and uncertainties involved in the process, predicted vibration values cannot always guarantee the performance of a building. The more complex a building structure is, the more difficult is to provide assurances that modelling predictions will reflect the ‘as-built’ performance of the building following construction and commissioning. In this paper, a direct comparison between predicted and measured vibration data on a science building is carried out. This provides an insight into the accuracy of assumptions and uncertainties during the design phase.

It should be noted that there is often the requirement for a laboratory environment to adhere to a fixed set of vibration performance requirements throughout the whole day, year and under all eventualities. However, this poses great difficulties to: a) the building contractor who needs to demonstrate compliance with the project criteria to the end client as per the legal contractual requirements, and b) the design team since it is often the case that predicted values need to be used as actual ‘guarantees’ in the project. It is easy to apply a safety margin or uncertainty factor to the predicted values, but in reality there is little headroom in the predicted vibration values especially when these are already compared against very stringent vibration requirements. Therefore, predicted values should instead be used as best estimates, given a set of input parameters, assumptions and design limitations, without any additional arbitrary adjustments.

The vibration analysis of a building also has an inherent difficulty unlike its static analysis/structural assessment: the building is exposed to a dynamic environment that is constantly evolving with time and as such its predicted vibration performance will always be bounded by the number of imposed assumptions and considerations at the time of the assessment.

2. FEA Modelling inputs

Whether it is for a simple modelling representation of a building or a more complex one, the following inputs are considered prior to carrying out vibration predictions in sensitive laboratory areas:

- All structural elements, representing the floors, walls and lift shafts are modelled as two-dimensional plate elements, so that computational time is optimised. Columns between floor levels are also modelled as two-dimensional beams with representative cross-sectional properties. However, in recent years, it seems that more buildings are adopting thicker than normal slabs, e.g. over 1 m, in order to improve their vibration performance through their increased stiffness and low mobility characteristics. Therefore, structural parts of the building having considerable thickness are more appropriately modelled as solids representing three-dimensional elements. The presence of blockwork in laboratory areas is not often explicitly modelled due to: a) the increased size of the FEA model and b) the fact that such elements do not form part of the structural fabric of the building. Heavy blockwork partitions may however have an effect on the local, higher-order modes of vibration of the building. The presence of partitions is accounted for as an additional damping factor in the FEA model. A level of non-structural mass is added to each floor level of the modelled building based on the static loading of the partitions, furnishings and any false floors, including a representative percentage of dynamic live load. Movement joints are also modelled, through appropriate boundary conditions in the translational and rotational degrees of freedom since they are designed to isolate vibration sensitive areas from plant room areas.

- The ground/substrata stiffness needs to be included in the model provided there is appropriate data from a geotechnical survey. In the case of modelling vibration propagation from external sources, e.g. road traffic, to sensitive laboratory areas in the building, the ground can incorporate Perfectly Matched Layers (PMLs) in order to supress reflections at the boundaries. Alternatively, the mass and stiffness matrices of the foundation slab of the building can be exported and coupled with an analytical representation of the ground [4 and 5]. The latter assessment can then take place outside the FEA domain. This in effect bypasses the need for PMLs, which are often used as 'black boxes' within an FEA package. In the case where the ground is not explicitly modelled, then more traditional soil-building coupling loss factors can be considered based on published empirical correction factors for typical foundation layouts [6]. However, the latter correction factors may not be so accurate for buildings with more unusual layout and foundations, e.g. a building with multiple basement levels and deep piles. Piles buried into the underlying strata can be modelled with an equivalent spring stiffness, including torsional stiffness considerations [1]. The interaction of the piles and substrata is a highly complex problem and carries a high level of uncertainty.
- Most high-performance buildings are made of concrete, rather than composite decking, and as such it is important to accurately represent the stiffness of the main structural elements through the dynamic Young's modulus of elasticity. However, it may be difficult to assign a fixed value to the stiffness of concrete over the complete lifetime span of the building. 'Cracking' of concrete may occur either at the early stages during construction, e.g. through thermal expansion and rarefaction due to temperature gradients, or at a much later stage when cracking may develop due to ageing effects or concentrated loads. However, there is no fixed rule for this effect due to the non-linear mechanism involved in the development of cracks. Typically, for non-cracked concrete, the dynamic Young's modulus of elasticity will be at least 5% to 15% higher than the static value [7].
- The level of structural damping in the building should carefully be selected and will depend on how heavily furnished, or not, each floor level is. Therefore, different values of damping are normally assigned to different floor levels of the building [2]. The chosen value of damping may have a direct effect on the predicted vibration responses, especially when the response locations are close to a resonance (or vibration mode) of a slab.

3. Comparison of FEA predicted and measured vibration data

In this section, a set of measured and predicted data is presented for assessing the impact of typical vibration sources on a new science building which would house sensitive microscopes, lasers and analytical instruments on two separate basement floor levels dedicated to experimental work.

An FEA model of the building (ground floor, two basement levels and raft foundation) was prepared based on the modelling considerations of Section 2 and vibration predictions were carried out accordingly. Figure 1 shows the FEA model with a manageable size of 60,000 nodes (or about 243,000 Degrees-Of-Freedom) in total covering a typical frequency range between 1 and 63 Hz. At higher frequencies, the modal density of the building will increase considerably with frequency and render the FEA solution computationally expensive. However, the latter frequency range is deemed to be appropriate for predicting vibration responses in sensitive labs due to primarily low-frequency excitation sources:

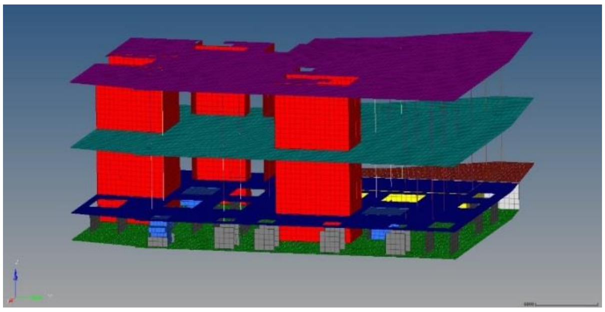

Figure 1: FEA model of a science building.

Following the construction of the building, measured data were obtained and compared against the FEA predicted data during the design phase of the project. This paper only focusses on the effect of footfall and mechanical services vibration on typical sensitive labs of the science building.

3.1 Footfall vibration assessment

In this section, a comparison of FEA predicted and measured data is presented when assessing the impact of local footfall excitation in the proximity of a sensitive lab.

For the predicted data, the assessment considers a typical continuous footfall excitation spectrum of a single 76 kg person walking at 2 paces per second, i.e. 2 Hz (fundamental frequency or 1^{st} harmonic), followed by three harmonically-related frequencies (2^{nd} harmonic: 4 Hz, 3^{rd} harmonic: 6 Hz and 4^{th} harmonic: 8 Hz). The forces at these excitation frequencies are respectively: 341 N, 73 N, 58 N and 52 N [2]. The loading location of the walker is applied to a typical location associated with the physical boundaries of the lab whilst the response location is midspan of the slab. Similarly, during the actual experimental tests, the person walked along the same boundaries of the lab, whilst vibration was measured midspan of the slab. A metronome was used to provide an acoustic feedback to the walker, so that the pace frequency was kept constant throughout.

Data is presented in the frequency range from 1 to 8 Hz and plotted against the VC-D project criterion, which is defined in 1/3 octave band centre frequencies [8]. It can be seen from Figure 2 that there is good correlation between the predicted and measured data:

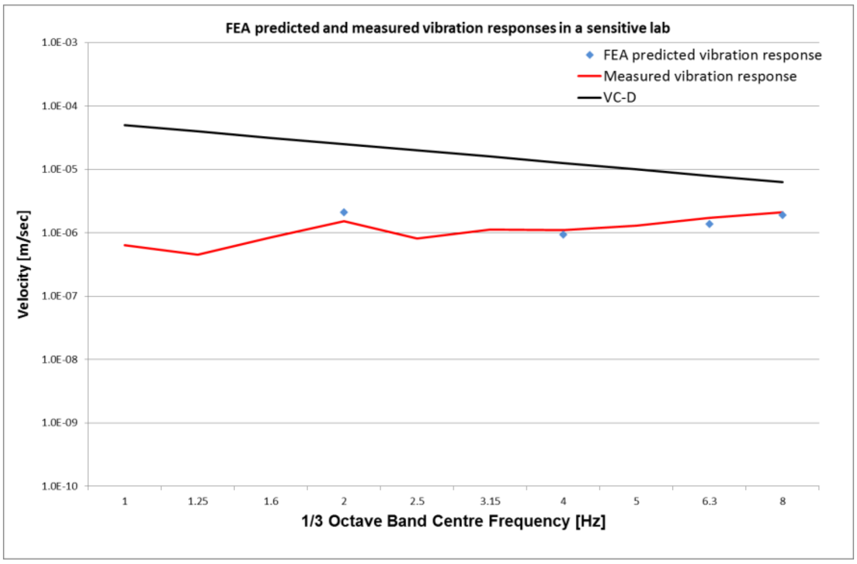

Figure 2: FEA predicted and measured vibration in a sensitive lab due to local footfall excitation.

From Figure 2, it can be seen that predicting local vibration responses, e.g. on the same floor level, can be as accurate as the measured data. This is due to the fact that the excitation and response locations are closely coupled with each other and any inherent modelling uncertainties are not so critical due to the short vibration propagation path. Also, it can be seen that despite the reduced input force in the higher frequency bands, i.e. 6 and 8 Hz, the vibration response of the slab will be higher. This is because the mobility of the slab increases as a function of frequency due to the presence of higher-order vibration modes.

In the next section, we are assessing the implications of predicting vibration when there is one floor level, or more, difference between the excitation and response locations.

3.2 Mechanical plant vibration assessment

A comparison of FEA predicted and measured data is presented here when assessing the impact of mechanical services, whilst the response locations are now situated on two different floor levels of the building.

A large electrodynamic shaker was installed on the ground floor plant room in order to provide vibration excitation all the way down to the two basement floor levels of the building. The input energy, as measured on the concrete slab of the ground floor level, was then scaled based on measured vibration data from a previous building project in order to obtain absolute levels. A set of transfer function measurements was obtained between the vibration response on the ground floor plant room and the response on the two basement levels housing the sensitive labs. As a measure of assessing the quality of the measured data, the coherence parameter γ^2 was estimated between the excitation and response locations. This parameter is used to assess whether two signals are linearly related to each other. The shaker does not generate energy below 5 Hz and in most cases it was difficult to generate adequate energy below 15 Hz, especially for vibration transmission from the ground floor level to the lowest basement level. High frequency excitation of the building between 20 and 50 Hz was more successful. Poor coherence can also be attributed to the effect of ambient vibration interference on the measured data.

Overall, only a few measurements had good coherence, close to unity, in the complete frequency range of excitation between 5 and 50 Hz. Figure 3 shows a comparison between FEA predicted and measured data when the excitation and response locations are only one floor level apart. The sensitive laboratory is in fact right under the excitation location. Also, Figure 4 shows the comparative data when the excitation and response locations are two floor levels apart. Data in both figures is plotted in the frequency range of 5 to 63 Hz against the VC-D project criterion:

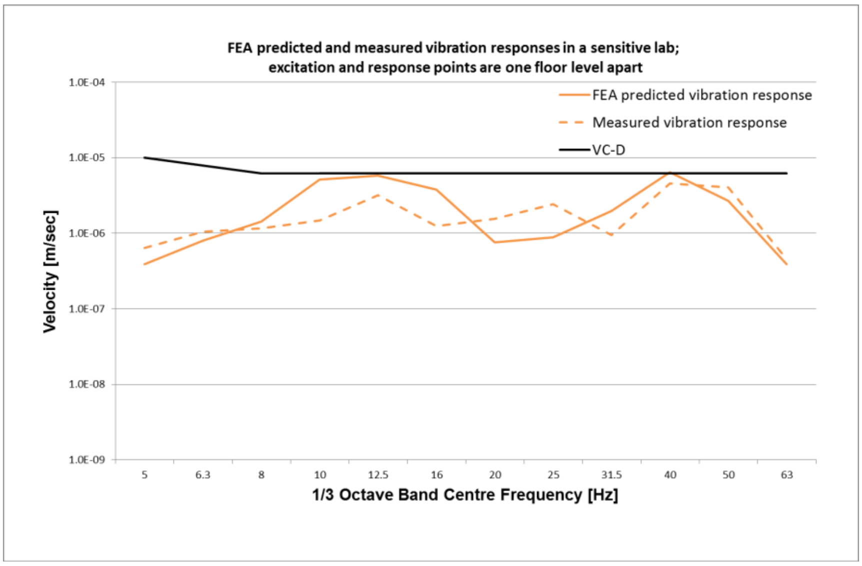

Figure 3: FEA predicted and measured vibration due to mechanical services; excitation and response locations are one floor level apart.

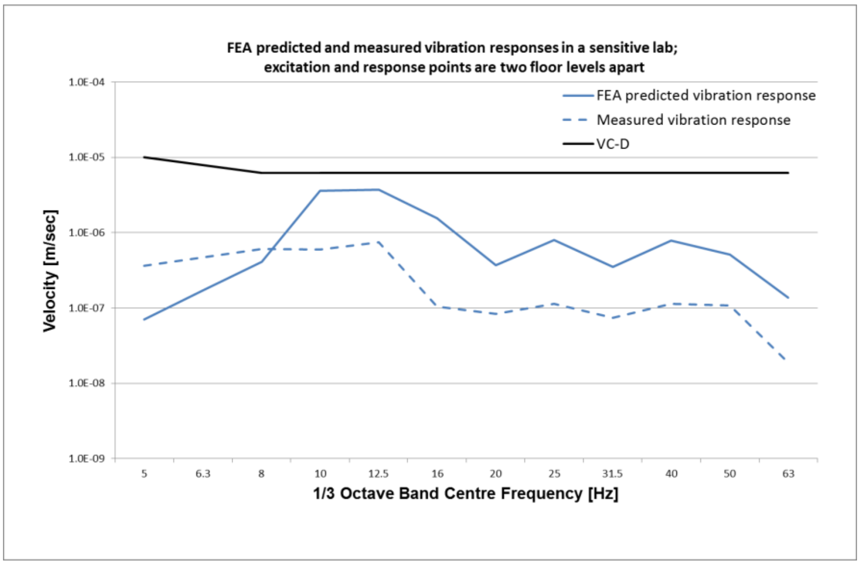

Figure 4: FEA predicted and measured vibration due to mechanical services;
excitation and response locations are two floor levels apart.

From Figures 3 and 4, it can be seen that the longer the vibration propagation path is between the source and receiver, the greater the discrepancy between the measured and predicted data. This is due to inherent differences between the ‘as-built’ and FEA modelled structure; either due to variations in the boundary conditions, or the presence of more actual damping in the building, which is more apparent over longer distances.

4. Conclusions

Traditional FEA modelling methods can be used as an indispensable tool in the arsenal of the design team when assessing vibration in new research and development facilities with stringent requirements/targets. With the advent of current computational power, FEA modelling of buildings can be carried out over much broader frequency ranges, e.g. up to 63 Hz or more, in order to cover the assessment of low-frequency footfall and mechanical plant sources extending above 50 Hz. FEA modelling effectively provides a direct means of understanding particular design aspects of the project and can help in the decision-making process. At the same time, there is a plethora of assumptions and input considerations that need to carefully be selected before providing any robust vibration predictions for such sensitive laboratory environments at the conceptual and design phases.

This paper has highlighted several issues in relation to the accuracy of the FEA predicted against measured data. The longer the vibration propagation path is between the source and receiver, the greater the uncertainty in the vibration predictions will be. This is due to inherent differences between the ‘as-built’ and FEA modelled structure, or assumptions associated with the true boundary conditions of the building. Also, when carrying out any vibration testing on site, it is particularly difficult to provide enough excitation to the building at low frequencies despite the use of an appropriate size electrodynamic shaker. This is because at low frequencies the modal mass of the building is very high and as such the whole building ‘participates’ in these low-frequency global modes. On the contrary, it is much easier to provide vibration excitation at higher frequencies, where local, higher-order floor modes are associated with lower modal masses.

Overall, there tends to be a good comparison between measured and FEA predicted vibration responses, as long as the excitation and response points are confined on the same floor level or one floor level apart, where there is a direct transmission of the energy. A careful consideration of the input modelling parameters and a good set of measured transfer functions during vibration testing complete the investigations at hand.

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