Vibration caused by human footfall has been recognised for some time and the advent of longer span and lighter structures has brought new issues to the fore. Peter Debney of Oasys Software describes how modern design and analysis software can help provide engineers with the answers

Footfall vibration and finite element analysis

The possibility of human footfall loading leading to excessive vibration of structures has long been recognised. Soldiers marching across a cast iron bridge in 1831 generated vibrations that caused the bridge to collapse; many bridges now display notices instructing soldiers to break step when crossing. Other collapses of floors and stadium structures have been induced by crowds dancing or jumping in unison.

The introduction of lightweight long span composite construction and open plan offices in North America in the 1960s led to concerns not over safety, but that normal walking caused uncomfortable vibrations for occupants of the buildings. Until this time, serviceability was checked using only simple stiffness-based criteria, such as limiting imposed load deflections to a ratio of the span.

Market drivers

There are numerous market forces causing clients to insist on floor vibration checks:

- Hospitals – operating theatres require the utmost stability for delicate operations, while night wards are nearly as onerous.
- Laboratories – equipment, such as optical and electron microscopes to laser research systems, are very sensitive to vibrations. Such floors must comply with the BBN or Ashrae standards (Fig 1).
- Airports – airport owners require maximum response values for the passenger waiting areas as floor vibrations can upset nervous travellers.
- Retail – many major retailers require a maximum liveliness for their display floors, such as where they are displaying glasses on glass shelves: if the floor is too lively then the glasses will rattle.
- Commercial – on lively floors, computer users complain because their screens wobble, making it difficult to work.

The vibration problem

For many years now, serviceability requirements have been a part of structural design. Initially, these were just deflection limits to prevent finishes from cracking and building occupants noticing the floors sagging. These proved adequate for decades, until advances began to be made into more efficient, lighter structures, such as composite beam or post-tensioned slab floors. Unfortunately, the users of these buildings found that the floors could be rather lively.

The first proposed remedy to this problem was to restrict the natural frequency of the floor beams, as it was felt that if this was kept above walking pace, then resonance should not occur. The fact that finding this frequency is a simple hand calculation encouraged this approach.

Two problems emerged with this solution however. The first was that floors are excited by the harmonics of the pedestrian's footstep frequency; the second was that while short spans had high natural frequencies, they had a low mass in ratio to the weight of a person, in comparison to long span floors that may have a low frequency but also a large floor area, making them more difficult to excite. What the industry needed was a solution for all materials and for all framing layouts.

Industry solutions

Industry experts recognised that what was needed was not a measure of the floor frequency, but of how much the floor responds to the footsteps of a person walking over it: a footfall response calculation. Various trade organisations, such as The Steel Construction Institute

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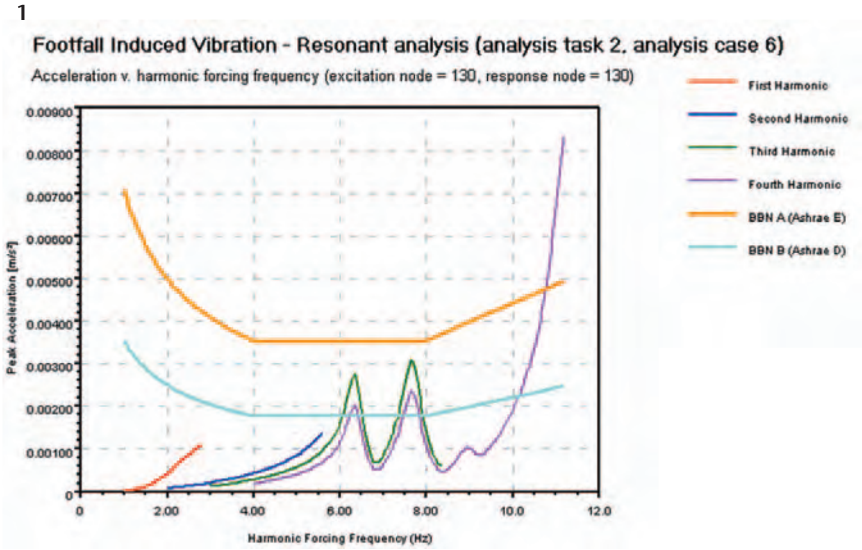

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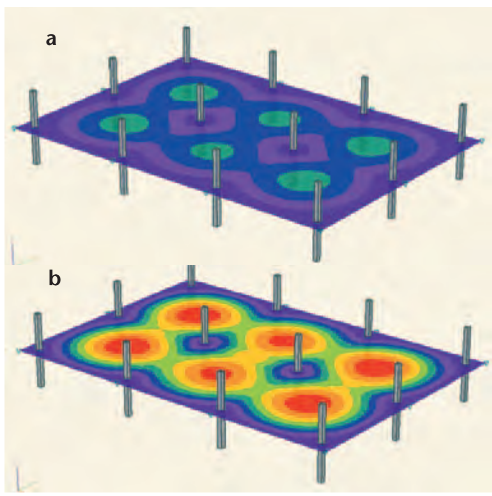

Fig 1. BBN/ASHRAE laboratory equipment check / Fig 2. Response factors a) 8m bay rc flat slab; b) 8m bay PT slab

(SCI), the American Institute of Steel Construction (AISC), and The Concrete Centre, have produced guides on how to find this floor response.

Floor vibration problems are not restricted to just steel floors; while flat slabs tended to avoid these problems, thinner post-tensioned slabs do not have sufficient mass to resist the forced vibrations (Fig 2).

Measuring vibration

There are a number of sources of vibration, or rather force excitation, in structures. Examples include footfalls from walking individuals and groups, rhythmic people inputs, such as dancing and aerobics, machinery, transportation (roads and railways – sometimes integrated with the structure) and temporary inputs such as from demolition and construction.

The three general characteristics of the way the structure responds to the force inputs are Impulsive or Transient Response, Resonant Response, and Radiation as an audible sound.

Design criteria generally considers human comfort (perceptible or tactile vibration or noise), interference with equipment or processes, and structural damage.

Response factors

The response factor (R) is simply a multiplier on the level of vibration at the average threshold of human perception. Therefore a response factor of 1 represents the magnitude of vibration that is just perceptible by a typical human, a response factor of 2 is twice that, and a response factor of 8 is eight times that (Fig 3). The response factor considers the amplitude (acceleration) and frequency of the vibration.

The difficulty with some floor vibration guidelines was that in order to reduce the complexity and avoid finite element analysis, they offered solutions only for regular, rectangular floor layouts; unfortunately, very few modern buildings have such simple framing. Some software suppliers have suggested that irregular frames cannot experience resonant problems, but in practice this is found to be untrue.

The ideal solution

The ideal methodology for assessing the susceptibility of a structure to footfall vibration would be:

- Applicable to as many structural forms as possible, whether simple or complex (Fig 4)
- Straightforward to use, enabling the consequences of various design iterations to be readily and quickly assessed
- Applicable to structures whose structural properties may be ascertained by:
  - Hand calculation type procedures under taken early in the design procedure or to verify more complex analysis
  - Finite element analysis
  - Measurement

Most of the existing published methods rely heavily on 'rules' that classify different structural forms and hence the details of the analysis to be used. If the structure does not readily fit into one of these classifications, then approximations must be made. If the underlying methodologies to the empirical rules are not fully understood then the assumptions made are likely to be inaccurate.

GSA footfall

For many years, GSA has been one of the leading PC based packages for structural analysis. Developed by Arup to meet the demanding and diverse requirements of Arup, one of the world's leading firms of international consulting engineers, GSA's capabilities are proven on thousands of complex and prestigious projects world-wide.

GSA Footfall analyses structures to the Arup method (as adopted by The Concrete Centre), The Steel Construction Institute specification, and more. Not only that, but because it analyses which floor areas have high and low responses; it enables consultants to position sensitive equipment and services or to improve problem areas in a cost-effective way.

Benefits

Full FE analysis is the only way to sensibly predict the footfall response of any floor that is not part of a regular rectangular frame. Even with a rectangular frame, the calculations are quicker using FE than hand calculations. Thus you get quick and accurate predictions of floor resonant and transient response to footfall vibrations, including Response Factors, peak accelerations, and peak, RMS and RMQ velocities (Fig 5).

GSA analysis enables you to locate regions of high and low response to enable sensible locations of sensitive equipment or activities and to assess localised modifications to floor structures for sensitive equipment or activities to minimise cost to the client. Also, because GSA is FE analysis not empirical examples, you can calculate the footfall response of any structure, including

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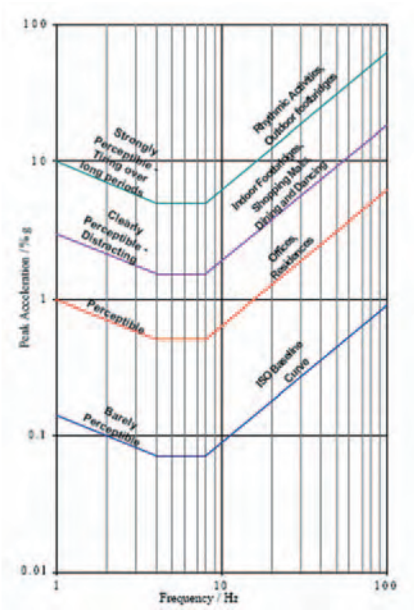

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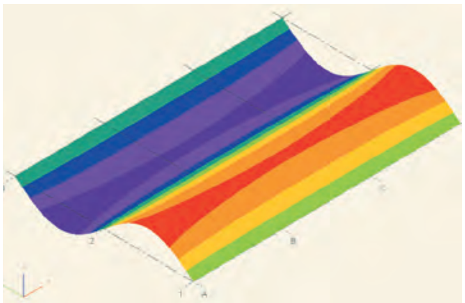

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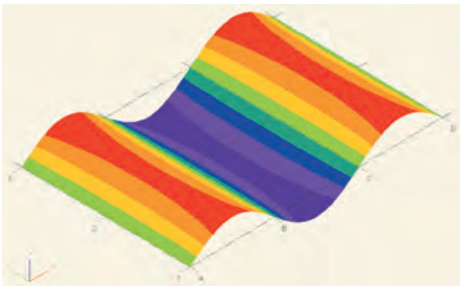

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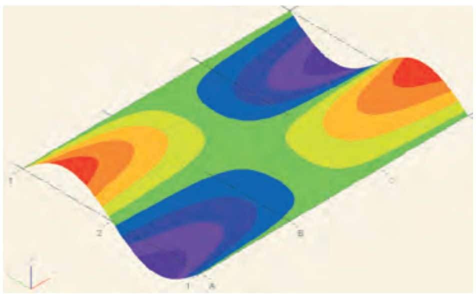

Fig 3. Building vibration z-axis curves for acceleration (r.m.s) / Fig 4. Typical floor vibration modes a) Mode 1; b) Mode 2; c) Mode 3

stairs, bridges, concrete flat slabs, and steel composite frames

Because you can define exactly where on a model to examine, you can check particular areas, such as the effect of running down a corridor next to an operating theatre. You can also examine the resonance of a structure to vibrating machinery and dance loads using harmonic analysis

Features

Modal analysis

- Choice of vibration analysis: Modal, Modal P-delta, Ritz, Ritz P-delta
- Choose number of vibration modes and start mode
- Include additional horizontal or vertical restraints
- Specify mass or derive mass from loads and self weight
- Calculate modal damping
- Include stiffening effects of loads

Footfall analysis

- Quick or full excitation methods
- Check full model or set areas
- Damping by user input values, modal damping or table
- Vary number of footfalls for resonant response
- Vary weight of walker
- Choice of excitation force methods: Arup / Concrete Centre, Steel Construction Institute, or Arup Stair
- Adjust minimum and maximum walking frequencies
- Detailed chart views of results

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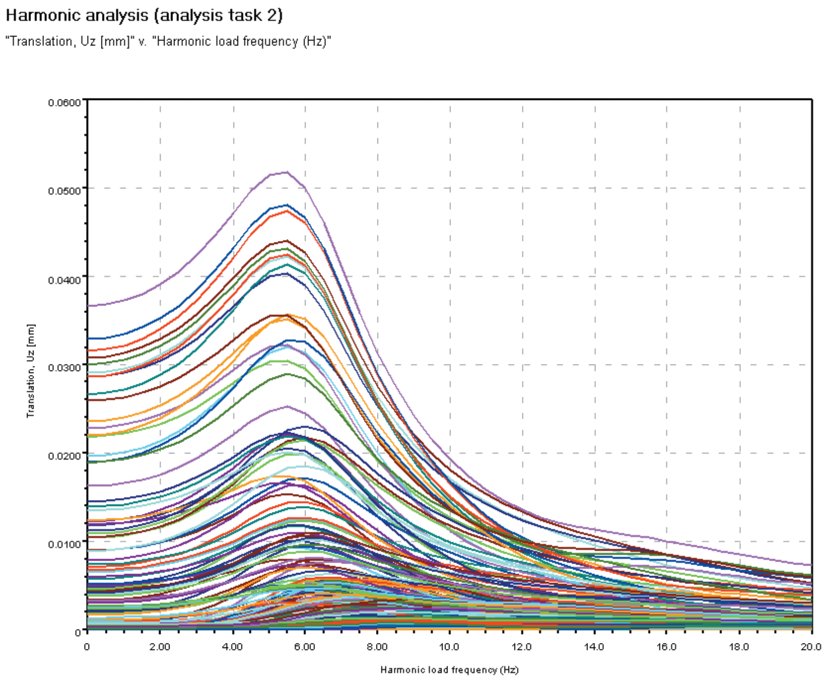

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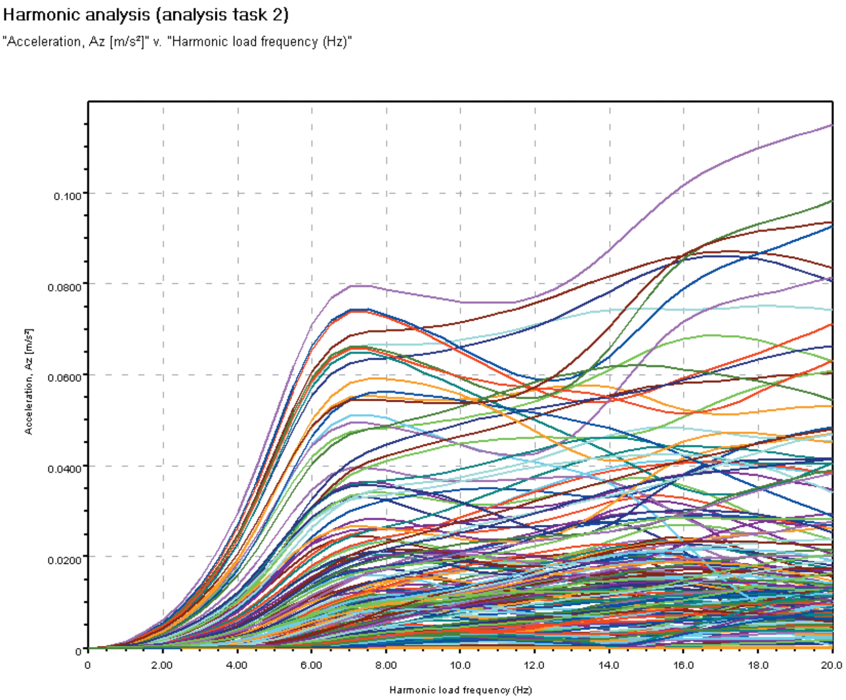

Fig 5. Harmonic analysis results a) Displacement; b) Acceleration

Harmonic analysis
- Displacement, velocity, and acceleration elastic response to steady state harmonic loading

Step-by-step guide
Sub-frame model
Create a model of the floor in question (Fig 6). As the vibration strains are so small:
- connections are generally modelled as fully fixed
- full height partitions and cladding can generally modelled as vertical restraints

As the footfall analysis is only concerned with vertical vibrations, eliminate vibrations that have no vertical component. This may not be possible for staircases and similar structures.

Modal analysis
Run a modal analysis to find the vibrations up to the limit specified in the relevant design guide (Fig 7). These are typically 10Hz, 15Hz or twice the fundamental frequency. Options include calculating the modal damping of the structure and converting applied loads to masses.

Footfall analysis
Run a footfall analysis (Fig 8). Options include method (including SCI and Arup), area of excitation, walking frequencies, and damping.

Summary
GSA Footfall is for structural engineers who need to accurately predict the response of a structure to momentary or vibrational loading. It is a finite element analysis program that provides the ability to analyse any structure for footfall response, whether steel or concrete, bridge, floor or stair (Fig 9). Unlike other programs or manual methods, it gives you the tools to assess your structure using the SCI, Concrete Centre and Arup methods. se

• Further information: Peter Debney; a free download 30 day trial version is available (tel: 0191 238 7559; web: www.oasys-software.com / GSA).

FURTHER READING

- Willford, M.R. and Young, P.: *A Design Guide for Footfall Induced Vibration of Structures*, The Concrete Centre, 2007
- Smith, A. L., Hicks, S. J., and Devine, P. J.: *Design of Floors for Vibration: A New Approach*, SCI, 2007
- Murray, T. M., Allen, D. E., and Ungar, E. E.: *Floor Vibrations Due to Human Activity*, AISC, 20031974, pp197–207

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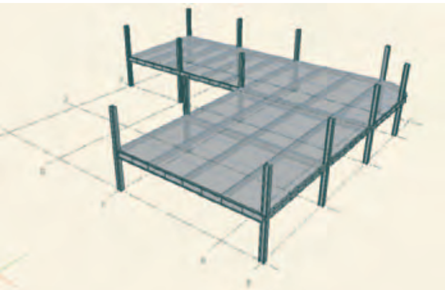

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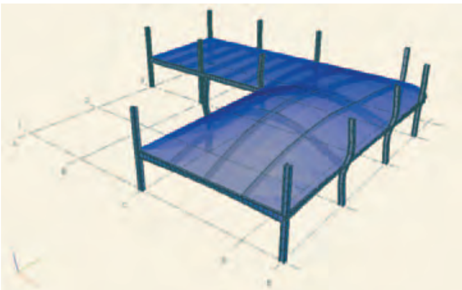

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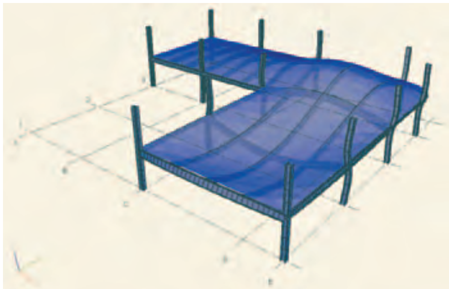

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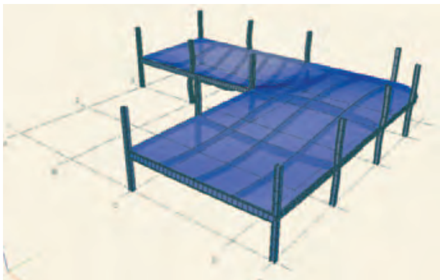

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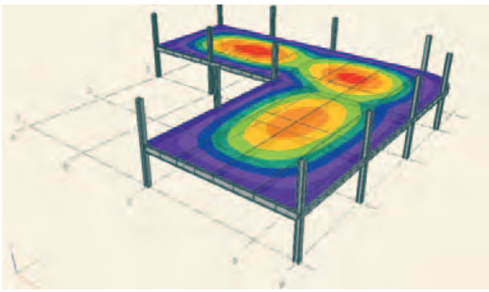

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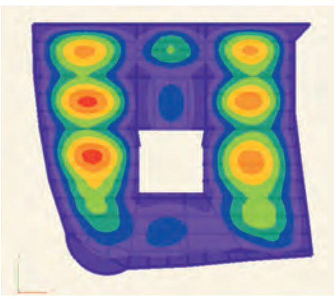

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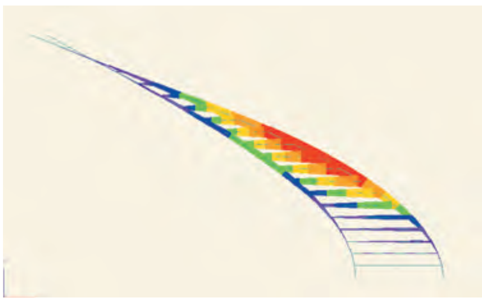

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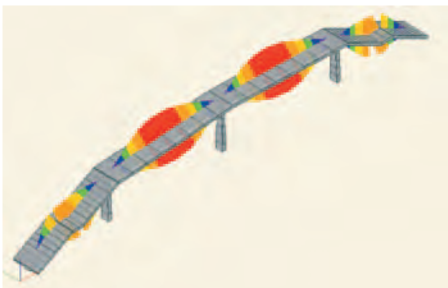

Fig 6. Composite frame / Fig 7. Modal analysis a) Mode 1: b) Mode 2: c) Mode 3 /Fig 8. Footfall results / Fig 9. a) Hospital floor b) Helical stair c) Bridge