Evaluation of Footfall Vibration in Commercial Buildings

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ABSTRACT

Structural engineers frequently use the prediction method developed by Murray to estimate the natural frequency and response of building floors to foot fall vibration.

The Murray method was developed over a long period has had several revisions and is widely used. The ASI (Australian Steel Institute) has published a design guide for common floor scenarios that enables standard floor designs to be checked for compliance against Murray's acceptability criteria of 0.5%g (0.5m/s^2) at frequencies between 4 and 8Hz.

The assumptions and simplifications in Murray's method are sometimes criticized. In addition, perceptible and potentially annoying floor vibrations have been found in floor systems that, according to his method, are deemed to be acceptable.

Consequently, field tests have been performed on three long span floor systems, including two new composite construction buildings. Measured natural frequencies and vibration amplitudes have been compared against the Murray predictions and the reasons for any discrepancies are evaluated and discussed.

INTRODUCTION

Structural engineers frequently use the prediction method developed by Murray to estimate the natural frequency and vibration response of building floors. Previous a criterion based solely on natural frequency had been used (Ref Ng & Yum).

Murray sets a criteria of 0.5% g (0.049 m/s^2 = 0.05 m/s^2) over a range of 4-8Hz. This coincides with the criterion curves in ISO 2631.2 and AS 2670.2 for offices and residences, being recommended peak accelerations for human comfort from vibrations.

In velocity terms this criterion is equal to 1.95mm/s peak at 4Hz and 0.97mm/s peak at 8Hz, or 1.38mm/s RMS and 0.69 mm/s RMS respectively.

After the establishment of a criterion, a calculation is then made of the expected footfall response as a function of the floor walking speed and harmonics. Walking motion usually varies from 75 to 125 steps/minute (spm) roughly equivalent to 1.25 to 2.1Hz. Since the floor impact is a transient pulse with a square wave profile; there are usually numerous harmonics eg. For a 2Hz step, significant harmonics exist at 4, 6, 8 and 10Hz.

MURRAY METHOD

The peak acceleration due to walking is estimated by selecting the lowest walking frequency harmonic that matches a natural frequency of the building floor. Since the vertical force applied by a person walking is 0.25 – 0.30 kN and the relative (Ref Murray) response of each harmonic is exponential, the estimated peak acceleration a_p is given by

$a_p = Po\, e^{(-0.35fn)} / \beta W$, where

a_p = estimated peak acceleration, m/s^2
Po = applied force (kN)
f_n = floor natural frequency, Hz
β = modal damping (typically 0.02 ± 0.05)

W = effective floor weight kN

The design process then becomes one of calculating the floor natural frequency. It is at this point that the Murray method becomes difficult, since due to the complex floor geometry and stiffness determination approximations are required.

The floor natural frequency, fn, can be calculated from:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$

where k = floor stiffness N/M
M = dynamic mass

or using the well known equation (where d = Mg/k)

$$f_n = 5.63\sqrt{d} \qquad \text{(d=deflection, in cm)}$$

When the expected deflection cannot be determined by advanced structural or vibration analysis (as is usually the case), it is calculated from simple beam theory and Dunkerley's equation, that is, for a distributed load:

$$\omega_n = (2\pi f) = A\sqrt{\frac{EI}{wL^4}} \text{ and } \frac{1}{f_{n^2}} = \frac{1}{f_{j^2}} + \frac{1}{f_{g^2}}$$

E = Young's Modulus, N/m^2
I = Area moment of Inertia, mm^4
f_i = Natural frequency of element i
L = Length of beam, m
w = Uniformly distributed length load per unit (actual live and dead loads) N/m
j = Joist (secondary beam)
g = Girder (primary beam),

The factor A will vary according to the end conditions. For a fixed cantilever, simply supported or fixed – fixed beam values of A are given by well known reference books. (For example for a cantilever A = 1/8, for a simply supported beam A = 1/77, and for a fixed beam A = 1/384.

Following this approach Murray gives a simplified formula for the calculation of the natural frequency of composite (steel framed grid / concrete deck) floors. For reinforced concrete structures the value of f_n must be determined by predictions (eg. Ungar) or Finite Element Modelling. In these cases, the effect of pre stressing and the behaviour of RC junctions then become very complex.

Murray determines an effective floor width Bj for joists or secondary beams and an effective width Bg for girders that enables the combined panel mode floor deflection, and hence natural frequency to be calculated.

Where Murray is sometimes criticised is in the use of an apparently arbitrary coefficient Cj for joists and Cg for girders (Ref X). For example Cj abruptly changes from 1.0 to 2.0 at an interior edge and Cg changes from 1.6 to 1.8 when joists or beams are connected to the girder web rather than the flanges. Where the girder span is less than the joist width Bj the floor stiffness is reasonably increased and the deflection reduced. In this case Murray suggests a correction to the girder deflection based on the ratio of L/B_j but this connection is restricted to between 0.5 – 1.0. In addition further adjustments are made for continuity of joists or girders, where this occurs.

As a result of these assumptions the calculation of the floor deflection and the natural frequency are at best approximations.

Figure 1 shows a typical floor grid plan (Urban Workshop).

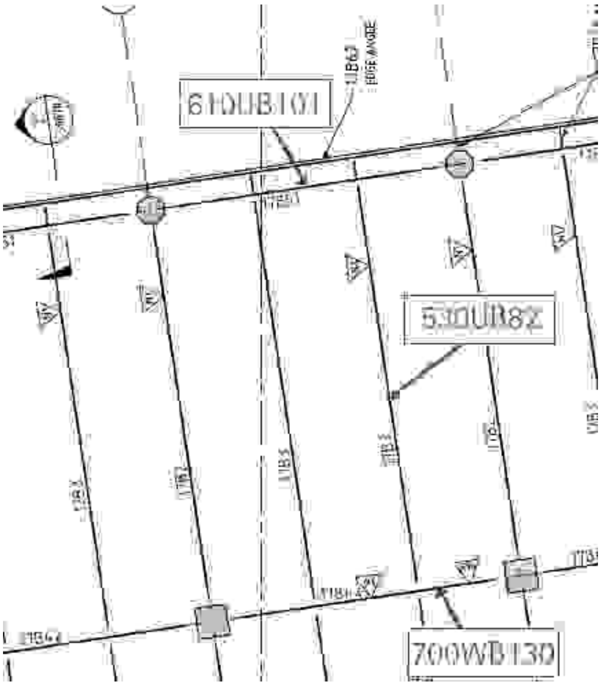

Figure 1. Urban Workshop floor grid

VIBRATION STUDY

Vibration measurements were conducted on two recently completed unoccupied multistorey composite steel commercial buildings in Melbourne. These were the Urban Workshop (50 Londsdale Street) and the Southern Cross Building (Exhibition Street).

The object of the study was to compare the measured vibration response and floor natural frequency against the ASI Code developed by Murray.

At Southern Cross it was also possible to measure on another level on which fitout had begun. This level had carpeting, services, suspended ceilings and partition fitouts, all of which are usually expected to increase floor damping from between 1-2% & 3-5%.

A brief description of each building follows

Urban Workshop

The Urban Workshop development includes two glass-office towers of 33 and 14 levels, shops, bars, outdoor bistros, café and a retail atrium precinct. All three heritage listed buildings on the site have been incorporated into this futuristic site development.

The Urban Workshop provides some $54{,}000m^2$ of nett lettable area (NLA) in a side-core configuration. Each of the 28 floor plates in the larger tower have been designed to ensure that the majority of the building's workforce work within 12m of a window. The building's podium contains a variety of interwoven spaces that support the day-to-day culture of this "New Office" building.

Southern Cross

This is new commercial building for Victorian Government Department offices, comprising 2 high rise towers. The former Southern Cross Hotel site has been transformed into a new office precinct that includes a community space and retail hub. It comprises two attractive designed office towers, a 38-level east tower of approx. 2,000 m^2 per floor and a 17 level west tower of approx 2,100 m^2 per floor that features elegant curtain wall facades and leading edge building technologies. It also includes retail and public-orientated activities at street level and a new civic space providing a diverse retail, cafe and urban art scene. Total NLA is 121,200 m^2 and there is underground car parking for 950 cars.

MEASUREMENTS

Several tests were performed at both sites, including continuous walking, single step (or jump) and floor impulse response.

Accelerometers with a sensitivity of 100 MV/g were placed at positions equal to L/2 L/4 and L/8 of the joist span and with each of the test conditions described.

Using a 4 channel OROS 763 FFT analyser and force transducers in the impact hammer it was possible to measure:

- floor fundamental frequency
- structural damping
- vibration response to each excitation type.

As described, at Southern Cross the test was repeated to evaluate the effect of increased damping on all three parameters. Then tests were conducted on level 16 (bare open plan office, and 17 (partitioned and carpeted open office) of the east tower.

Figures 2 and 3 slow the building design and partition layout of the two levels.

Figure 2. View of Southern Cross Level 16

Figure 3. View of Southern Cross Level 17

TEST RESULTS AND COMPARISON WITH THEORY

Tables 1, 2 and 3 presented the measured and predicted (acc to the Murray AISC method) vibration levels and natural frequency on two levels at Southern Cross and on Level 20 of Urban Workshop. The damping parameters used in the predictions were those recommended by Murray or Ng & Yum.

Table 1. Southern Cross, Level 16, bare floor, open plan

	Measured		
Frequency (1st mode)	5.5 Hz	4.1 Hz	+34%
Damping (%)	2.1%	2.0%	+5%
a_{max} – walking (%g)	0.6%	0.34%	+76%

Table 2. Southern Cross, Level 17, carpeted offices; partitioned

	Measured		
Frequency (1st mode)	5.5 Hz	4.1Hz	+34%
Damping (%)	2.5%	3.0%	-17%
a_{max} – walking (%g)	0.4%	0.23%	+74%

Table 3. Urban Workshop, Level 20, bare floor, open plan

	Measured		
Frequency (1st mode)	6.8Hz	4.90Hz	+38%
Damping (%)	1.8%	2.0%	-10%
a_{max} – walking (%g)	0.6%	0.32%	+75%

Detailed analysis of the results from Southern Cross also established that in some cases greater responses occurred at higher harmonics, between mode 7 (40Hz) and mode 12 (70Hz). At these frequencies the vibration response was up to 2% g for the continuous walking and 6% g for the heel drop. Under these circumstances the overall floor vibration was clearly perceptible.

Figures 4 and 5 show the vibration response to impact for bare and fitted partially out offices at Southern Cross.

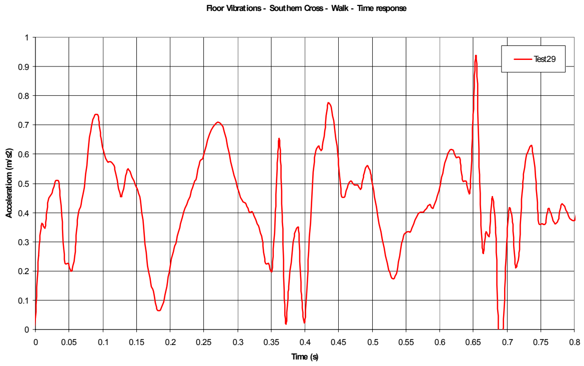

Figure 4. Floor acceleration time history

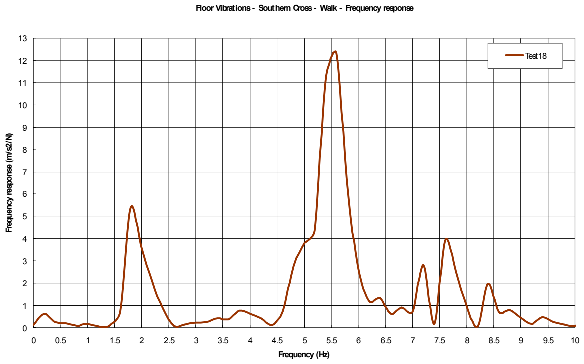

Figure 5. Floor frequency response

Table 4. Key design parameters

Project	Urban Workshop	Southern Cross
Primary beam (girder)	700WB130	610UB101
Primary beam span, m	9m	9m
Slab thickness	120mm	120mm
Secondary beam (joist)	530UB82	610UB101
Secondary beam span, m	12m	15m
Joist separation	3m	3m

FURTHER CONSIDERATIONS

When reinforced concrete construction is used the floor deflections can be predicted using the method according to Ungar. Further tests will be conducted when an appropriate (biotechnical laboratory) is completed, but the initial analysis this is a very conservative approach resulting in predictions of significant levels of vibration.

DISCUSSION

The results show that the floor natural frequency can exceed the predicted value by up to 25%. This is most probably due to the fact that the deflection theory is based on simple beams (or pinned connections) when in fact the beams are clamped.

In addition the damping, which has a significant effect on the vibration response at the natural frequency generally lies between 2-3%. This is consistent with the comments made by both Murray and Ng & Yum (ASI).

The vibration response (measured as an acceleration) at the floor fundamental is less than predicted by Murray. However, vibration at higher modes is greater than at the fundamental and can be clearly perceptible. In such cases the overall level of vibration can exceed the acceptable criterion particularly below 20Hz.

The only method of predicting floor response is prestressed concrete construction is given by Ungar but this approach is very conservative and is suspected of over predicting the magnitude of the vibration response. Further tests on a representative project will assist in evaluating this procedure.

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