State of the art on Dynamic Behavior of Structures under Human Induced Activities

G.Gajalakshmi[1], Dr. J. Abbas Mohaideen[2], Prof. A.R. Santhakumar[3],

[1]Dept. of Civil Engineering, Sathyabama University, Chennai,
[2] Maamallan Institute of Technology, Sriperumbudur,
[3]Former Dean, Anna University.
gajalakshmidhran@gmail.com

Abstract-

Traditionally, buildings constructed with concrete floors have performed well in concern with vibration serviceability. This is due to heavy weight with high mass stiffness of floors. Modern building designs are concentrated on light weight floor system, efficient structures with high strength materials. Such system of designing compromises strength as well as span length. This light weight floor and decreased mass with long and slender spans along with minimum partitions leads vibration problems in buildings. This phenomenon is often visualized in structures subjected to dynamic loads. Dynamic loads are generally generated by human activities such as aerobics, dancing, sporting events and free jumps.

Key words: Vibration, dynamic loads, acceleration, frequency, displacement.

I. PREVIOUS RESEARCH DETAILS

Many researchers made attempts in finding the solution for these vibration problems. Starting from Reiher 1931(Ellingwood, 1983), he developed the tolerance limits for steady state excitation. In 1983, Ellingwood modifiedthe concept of Reiher to account for the transient type of excitation using limit state. He suggested that large amplitude of transient motion which will be dissipated within few cycles can be accepted easily when compared to the steady state motion. His analysis confirms the observation, communicated to the writers by several practicing engineers, that no particular problems have been encountered with several floor systems that would be classified as unacceptable according to a heel drop test. Thus, the use of realistic force functions is important in assessing the sensitivity of floors to disturbing dynamic motion. He has pointed out two options from his analysis: One being low level vibrations that occur frequently and the other, a large transient vibration that occur infrequently. He also extended that force-time relationship against dynamic effects was not supporting at that time. He mentioned stiffness and mass are the criteria responsible for dynamic effects in which if stiffness is increased, it is not the solution for reducing acceleration but at the same time there is a possibility for reducing the resonance. If mass is increased for reducing dynamic responses, the solution suggested by him was to provide topping of concrete with minimal thickness. In his conclusion he mentioned maximum permissible deflection or increased span to depth ratio are not sufficient to meet the problems against vibration.

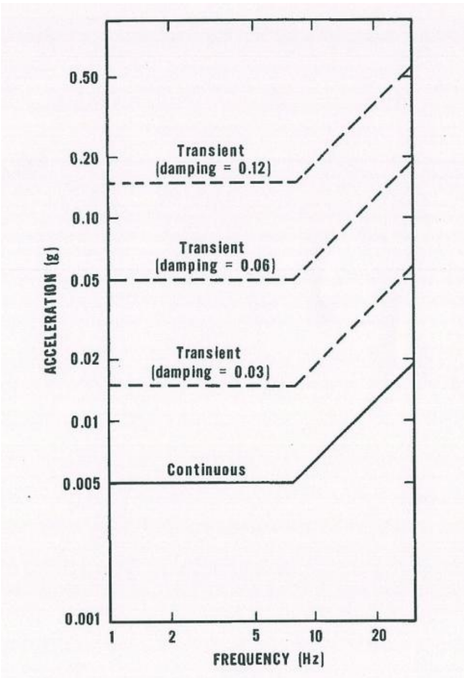


Fig.1 Frequency Vs Acceleration

Allen (1987), made several research on human induced vibration on building structures. Up to his period it was concluded that dynamic actions from human body motions were simulated by a simple harmonic function with a frequency equal to the activity rate. After few years later it was found that upper harmonics also (as part of the Fourier decomposition of the forcing function) may be critical for the dynamic design of a structure.

Table-1 Recommended acceleration limits for vibration due to rhythmic activities

Occupancies affected by the vibration	Acceleration limit, percent gravity
Office and residential	**0.4 to0.7**
Dining,Dancing,Weight-lifting	**1.5 to 2.5**
Aerobics,rhythmic activities only	**4 to 7**
Mixed use occupancies housing aerobics	**2**

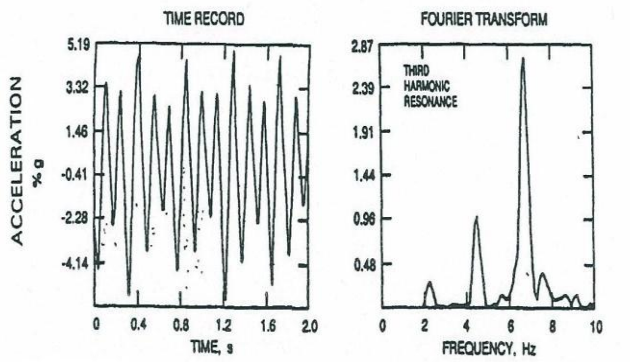
Table-2 Minimum recommended natural assembly floor frequencies, Hz.

Type of floor construction	Dance floors*, Gymnasia**	Stadia, Arenas**
Composite (steel-concrete)	9	6
Solid concrete	7	5
wood	12	8

* Limiting peak acceleration 0.02 g.

** Limiting peak acceleration 0.05 g.

Natural assembly floor frequencies, Hz3.Floors*, stadia,



Vibration of a 6.7 Hz floor due to aerobics at 2.25 Hz .

Fig-2 Vibration due to aerobics- Time Vs Acceleration

$$\frac{a}{g} = \frac{1.3\,\alpha\, w_p/w \cdot \sin 2\pi f t}{\sqrt{\left[\left(\frac{f_o}{f}\right)^2 - 1\right]^2 + \left[2\beta \frac{f_o}{f}\right]^2}} \quad (1)$$

$$f_o \geq f \sqrt{1 + \frac{1.3}{a_o/g} \cdot \frac{\alpha\, w_p}{w}} \quad (2)$$

Bachmann considered the above studies and has examined many case studies such as that of footbridges, gymnasiums and sports halls, dancehalls and concert halls without fixed seating, concert halls with fixed seating, and high-diving platforms. With these structures he studied the dynamic behavior, fundamental frequency range, forced vibration and acceleration values. He compared these values with available standards, and suggested that the structure needs to be modified in a planning stage or in the existing stage also. He adopted a method for frequency tuning of the structure. The above said cases has corrected the vibration problems and concluded that in normal cases, frequency tuning of a structure is a useful countermeasure to reduce excessive vibrations.

Later on, the necessity for check against vibration was realized. Based on this requirement along with the revision of National Building Code of Canada by Allen (1990), Farzad Naeim (1991) published Design practice to prevent floor vibration. Floor vibration under rhythmic activities is a topic under this guidance. It is mentioned that for rhythmic activities, first harmonic natural frequency is sufficient. In case of aerobics and jumping exercises, the 2nd and 3rd harmonics play a significant role which is the important part to be considered. He developed a design procedure to prevent floor vibration from rhythmic activities. He solved some problems related to the different structural properties under different usage by incorporating the design parameters from NBC.

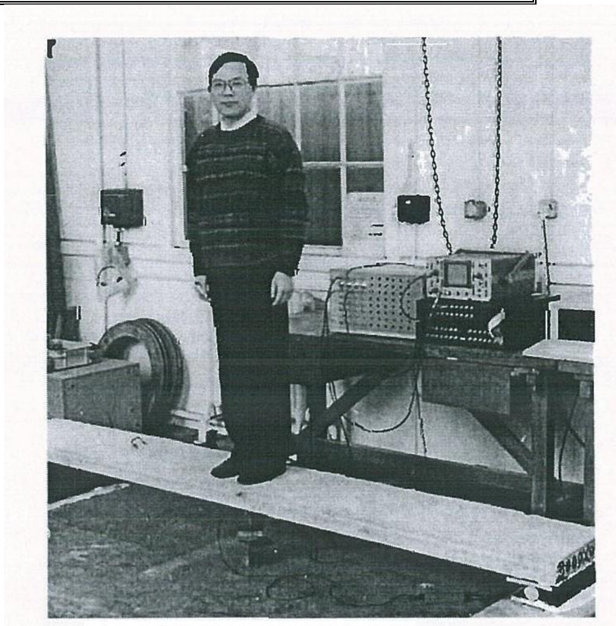
Table 3 Recommended Natural Frequencies of Structures with man-induced Vibrations

Structure type (1)	Construction Type			
	Reinforced Concrete (2)	Prestressed concrete (3)	Composite steel-concrete (4)	Steel 5
Gymnasiums and sports halls	>7.5	>8.0	>8.5	>9.0
Dance halls and concert halls without fixed seating	>6.5	>7.0	>7.5	>8.0
Concert halls, theaters, and spectator galleries with fixed seating				
With classical concerts or “soft” pop music concerts	>3.4	>3.4	>3.4	>3.4
with “hard” pop music concerts	>6.5	>6.5	>6.5	>6.5
In horizontal direction	>2.5	>2.5	>2.5	>2.5
Note: Footbridges: Avoidance of 106-2.4 Hz(with Low Damping also 3.5-4.5 Hz)				

For aerobics and jumping exercises, the first three harmonics of the forcing frequency should be considered. However, since these harmonics add together, the factor 1.3 in [15] should be increased to 2.0. Hence, the governing criterion for aerobics becomes:

Ellis (1994) described his research by comparing the analytical results of dynamic response with Finite Element and also by comparing analytical with Experimental values. This research has-been undertaken by keeping in mind that in UK the knowledge about vibration activities induced by human was there, but there was no such standards for vibration problems.

He considered dance type loading system induced by human. He concentrated on resonance response by sixth multiple of dance frequency. He concluded that based on his numerical values related to potential resonance almost verified with experiments and confirmed that significant accelerations could occur on a relatively stiff dance floor which cause serviceability problems (F11>10). He has also extended that this design criteria cannot be applicable for all types of floors based on simply supported beam. It is suggested that the structural coefficients can by considered as 1.62 instead of 1.3 for other types of floors



View of the beam used for the experiments

Fig.3 Experimental study

In the year 1997, a cover story was published under the title "Annoying floors- Help coming to keep floors from being too flexible for comfort" in Building Design on May-19th-ENR 33. The cover page is about vibration shaking of the Ballroom under synchronized dancing. For this incident, many researchers and Engineers have come out with their ideas and comments like too flexible floors may get collapsed if the damping values are low and with low stiffness. The comment of Thomas Murray was "Floor serviceability design is still a development ". It was concluded by experts that columns or posts can be added, so that in future such types of problems can be avoided. If the floor is with Theatre or Gymnasium hall, they adopted Thornton-Tomasetti devise systems of TMD.

For floor vibration, the human tolerance side of the equation by Thomsan Murray providing the comparison of tolerance criteria of North American and Europeans, has started with Tregold 1828 in his paper.

For longer spans, it should be made deeper to avoid vibration problems. Later he has mentioned so many authors view in applying parameters like Acceleration limits, natural frequency for different structural configuration and the allowance of damping. He concluded that the European criteria against human tolerance are very strict and severe than North American Criteria.

In the year 1998, under the updating article of control of vibration by D.E. Allen and G.Pernica it is suggested to counteract resonance due to rhythmic activity, the floor must be designed to have natural frequency greater than the forcing frequency of the highest significant harmonic.

He mentioned the vibration limits in terms of acceleration as percentage of gravity. In this paper they said that the vibration impact not only depend on the nature of material of the floor, its thickness and span but also depend on the nature of activity of the people. For example, people sitting or lying down in offices or residences find distinctly perceptible vibration (accelerations of about 0.5% g) unacceptable, whereas those taking part in an activity such as aerobics will accept much greater vibration (about 10% g). People dining beside a dance floor or standing in a shopping mall will find vibrations that fall between these two extremes (about 2% g) acceptable. He has pointed out that the collapse failure due to overloading the NBC requires the design against structure of natural frequency less than 6Hz.

For design purposes, the natural floor frequency (fn in Hz) can be estimated using a simple formula, in (3)

$$fn\ (Hz) = 18 / D\ (mm) \qquad (3)$$

Where D is the total deflection of the floor structure due to the weight supported by all its members (joists, girders and columns). For example, if the floor deflects 9 mm, the natural frequency is 6 Hz. To get a natural frequency of 9 Hz, the floor must deflect only 4 mm, which is practically impossible for floors supported on very long members to achieve.

2007-AVA Mello et al described the dynamic behavior of composite structures with steel beams and concrete slab of span varying from 5m to 10m. They have considered four load human induced models like jumping, walking, running, and sitting activities. In the first load model only one resonant harmonic of the load was applied on the highest modal amplitude of the floor. In the second loading model, phase angle is included. In third model the position of the dynamic loading with respect to individual position and the general time function has a space and time description. In the fourth model, human heel effect has also been considered. The structural model is analysed using ANSYS. The results obtained from the four loading models are compared with design codes of AISC and ISO to evaluate the possible occurrence of unwanted excessive vibration levels and human discomfort. In conclusion part, the

First and second load models are in good design critical compared to codes AISC and ISC. The third and fourth load models incorporate a more realistic load in which the position of the dynamic action is changed according to the individual position. On the other hand, the AISC recommendations considered only one harmonic applied in the middle of the main span of the pedestrian footbridge, without varying the load position.

According to Russell (2008) A. Parnell the fundamental frequency, static deflection and acceleration were experimentally found and compared with ATC, AISC and SCH design guides. He concluded that the reliable method is ATC and suggested the most efficient way to increase fundamental frequency is to increase the moment of inertia of the joists, which adds bending stiffness and relatively little mass. He concluded that the ATC procedure is more accurate for floor systems without a topping and ceiling, which is relevant in single occupancy residential construction. Based on the prediction of static deflection, the ATC method, in its current state, is the best option for designers. This recommendation has the added benefit of requiring one design method for calculating static condition. Several recommendations for modifying the ATC design method were made so that it will be more accurate and applicable to the materials used for cold-formed steel floor systems. The following modifications can be made to the calculation procedure:

They use design damping ratios presented in Table 4-9 when calculating dynamic response, and reduce limiting acceleration based on ISO limiting curve when fundamental frequency is above 8 Hz.

Fig.4 Human Dynamic Loading- Jumping

Silva et al obtained the dynamic loads from Faisca 2003 whereas he conducted experiments based on rhythmic andnon-rhythmic activities. Faisca concluded with the mathematical representation with human dynamic loading with weight if the person, contact period is as below

By utilizing this equation, the authors conducted analysis of 14m long span of composite floor using Finite element Method-ANSYS. They compared their results with ISO 2631-2, 1989. They concluded that results were not satisfied with the recommended codalprovisions. Such fact shows that these rhythmic activities may generate peak accelerations that violated design criteria related to human comfort.

The present investigation also indicated that these dynamic loads can even be generated with considerable perturbations on adjacent areas, where there is no human rhythmic activity of such kind present. Despite this fact there is still a surpassing of the associated human comfort criteria

M. Feldman et al in 2009 Design of floor structures for human induced vibrations states that for ultimate limit state verifications and for the determination of deflections design codes provide sufficient rules. However, the calculation and assessment of floor vibrations in the design stage has still a number of uncertainties. The uncertainties are associated to a suitable design model including the effects of frequencies, damping, displacement amplitudes, velocity and acceleration to predict the dynamic response of the floor structure with sufficient reliability in the design stage are,

- the characterisation of boundary conditions for the model,
- the shape and magnitude of the excitation,
- the judgement of the floor response in light of the type of use of the floor and acceptance of the user.

They formulated design charts based on modal mass and Eigen frequency for respective damping ratios varying from 1% to9%. This report gives a procedure for the determination and assessment of floor responses to walking of pedestrians which on one side takes account of the complexity of the mechanical vibrations problem, but on the other side leads by appropriate working up-to easy-to-use design charts.

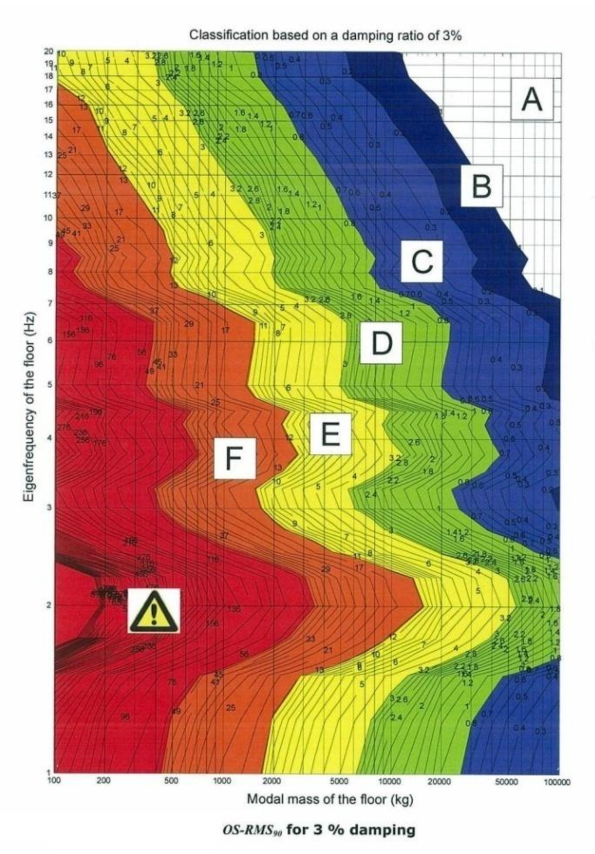
S. Sandun De Silva, David P. Thambiratnam (2009) states that steel deck composite floor with increased displacements and acceleration cause discomfort to the occupants. They analysed the composite slab system under FEM with four damping values as 1.6%, 3%, 6% and 12%.They have plotted the results one with forcing frequency Vs Dynamic amplification and second is with frequency Vs Acceleration with four damping values. Loads are applied as four different loads that could be excited with multi-modal vibration in the structural system. They concluded that load intensity alone is not responsible for vibration, the higher harmonics (2nd and 3rd) modes also cause vibration of the floor. Vibration assessment in terms of deflections and accelerations need to be considered together. The dynamic amplification in deflection and the acceleration response of the floors are

Table.4- Performance Requirement Table.

Class	OS-RMS90 Lower Limit	Upper Limit	Critical Workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Prison	Industrial	Sport
A	0.0	0.1											
B	0.1	0.2											
C	0.2	0.8											
D	0.8	3.2											
E	3.2	12.8											
F	12.8	51.2											

Recommended
Critical
Not recommended

Recommendations for performance requirements



OS-RMS90 **for 3 % damping**

Fig.5-RMS for 3% Damping

significantly influenced by the type of activity or foot contact ratio, with lower contact ratios giving higher responses.

Pia Johansson (2009) analysed the vibration of hollow core concrete elements induced by walking. In this paper, he tells that in Sweden, the hollow core elements are widely used due to its light weight and longer span structure. But the people who are walking over such structures are experiencing the impacts of vibration and they had started to give complaints generally in office buildings. Even Swedish Design code does not provide any general rules with respect to vibration, but some advices for wooden floors under vibration. In the current ISO standard concerning whole-body vibration in buildings, no guidance values regarding acceptable magnitudes of vibration are included since their possible range is too widespread to be reproduced in an International Standard. They conducted a test to investigate the dynamic response under different conditions by considering the topping of concrete. This sensitivity to the frequency content of the applied load means that it is difficult to draw any clear conclusions based on the three different load functions that were used in this study. For instance, another choice of load function may result in higher magnitudes of acceleration.

Therefore, as a suggestion for further work, and when designing for vibration serviceability, it is recommended that many different load functions may be tested, and the one that results in the highest acceleration magnitudes be chosen to be the governing load case. Another approach would be to design a load function that contains the natural frequencies of the floor structure, for instance by using Fourier series. Of course, the constructed load function must be within reasonable limits compared to results from measurements of the reaction force time history of gait loading. Because of the limited time frame of this paper it was not possible to try these approaches.

Author D.Varela, Rolando C Battista (2011) suggests the usage of passive control system for the lack of damping against vibration problem. They considered TMDs-tuned Mass Dampers which is economical, low maintenance, and considerably efficient. It can be designed in different shapes and sizes as per the requirement. They conducted tests over the composite floor deck induced by six volunteers walking. Volunteers are allowed to walk over the slab and finally they gave their feel during walking and one may feel by standing and others are allowed to walk and with different probable situations were made. All of the volunteers changed their opinion positively on the vibration level when the TMDs were in full operation as compared to the situation when the TMDs were locked .When the TMDs were locked, half of the volunteers felt uncomfortable, and the other half could not tolerate the vibrations. When the TMDs were released, four of the six volunteers classified the vibrations as only perceptible, one of the other two classified them as imperceptible, and only one still classified them as uncomfortable. Moreover, better results could be achieved with extra units of the same TMD, that is, by increasing the ratio between the TMD mass and the structural modal mass. They have proved that using such type of passive control system reduces the vibration impacts and it is improving the dynamic response of the structure which can be recommend in any type of usage.

They developed a numerical model using FEM SAP 2000 for the effect of change in various floor parameters on vibration performance of timber floors. The parametric study under this research involves varying the joist spacing, joist depth, sheathing thickness and nail spacing. The corresponding fundamental frequency, modal separation factors and Rms acceleration values are obtained and tabulated. They concluded human induced activity like footsteps loading cannot be isolated as it is the main source of floor vibration especially if made of timber. It is advised to consider the vibration analysis during design process itself.

The author from his study found that under human induced activity like walking, jumping which creates vibration problems are consistent with that. To control such vibration problems they investigated the dynamic performance of an innovative Hybrid Composite Floor Plate System (HCFPS). It is made of Polyurethane (PU) core, outer layers of Glass–fiber Reinforced Cement (GRC) and steel laminates at tensile regions. They conducted experiments using Finite Element (FE) modeling, included heel impact and walking tests for 3200 mm span HCFPS panels. Their results were compared withISO 10137 and BS 6472 and concluded that the first mode natural frequency of HCFPS floor system is greater than 10 Hz and hence HCFPS can be categorized as a high frequency floor system. The maximum possible fourth harmonic of the walking frequency (2.4 Hz) is lower than the first mode natural frequency and this makes resonant vibration a rarity.

Human - structure interaction system has been analyzed

by Nicholas Noss. They concluded saying that it is expected that the crowd characteristics, including size, density, distribution, and posture, will affect the dynamic properties of the empty structure, including natural frequency, damping ratio, and possibly mode shapes.

II. CONCLUSION

From the above literature study, it is observed that the understanding of the human interaction to the structure is a complex phenomenon. All researchers arrived some equations and formula from their input data based on the corresponding activities from human. Even current designs guide uses the natural frequency for assessing the vibration serviceability. But the dynamic interface between passive occupants and the structure can alter the natural frequency of thee system. The dynamic response are depending upon the posture of the occupants , the dynamic properties of the structure and the mass of the people inducing activities like jumping, walking, aerobics . There is no straight calculation available for fundamental frequency under human rhythmic activities. Even if a single person is doing any type of activity, it may generate perceptible levels of vibration in many floors. The results obtained from previous researchers are noteworthy, but are limited in their application because the data is sparse, disjointed, and lack continuity.

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