Structures with Human-Induced Vibration – How Serviceability Requirement Improves Vibration Design Concept

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1. Introduction

In the past few years, human body motions have quite often caused serious structural vibration problems. We have seen several excessive vibration problems caused by human motion during the service of structures. Human-induced vibrations were sometimes not considered in vibration suppression design due to the fact that the problem itself is primarily serviceability problem. Main considerations for structural dynamic design are safety against the occurrence of major vibration impact to the structures such as: earthquake, wind-induced vibration, traffic-induced vibration or/and impact-induced that might lead to structural failure at a catastrophic level. Human-induced vibrations, which were perceived only as serviceability problem in term of annoyance and disturbance to the users, accordingly have not been addressed properly in design code.

Several latest reports on cases, where human-induced vibrations were found excessive and annoying, however, have changed the common perspective on this problem. The closing of Millenium Bridge in London right after its completion due to excessive human-induced lateral vibration is one major case that took public attention. Thus following this report and some other previous cases, researcher, structural engineers and building authority have work together to accommodate users convenience requirements (serviceability) to provide better structures that suppress the anticipated human-induced vibration.

It is in author perception that this phenomenon has emerged as one challenge in structural dynamic resulted from the feedback of structure's users to obtain better structures performance. In this report a state-of-art of structures with human-induced vibrations is presented. The report is arranged in the following sections: cases of human-induced vibration, study of human-structure interaction, ongoing investigations and research, and some recommended countermeasures.

2. Cases of Human-Induced Vibrations

There are several important types of structures that likely suffer from human-induced vibrations (Bachmann 1992):

1. Footbridge or pedestrian bridge
2. Gymnasium and sports halls
3. Ballroom, concert halls, theatres with or without fixed seats.
4. High-diving platforms in swimming pools

These structures suffered from several types of rhythmical human activities that might lead to almost periodic dynamic forces acting on structures. Such activities are often performed as response to music (such as the case of vibrating concert halls) or to synchronize motion when several more people involved (such as the case of gymnasium and pedestrian bridge). Since the dynamic forces in most cases increase almost linearly with the number of participants, it is important to check the possible dynamic forces induced by human motion for design purposes. Thus, the following representative activities *en ensamble* were recommended to be checked: (1) walking, (2) running, (3) jumping, (4) dancing (5) hand clapping with body bouncing while standing, and (6) lateral body swaying. These motions induce significantly vertical force vibration and occasionally lateral vibrations. Most of the problems in human-induced vibration caused by resonance that occurs when the forcing frequency of input human activities mentioned above correspond to fundamental natural frequencies of structures.

3. Design Improvement and Remedial Measures

For treating the human-induced vibration problems in planned or existing structures, in general the following measures are recommended:

1. Frequency tuning the structure, which is based on the frequency of critical harmonic of the type of activity that were representative of the dynamic forces likely to be anticipated acting on structures. This measure is basically designed to avoid the occurrence of resonance between structural fundamental frequencies with the input dynamic force. Detail of frequency tuning: analysis and experimental results will be presented in the following section.
2. Calculating the forced vibration response of the structure and comparing the amplitudes with acceptance criteria. In special cases, lower structural frequencies than those resulting from frequency-tuning criteria are possible and may be accepted
3. Enforcing special countermeasures such as stiffening of the structure, increasing damping, or applying active or semi-active control measures
4. Restricting the use of structures and avoiding several activities inside the structures.

3.1. Frequency Tuning

Frequency tuning is the most favourite countermeasure. Frequency tuning the structure is a simple measure that has proved to be efficient in numerous cases. In this measure, the fundamental natural frequencies of structure are kept away from the range of critical harmonics of human activities. Several applications of this measure, which were based on experiments are given in Bachman and Amman (1984) and listed here as examples:

a. Footbridge or Pedestrian Bridge: avoidance of the frequency of the first harmonic of dynamic force from walking with the range of 1.6~2.4 Hz
b. Gymnasiums and sport halls: fundamental frequency of floors must be higher than the second harmonic of the dynamic force from jumping (3.4 Hz)
c. Dance and concert halls: fundamental frequency of floors must be higher than the second dynamic force of dancing (3.0 Hz), and so on.

In the case of existing structures, additional stiffening or damping must be installed to achieve the aforementioned prerequisite. In term of structural modification, several cases of frequency tuning were reported in literatures. Some basics structural modifications by frequency tuning are recommended as feedback from reported excessive human-induced vibration.

3.1.1. Footbridge

One interesting report of structural modification was reported in [Bachman 1987] is the modification of Footbridge in Switzerland. From several measures proposed (i.e. increasing the height of wall parapet walls, increasing the weight of railing portion, altering the span ratio and haunching the slab over the intermediate supports), the authority finally adopted the span-altering-ratio measure to raise the natural frequency from ~2.0 to ~2.4 Hz and reduce the vertical acceleration due to human motion to only ~4% g. Since this additional measure was performed in 1988, no further complaints were known from users.

A German report in 1972 quoted by Bachmann and Ammann in their IABSE book (1987), described how a new steel footbridge had experienced strong lateral vibration during an opening ceremony with 300-400 people. They explained how the lateral sway of a person's centre of gravity occurs at half the walking pace. Since the footbridge had a lowest lateral mode of about 1.1 Hz, the frequency of excitation was very close to the mean pacing rate of walking of about 2 Hz. Thus in this case *"an almost resonating vibration occurred. Moreover it could be supposed that in this case the pedestrians synchronised their step with the bridge vibration, thereby enhancing the vibration considerably"* (Bachmann, 1992). The problem is said to have been solved by the installation of horizontal tuned vibration absorbers.

3.1.2. Gymnasium Hall

One example of frequency tuning to suppress human-induced vibrations in Gymnasium hall was reported in Ontario Canada. (Bachmann 1984). The two-storey gymnasium showed severe vertical vibration during service, which was caused by the jumping activities. Further investigations and dynamic testing of the floor revealed that the fundamental frequency of the floor was ~4.9 Hz, while the strongest response of major jumping activities were recorded at ~2.48 Hz. This means that the second harmonic force caused by jumping activities excited the floor resonance. To improve the structure serviceability and to avoid effect of fatigue to the floor, the fundamental floor frequency have to be brought to ~ 7.5 Hz. And this can be achieved by increasing the stiffness. Additional bottom flanges were installed on the bottom of the beams made of still plate composite. This measure brought new fundamental frequency to ~7.3 Hz. Further details of frequency tuning to suppress human-induced vibration can be found in Bachmann (1984).

4. New Challenges in Current Design Improvement and Remedial Measures

Modifying the existing structures by frequency tuning or by installing additional stiffness and damping maybe simple and practical measures. However, there exist cases where the human-induced vibration becomes more complicated. In the most cases human-induced vibration were seen as a forward system, where there is no feedback to human motion due to the structure response. In this sense the vibration is one-way system – so to speak. However, the latest investigation (Fujino 1993) reveals that human motion is in fact an interactive system, in the sense that human's responses to vibrations induced by human motion are synchronized. In structure like pedestrian bridge this phenomenon was reported. This phenomenon offers new challenge to the human-induced vibration, since the conventional measures usually used to study human-induced vibration cannot satisfactorily be applied. Some cases of these synchronized human-induced vibrations are detailed in the following sections.

4.1. London Millenium Bridge: Synchronization Human Motion

London Millenium Bridge is a pedestrian bridge located across the Thames River in Central London. The bridge opened on 10 June 2000. For the opening ceremony, a crowd of over 1000 people had assembled on the south half of the bridge with a band in front. When they started to walk across with the band playing, there was immediately an unexpectedly pronounced lateral movement of the bridge deck. This movement became sufficiently large for people to stop walking to retain their balance and sometimes to hold onto the handrails for support. Video pictures showed later that the south span had been moving through amplitude of about 50 mm at 0.8 Hz and the centre span about 75 mm at 1 Hz approximately. Probably higher amplitudes occurred periodically and several modes were involved. It was decided immediately to limit the number of people on the bridge, but even so the deck movement was sufficient to be uncomfortable and to raise concern for public safety so that on 12 June the bridge was closed until the problem could be solved. It was not reopened to the public until 22 February 2002.

There was a significant wind blowing on the opening days and the bridge had been decorated with large flags, but it was rapidly concluded that wind buffeting had not contributed significantly to vibration of the bridge. Another possible explanation was that coupling between lateral and torsional deck movements was allowing vertical footfall excitation to excite lateral modes, but this was not found to be a significant factor. Evidence in support of this conclusion was that the 1 Hz mode of the centre span was the span's second lateral mode; with nodes at its centre and at the two bridge piers, this mode had practically no torsional movement.

It was realised very quickly that the problem was one of lateral excitation and although allowance had been made for lateral forces it had not been expected that pedestrians would so easily fall into step or that the lateral force per person would be as great as was apparently proving to be the case. Some similar experiences had been recorded in the literature, although these were not well known and had not yet been incorporated into the relevant bridge building codes. In (Bachmann 1992), human-excited lateral bridge vibration is said to likely occur for pedestrian bridges which have low natural frequencies of swaying movement (less than 3 Hz) and for which the lateral modes have light damping. In the case of London's Millennium Bridge, both these conditions applied. Further investigation by Arup (construction consortium) revealed that the concept of human motion synchronisation turned out to be very important, and a later paper by (Fujino et al. 1993) was discovered which described observations of pedestrian-induced lateral vibration of Toda Bridge, a cable-stayed steel box girder bridge of similar size to the Millennium Bridge. It was found that when a large number of people were crossing the bridge (2,000 people on the bridge), lateral vibration of the bridge deck at 0.9 Hz could build up to an amplitude of 10 mm with some of the supporting cables whose natural frequencies were close to 0.9 Hz vibrating with an amplitude of up to 300 mm. By analysing video recordings of pedestrians' head movement, Fujino et.al concluded that lateral deck movement encourages pedestrians to walk in step and that synchronisation increases the human force and makes it resonant with the bridge deck. The findings were summarised follows: "The growth process of the lateral vibration of the girder under the congested pedestrians can be explained as follows. First a small lateral motion is induced by the random lateral human walking forces, and walking of some pedestrians is synchronised to the girder motion. Then resonant force acts on the girder; consequently the girder motion is increased. Walking of more pedestrians is synchronised, increasing the lateral girder motion. In this sense, this vibration was a self-excited nature. Of course, because of adaptive nature of human being, the girder amplitude will not go to infinity and will reach a steady state."

Although Fujino records the damping ratio of the 0.9Hz lateral mode as $\varsigma = .01$, they found that only 20% of the pedestrians on the main span of the bridge were completely synchronised to the girder vibration and the amplitude of vibration was only 10 mm (compared with 75 mm for the Millennium Bridge). Impressions from video clips of the Millennium Bridge are that a good deal more than 20% of walkers had synchronised their step. Also in Fujino's example, the very large movement of the suspension cables (300 mm amplitude) may have made these act as dynamic vibration absorbers and so limit the extent and consequences of synchronisation.

It was clear that data specific to the Millennium Bridge was urgently required and Arup undertook an extensive programme of testing to obtain this. In addition to commissioning tests on human gait and how movement of the walking surface affects this, the main tests were carried out on the bridge itself. These included artificially shaking the bridge to confirm mode shapes and damping and a comprehensive series of crowd tests. Detailed vibration measurements and video records were made with pedestrians walking at different speeds and densities on each span. These allowed reliable quantitative data on the synchronous lateral excitation phenomenon to be established and a self-excitation model to be developed which could give a reliable prediction of structural response.

One solution would have been (Bachmann 1992) to stiffen the bridge to increase its natural frequencies and take these outside the excitation frequency range. However it seems that the artistic design of the bridge would have been compromised by stiffening and this was regarded as most undesirable. In Dallart (2001), the alternative was to find a way of increasing the bridge's inherently low damping so that self-excitation did not occur. It has been found that, below a threshold damping level, motion would build up, but that above the threshold damping level, self-excitation would not occur. Determining what this threshold level was and then providing a means of introducing the required amount of added damping proved a challenging task. It has involved adding 37 linear viscous dampers and over 50 tuned mass vibration absorbers to the initial structure. As a result, this bridge is now probably the most complex passively damped structure in the world.

After the reopening of Millenium Bridge, several other footbridges human-induced lateral vibrations were reported. Solferino Bridge in Paris is one recent example. The bridge is immediately closed after its opening in 1999. A 100 year-old footbridge in Ottawa Canada also experienced strong lateral vibration in July 2000, when subjected to crowd loading, in this case by spectators of a fireworks display. And the most recent report was the George Washington bridge in New York which experienced lateral vibration last year when hundreds of people crossing the bridge during the famous New York blackout.

5. Conclusions and Recommendations

The Millenium Bridge case tells us, of how limited the current state of knowledge of the lateral loading effect induced by human motion in footbridges. Unlike the vertical human-induced loading effect which has been subjected to many research project, the loading effect on movable surface like lateral movement of footbridge has not yet been well studied and quantified. The specification for design of pedestrian bridge: The AASHTO (1997) was found inadequate to address the vibration phenomena observed in the Millenium Bridge (Dallart 2001). The British (BSI 1978) code, which contains clauses that limit the acceleration for pedestrian bridge is found in contrary to the phenomena occurred in Millenium Bridge. Both code thus need to be modified.

The lesson from Millenium Bridge, in author's opinion is one good example of how the feedback of structure service and observations improve the understanding of structural vibration under service load. In order to develop design code suitable for human-induced vibration, a fundamental understanding and the quantification of human-induced of the loading effect would be vital. Further research on this matter is required with main emphasis on the quantification of following effects such as:

1. variation in human respective motion in the terms of speed, footfall rate and footstep synchronisation that might be induced during structure service
2. effective excitation forces induced by human motion in vertical and lateral direction on movable or unmovable structure surface as function of amplitude and frequencies in such a way that can be applied in design code

In conclusions, human-induced vibrations, might lead to serviceability problem in term of annoyance and disturbance to the users. It sometimes is not considered in vibration suppression design code. The lack of specification in current design code represents the limited current state of knowledge in loading effect of human-induced vibration. In the normal cases frequency tuning a structure is a useful and effective countermeasure. In special cases, where the synchronisation of human motion is observed adding large amount of damping to suppress excessive motion might be necessary. A better understanding and quantification of loading (excitation loads) caused by human-induced vibration is needed and must be addressed in the future design code as a part of the structure serviceability requirements.

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