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Analysis of Dynamic Loads Induced by Spectator Movements in Stadium

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***Abstract*—**In the stadium structure, the significant dynamic responses such as resonance or similar behavior can be occurred by spectator rhythmical activities. Thus, accurate analysis and precise investigation of stadium structure that is subjected to dynamic loads are required for practical design and serviceability check of stadium structures. Moreover, it is desirable to measure and analyze the dynamic loads of spectator activities because these dynamic loads can not be easily expressed in numerical formula. In this study, various dynamic loads induced by spectator movements are measured and analyzed. These dynamic loads induced by spectators movement of stadium structure can be classified into the impact load and the periodic load. These dynamic loads can be expressed as Fourier harmonic load. And, these dynamic loads could be applied for the accurate vibration analysis of a stadium structure.

***Keywords*—**stadium structure, spectator rhythmical activities, vibration analysis.

I. INTRODUCTION

EXCESSIVE vibration of a stadium structure can be caused by spectator movements, and the spectator rhythmical activities could lead to such dynamic behavior as resonance of stadium structure. Therefore, examination of the safety and serviceability of a stadium structure is required. The NBCC of Canada firstly pointed out the vibration of a structure induced by rhythmical human movements in 1970 [1]. In 1975, the natural frequency of a structure was restricted to a certain limit in order to protect from the resonance damage caused by human movements. Design criteria for the structures subjected to rhythmical movements based on the dynamic load and structure response were introduced in 1985. ATC and AISC of the USA apply the CSA(Standard of Canada) for the structural design [2],[3]. The stadium structure consists of the stand structure, which is subjected to dynamic load of the spectator movement, and the frame structure, which supports the stand structure and the roof structure. The vibration caused by spectator movement occurs in the stand structure or the frame structure, but the roof structure is hardly affected by spectators. Therefore, the examination of the safety and serviceability of the stadium structure design is conducted based on the vibration analysis results of the stand and frame structure. Accurate analysis of the dynamic behavior of a stadium structure is necessarily required for its rational design. For an accurate analysis of the dynamic behavior of a stadium structure, an actual dynamic load induced by the spectator movement should be applied. In this study, the dynamic loads induced by various spectator movements are measured and analyzed, these dynamic loads are applied for the accurate vibration analysis of a stadium structure.

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II. EQUIPMENT FOR MEASURING OF DYNAMIC LOADS

Above all, an accurate analysis of the stand structure vibration is necessary to evaluate exactly dynamic loads induced by spectator movements. Thus, the various dynamic loads induced by spectators' movements are measured and analyzed exactly. Spectator movements are manifested in various ways such as sudden rising and sitting, foot tapping, upper body swaying and jumping in place. These dynamic loads induced by spectators movement can be classified into impact load of sudden movement and periodic load of repetitive movement [4].

The various dynamic load induced by spectators movement is measured with the exclusive load cells for this study. This load cell that is piezoelectric force platform type is 40m by 40cm in size. Electronic charge linearly proportional to the force were generated when force platform were loaded. And Amplifier and A/D board are used for load data conversion in real time. Sampling rate is 100 samples/sec. Spectator movements often frequently observed at stadium were duplicated on the force platform. Fig. 1 shows the data conversion process of dynamic loads measured by load cells [5].

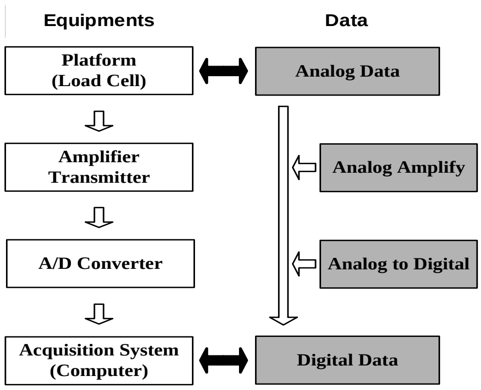


Fig. 1 Measuring process of dynamic loads

III. Impact Load due to Spectators' Sudden Movement

Spectators' sudden rising, sitting and jumping is classified as impact load because these loads occur in a very short time. Fig. 2 depicts the dynamic loads induced by spectator sudden rising and sitting movement. These loads are measured with load cells that are placed on the spectators' foot and hip.

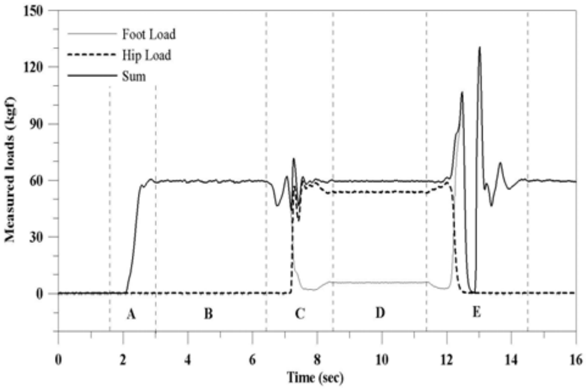
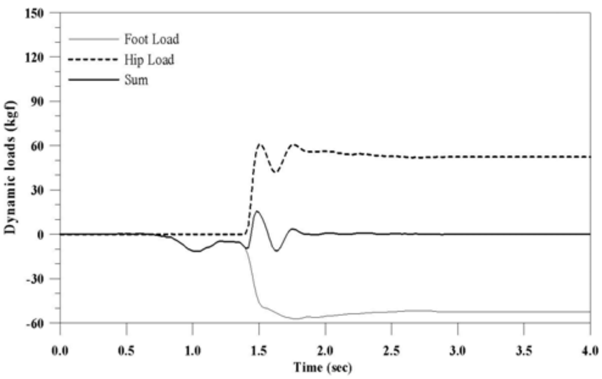
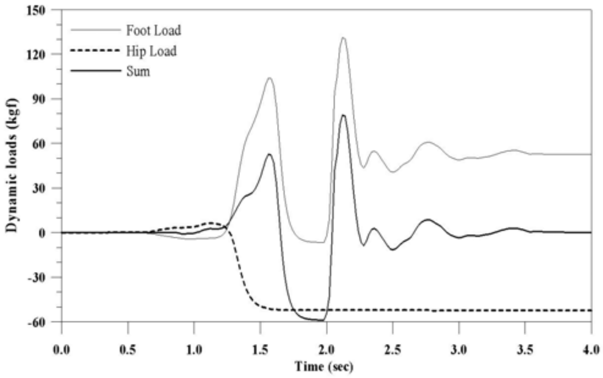


Fig. 2 Dynamic loads of spectators' sudden movements

In Fig. 2, the region A depicts the dynamic load measured with the load cell on the foot when the weight of the subject shifts to the foot (i.e. when the subject stands). The region B illustrates the static load of the subject whose weighs 60kgf as the weight of the subject is already exerting on the load cell already. The region C represents the dynamic loads induced by the subject's sudden sitting. This dynamic load is larger than the subject's weight because of the impact effect. And then the load of the foot is close to zero, and most of the load is carried on the hip when the subject sit suddenly on the stand. Region D illustrates the static load of the subject having seated, and most of the load has been shifted to the hip. Very little weight is carried on the foot. Region E is the dynamic load resulting from the subject's sudden rising and jumping. The load measured on the foot is smaller than the subject's weight because the dynamic load exerts in the direction opposite to the gravity. In this case, the dynamic load shows a large value because of the impact effect induced by the subject's rising and jumping.



(a) Sudden sitting down



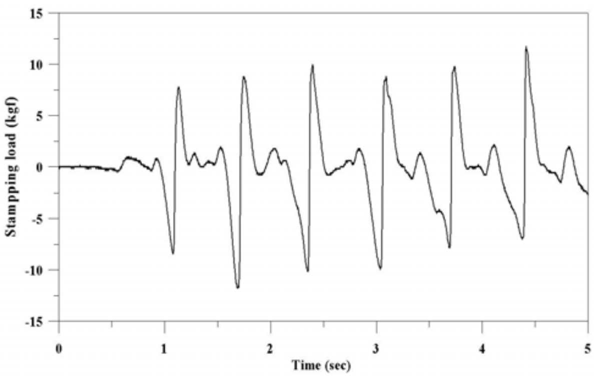
(b) Sudden standing and jumping up

Fig. 3 Impact loads due to spectators' sudden sitting down and standing up

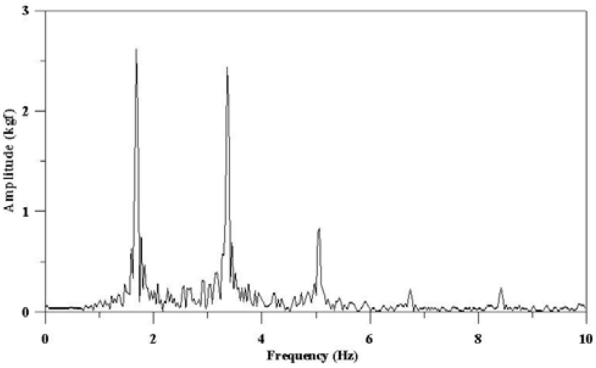
Fig. 3 shows the dynamic load and impact load with time as the subject sits down or stands up suddenly. The load cells on the foot and hip were calibrated to zero before measuring the dynamic load. When a subject sits down suddenly on the stand seat, the impact load is manifested on the hip. The impact effect is very small as shown in Fig. 3 (a). When a subject stands up suddenly for jumping from the stand, the impact load of the feet peaks at two locations as illustrated in Fig. 3 (b). The first peak point results from the impact effect of the subject's rising up, and the second peak point is brought about by the impact of the subject's jumping up.

IV. Periodic Loads due to Spectators' Repetitive Movements

Among spectators' movements, waking and jumping in place, upper body swaying, foot stamping are classified as continuous and periodic dynamic loads. These continuous and periodic dynamic loads can result in a very bad influence on the safety and serviceability of a structure. Accordingly, the subjects were instructed to perform a series of movements in synchrony with the periodic signal of a metronome, and then the dynamic load of the subjects' movements was measured.



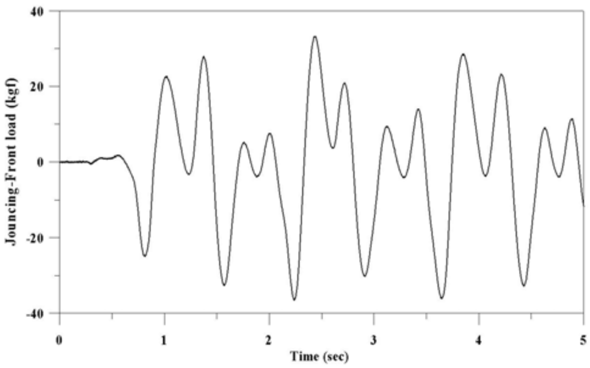
(a) Dynamic load due to foot stamping



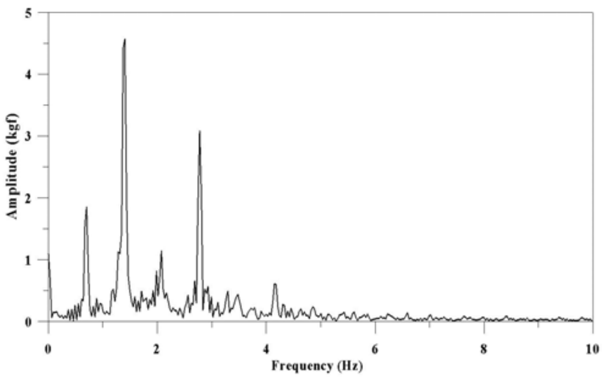
(b) Load spectrum associated with foot stamping

Fig. 4 Dynamic load due to spectators' foot stamping

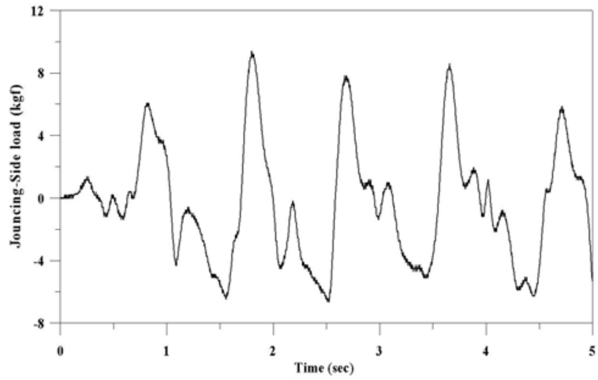
Spectators may stamp their feet to the sound of a drum or any signal in cheering. The dynamic load on the stand induced by the spectators' foot stamping (one foot is fixed on the stand as the other foot stamps) is shown in Fig. 4. The periodic signal for the stamping is given by a metronome of 1.7Hz frequency. The dynamic load due to stamping is similar to the continuous impact load as shown in Fig. 4 (a). The peaks at approximately 1.7Hz, 3.4Hz and 5.1Hz frequency of the load spectrum in Fig. 4 (b) are presented in three series of stamping frequency because human beings can not physically generate the loads at higher frequency.



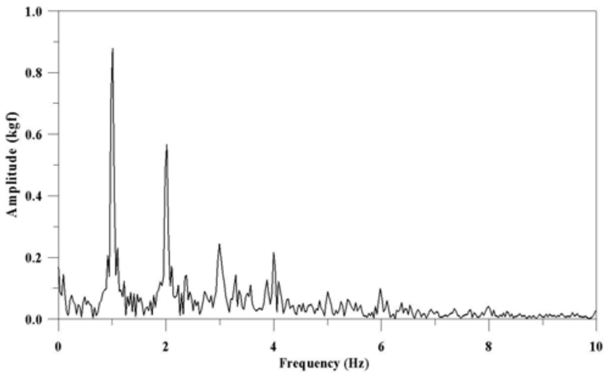
(a) Dynamic load due to swaying back and forth



(b) Load spectrum of swaying back and forth



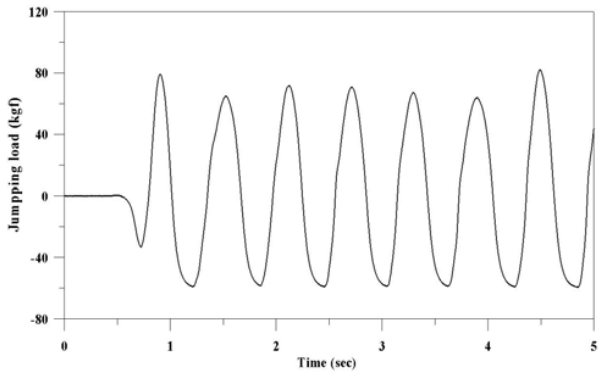
(c) Dynamic load due to swaying sideways

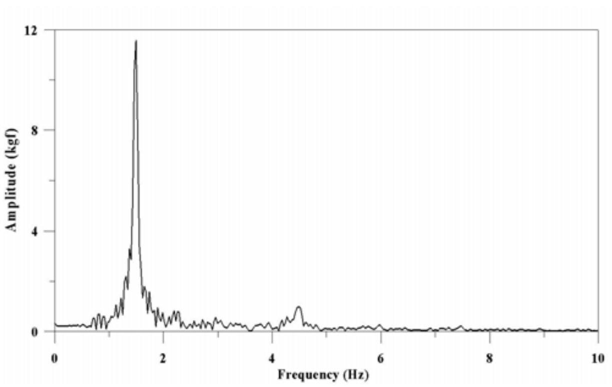


(d) Load spectrum of swaying sideways

Fig. 5 Dynamic load due to upper body swaying

Fig. 5 (a), (b) show the dynamic load and load spectrum induced by swaying back and forth of the upper body. The period of swaying of the upper body back and forth is 1.4 second, but the load amplitude of bending oneself backward is shown differently from that of bending forward. The peak load amplitude occurs at the frequency of 1.42Hz, which is about one half of the period of the swaying of the upper body. The forward tilting of the upper body is greater than the backward tilting in terms of the movement. So the dynamic load is shown larger when the subject bends oneself forward. Fig. 5 (c), (d) show the dynamic load and load spectrum induced by swaying of the upper body sideways. The dynamic load of swaying sideways is smaller than that of upper body bending back and forth because the movement of tilting the upper body sideways is smaller than the movement of bending back and forth. The period of swaying the upper body sideways is 2 seconds. The characteristic of the dynamic load is very similar regardless of the direction of tilting to the right or to the left. Accordingly, the dominant frequency of the dynamic load due to swaying sideways is 1.0Hz, which is one half of the period of the side movement.





(a) Dynamic load due to jumping in place

(b) Load spectrum of jumping in place

Fig. 6 Dynamic load due to jumping in place

The dynamic load of the spectators jumping repetitively in place is shown. This dynamic load is the largest among the dynamic loads induced by spectators in the stadium stand in Fig. 6 (a). Fig. 6 (b) shows that most of the energy input due to this spectator movement is confined to the basic frequency at 1.7Hz because the period of repetitive jumping is 0.6 second. The energy input at 3.4Hz and 5.1Hz, which are double and triple of the basic frequency, respectively, is very little. Additionally, the dynamic load induced by jumping in place can be simply expressed as a Fourier harmonic load.

V. Conclusions

An analysis of dynamic loads induced by spectators' movements is necessary for an accurate vibration analysis of stadium structure. Thus, the various dynamic loads induced by spectators' movements are measured and analyzed in this study.

The dynamic load due to the spectators' movements can be largely classified into two categories. One is the dynamic loads with the pattern of an impact load induced by spectators' sudden movements such as sudden sitting, sudden rising, sudden jumping in place. The other is the continuous and periodic dynamic loads induced by spectators' walking, upper body swaying, foot stamping, and jumping in place. And the dynamic load induced by spectators' foot stamping and upper body swaying shows that the amplitude is larger by a multiple of an integer than the load frequency, and most of the dynamic load induced by jumping in place appears at the natural frequency of the load.

Acknowledgment

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