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Human-Structure Dynamic Interaction

DEEPAK KUMAR[1], MD MOGHIS[2]

[1,2]*Department of Civil Engineering*

IIMT College of Engineering, Greater Noida(India)

ABSTRACT

This paper reviews more than 130 pieces of essential literature pertinent to the problem of human-structure dynamic interaction applicable to the design of civil engineering structures. This interaction typically occurs in slender structures occupied and dynamically excited by humans by walking, running, jumping and similar activities. The paper firstly reviews the literature dealing with the effects of structural movement on human-induced dynamic forces. This is the first of two aspects of human-structure dynamic interaction. The literature dealing with this aspect is found to be quite limited, but conclusive in stating that structural movement can affect the human-induced dynamic forces – significantly in some cases. The second aspect considered is how human occupants influence the dynamic properties (mass, stiffness and damping) of the structures they occupy. The body of literature dealing with this issue is found to be considerably larger. The published literature demonstrates beyond any doubt that humans present on structures should not be modelled just as additional mass, which is a common approach in contemporary civil engineering design. Instead, humans present on structures act as dynamic spring-mass-damper systems interacting with the structure they occupy. The level of this interaction is difficult to predict and depends on many factors, including the natural frequency of the empty structure, the posture and type of human activity, and in the case of assembly structures, relative size of the crowd compared with the size of the structure. One of the reasons for the existence of more papers in this area is the published biodynamical research into the mass-spring-damper properties of human bodies applicable to the mechanical and aerospace engineering disciplines. It should be stressed that results from this research are of limited value to civil engineering applications. This is because human bodies are, in principle, non-linear with amplitude-dependent dynamic properties. Levels of vibration utilised when experimentally determining mass-spring-damper properties of human bodies in biodynamical research are usually considerably higher than those experienced in civil engineering applications.

Keywords: literature review, human-structure interaction, dynamic occupant models, civil engineering.

I.INTRODUCTION

In civil engineering dynamics, human-induced vibrations are an increasingly important serviceability and safety issue. In recent years, there has been an increasing number of problems related to human-induced vibrations of floors, footbridges, assembly structures and stairs. Human-structure interaction is an important but relatively new consideration when designing slender structures occupied and dynamically excited by humans (Ellis and Ji, 1997).

Human-structure interaction is a complex, inter-disciplinary and little researched issue. To summarise the existing knowledge, this paper reviews two key areas of human-structure interaction:

(1) how structural vibrations can influence forces induced by human occupants (section 2) and

(2) how human occupants influence the dynamic properties of civil engineering structures (section 3).

Focusing more on the latter issue and limiting it to passive sitting or standing people, biomechanics research and models of the human whole-body are then reviewed (section 4). Furthermore, investigations analysing and modelling human occupants on civil engineering structures are presented (section 5). Next, research into the potential of human occupants to absorb vibration energy is reviewed and, finally, conclusions are presented.

II.EFFECTS OF HUMAN-STRUCTURE INTERACTION ON HUMAN-INDUCED FORCES

Human occupants can induce dynamic forces on civil engineering structures by various activities such as walking, jumping, dancing, or hand clapping. Research into quantifying such human-induced forces has been ongoing for many decades (Tilden, 1913; ASA, 1932; Galbraith and Barton, 1970; Nilsson, 1976; Matsumoto et al., 1978; Wyatt, 1985).

Since about 1980, experimentally established human-induced force time histories have usually been approximated by Fourier series. Thereby, the common key assumption is that the human-induced forces are perfectly periodic. The factors corresponding to each sinusoidal component of this Fourier series are named dynamic load factors (DLFs) and are reported in a number of publications (Pernica, 1990; Bachmann et al., 1995; Kerr, 1998). However, assuming human-induced forces as perfectly periodic is questionable because they are in essence narrow-band (Eriksson, 1994). An alternative approach is to define human-induced forces as auto-spectral density (ASD) functions (McConnell, 1995) in the frequency domain (Ohlsson, 1982; Tuan and Saul, 1985; Mouring and Ellingwood, 1994; Eriksson, 1994).

Dynamic forces induced by crowds are an issue of great concern (Kasperski, 2001), as can be seen in an increasing number of publications dealing with crowd-induced vibrations. Nevertheless, the quantification of crowd-induced forces still needs additional research. In particular, the dependency of the nature and magnitude of induced forces on the size of the active crowd and perceptible motion of the structure is currently not clear (IStructE, 2001).

Although it has been found that dynamic loads induced by groups of people are higher than those induced by individuals, the human-induced forces do not increase linearly with the number of people. This is so even if people are synchronised by a prompt (Ebrahimpour and Sack, 1992; Kasperski and Niemann, 1993) that can be provided by music, movements of other people, or perceptible movements of the occupied structure (Fujino et al., 1993; van Staalduinen and Courage, 1994).

Int estingly, visual and audio contact between people influences and, in principle, improves the syn oading, and thus amplif rom the oldest tory re perly amusing themselves, by trying the extent of this motion, produced such an agitation in all its parts, that important. It can lead to structural vibrations strong enough to disturb people in their movement (Da nic. used by this phenomenon, design proposals by Schulze (1980), Vogel (1983), Slavik (1985), Grundmann and Schneider (1990) and Gr little understood phenomenon, was prompted by strong pedestrian-structure er

chronisation of individuals (Hamam, 1994; Ebrahimpour and Fitts, 1996). Generally, the synchronisation of people on civil engineering structures can be deliberate or unintentional. Deliberate synchronisation, as in aerobic classes or cases of vandal lication of vibrations has been an important issue for a long time. The following quote freference in this review (Stevenson, 1821:243-4) clearly demonstrates this: It is observed by Mr John Smith, one of the gentlemen above alluded to, that when the original bridge of Dryburgh was finished, upon the diagonal principle like Fig. 2, it had a gentle vibramotion, which was sensibly felt in passing along it; the most material defect in its construction arising from the loose state of the radiating or diagonal chains, which, in proportion to their lengths, formed segments of catenarian curves of different radii. The motion of these chains wefound so subject to acceleration, that three or four persons, who were very impro one of the longest of the radiating chains broke near the point of its suspension. After almost 200 years, Quast (1993) and Kasperski (1996) are still raising the same issue. However, the unintentional synchronisation of human occupants is now also considered to be

llard et al., 2000) and, therefore, structures can become unserviceable or even unsafe due to panic.

It should be realised that human-structure synchronisation is only one aspect of human-structure interaction influencing human-induced forces. In fact, human-induced forces may depend on the stiffness of the surface on which people perform (Pimentel, 1997). Indeed, Baumann and Bachmann (1988) reported DLFs of walking to be up to 10% higher if measured on stiff ground and not on a flexible 19 m long prestressed beam. Similarly, biomechanical research on jumping identified higher human-induced forces on stiffer structures (Farley et al., 1998).

In this context, it is important to note that a vast amount of ongoing biomechanical research into human locomotion (Farley and Gonza1996; Ferris and Farley, 1997; Hoffman et al., 1997; Farley et al., 1998

Actually, civil engineers first investigated the interaction of human impactors and flexiblestructures more than 20 years ago. In this research, individuals shouldering partition walls (Struck, 1976) or dropping onto planks and boards (Mann, 1979; Struck and Limberger, 1981) were represented by simple mass-spring models and the flexible strc tures were modelled as mass-spring systems also. More recently, Foschi and Gupta (1987), Folz and Foschi (1991), Foschi et al. (1995) and Canisius (2000) looked at impactor-structure interaction.

III.EFFECTS OF HUMAN-STRUCTURE INTERACTION ON DYNAMIC PROPERTIES OF CIVIL ENGINEERING STRUCTURES

Human occupants present on civil engineering structures do not only excite the structure, but can also simultaneously alter the modal properties of the structure they occupy. Therefore, strictly speaking, modal properties of the joint human-structure dynamic system should be considered in a design against human-induced vibrations. However, little reliable information on the properties of occupied structures or even the modelling of occupants done is available. As a consequence, the majority of civil engineering design procedures neglect the influence of human occupants on the dynamics of the vibrating system.

However, when the influence of human occupants on the dynamic properties of civil engineering structures is considered, occupants are often modelled just as additional mass to the structure. This model has been widely accepted for a long time (Walley, 1959; Allen and Rainer, 1975; Ohlsson, 1982; Ebrahimpour et al., 1989). It was incorporated into Applied Technology Council (ATC) Design Guide 1 (Allen et al., 1999) by adding a percentage of the weight of occupants (depending on the posture of occupants and the natural frequency of the structure). Naturally, such a model leads to a frequency decrease, as observed by Lenzen (1966) for a group of people occupying a floor.

However, Lenzen (1966) also reported, similarly to Polensek (1975) and Rainer and Pernica (1981), a significant increase in damping due to human occupants. Based on these and other similar investigations, such as those by Eyre and Cullington (1985), Manheim and Honeck (1987), Ebrahimpour et al. (1989), Bishop et al. (1993), Quast (1993), and Pimentel and Waldron (1996), it is nowadays widely accepted that human occupants add damping to structures they occupy. Moreover, recent research by Brownjohn (1999; 2001) and Brownjohn and Zheng (2001) showed that an occupant absorbed significantly more energy than a concrete plank supporting the person. However, the potentially very beneficial effect of human occupants was included only into Canadian codes (NRCC, 1985; 1995) and the ATC Design Guide 1 (Allen et al., 1999), which recommend viscous damping ratios of up to 12% when designing heavily populated structures

The observed increases in damping due to human occupation cannot be explained by human occupants modelled as additional mass only. Nevertheless, this mass-only model is used in the National Building Code of Canada (NBC) guideline on human-induced vibrations of floors and footbridges (NRCC, 1995), in the ‘Green Guide’ (HMSO, 1997) and by Allen et al. (1999). It is also still employed in the design of structures such as balconies (Gerasch, 1990; Setareh and Hanson, 1992), stadia (Eibl and Rösch, 1990; Harte and Meskouris, 1991; Batista and Magluta, 1993; van Staalduinen and Courage, 1994; Bennett and Swensson, 1997; Reid et al., 1997) and footbridges (Beyer et al., 1995; Luza, 1997; Hothan, 1999).

To address this inconsistency, Ohlsson (1982) and Rainer and Pernica (1985) indicated that damped dynamic models of human occupants could be employed. In 1987, Foschi and Gupta adopted this approach because damped dynamic models of human occupants can, contrary to the mass-only model, explain significantly increased damping due to human occupation.

IV.ENERGY ABSORBED BY HUMAN OCCUPANTS

In 1977, Farah was prompted by prior biomechanical research (Pradko and Lee, 1966; Pradko et al., 1967; Lee and Pradko, 1968) to assess the serviceability of civil engineering structures using dynamic human models. Farah used the energy absorbed by the human body as measure of vibration serviceability, whereby more energy absorbed by the human occupant corresponded to less comfort. He re-evaluated data of several biomechanics publications presenting dynamic human models and decided to employ a 2-DOF model of the human body (Figure 3a). Parameters of this model (Table 11) are based on the re-evaluation of the modulus of the mechanical impedance ()fI of one standing person reported by Coermann (1962).

Since the work of Farah (1977), the energy absorbed by the human body has been an issue that was neglected in both biomechanics and civil engineering dynamics. However, since 1995, there has been an increase in the research into the energy absorbed by the human body (Lundström et al., 1995; 1998; Lundström and Holmlund, 1998; Mansfield and Griffin, 1998; Holmlund, 1999; Mansfield et al., 2000).

As for civil engineering applications, Brownjohn (1999; 2001) quantified the energies absorbed by a standing human occupant and the occupied prestressed concrete structure having a mass of 1200 kg simultaneously. Using another similar structure, Brownjohn and Zheng (2001) and Zheng and Brownjohn (2001) investigated the effect of different excitation levels. Additionally, Brownjohn and Zheng (2001) found the absorbed energies to be dependent on the posture (sitting and standing) of the occupant.

All this research highlights once again the potentially beneficial effect of including stationary human occupants into the dynamic modelling of occupied civil engineering structures. Moreover, it indicates absorbed energy as indicator for the serviceability assessment of civil engineering structures.

V.CONCLUSIONS

Human-structure interaction is an important aspect of human-induced vibrations. Nevertheless, its multiple effects are little researched and understood. However, this issue has to be well understood to successfully design slender structures occupied and dynamically excited by humans, in particular assembly structures.

Broadly speaking, human-structure and dynamic interaction covers two aspects: (1) how structural movement affects human induced dynamic forces, and (2) how humans change dynamic properties of structures they occupy. The literature dealing with the first aspect was found to be quite limited. However, the literature reviewed was quite conclusive in stating that structural movement can affect the forces - significantly in some cases.

To predict accurately the influence of human occupants on dynamic properties of structures they occupy, dynamic human occupant models are required. Biomechanical human whole-body models are only of limited value because the properties of the human body depend on the level of vibration and significantly lower levels of vibration are encountered in civil engineering than used to derive the reviewed biomechanical human models. Furthermore, in civil engineering, the effect of groups of occupants is of primary importance for vibration design although occupant models themselves could, via absorbed energy for example, also be used to assess serviceability.

So far, several SDOF models of single people standing on civil engineering structures have been proposed. However, all these SDOF occupant models are based on more or less unwarranted assumptions in respect to damping and/or the lumped mass of the occupant model. Furthermore, the experimental data presented in the literature and used to derive the properties of human occupant models were often incomplete and unreliable. Therefore, there is an urgent need for further research into modelling human occupants of civil engineering structures, particularly groups, which should employ sophisticated techniques yielding more reliable experimental data.

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