Vibration Serviceability Considerations in Footbridge Design

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Abstract—**Modern footbridges are becoming more and more flexible as they are constructed lighter and more slender than ever before. This has led to a vibration serviceability issue with many footbridges, as they can become 'lively' by pedestrians simply walking across them. Numerous codes of practice and guidelines are available to the structural engineer, in terms of footbridge design, all with their limitations in terms of overcoming this serviceability problem. This paper carries out a critical review of these guidelines and codes of practice, and their approach to addressing the issue of vibration serviceability. Moreover, the paper investigates human loading and the parameters that affect such loading, in both a qualitative and quantitative fashion. Furthermore, an explanation is provided on how an understanding of human loading and the parameters that affect such loading can be used to predict and address vibration serviceability problems on footbridges. Finally, walking trials conducted by the authors in which pedestrian loading at normal pacing velocities was examined are briefly described; along with a note on current and future studies to be undertaken.**

Keywords-vibration serviceability; footbridge; human loading; codes of practice; guidelines

I. INTRODUCTION

Footbridges serve two core purposes in that they are landmark structures and convenient crossing points for pedestrians. Two high-profile modern examples include the London Millennium Footbridge, opened in 2000; and the Sean O'Casey Bridge, Dublin, opened in 2005. Moreover, footbridges often need to blend into and complement the natural environment in which they are located. Examples include the Mizen Head Footbridge, Cork, opened in 2011; and the Langkawi Sky Bridge, Malaysia, opened in 2005.

The emergence of new materials, the greater understanding of existing ones, and the use of advanced engineering technology have together facilitated the engineer to design footbridges more slender, lighter, and more aesthetically daring than ever before. These new slimline and elegant footbridges can also be quite flexible, rendering them sensitive to pedestrian induced vibration in some cases. This has led to vibration serviceability issues in a number of high-profile cases in recent times (e.g. [1]) . These vibration serviceability problems can occur when the dynamic nature of pedestrian load application – related to the individual's pacing frequency – causes resonant vibration effects to occur in the structure. Such vibrations are quite often magnified when a large crowd cross the bridge in sync with one another. A further difficulty is that human response to vibrations is very complicated and it is often difficult to establish a comfort criterion that satisfies all users of a structure [2]. In addition, it seems that people are becoming more sensitive to vibrations and, therefore, are quicker to complain [3]; the same author suggested that this could be partly a reaction to increasing environmental influences.

Archbold (i.e., [4]) explained that there are two international approaches to addressing the vibration serviceability problem [5]. The first is to ensure that lower frequencies of vibrations of a bridge are outside those frequency ranges associated with typical pedestrian pacing rates while the second is to limit induced structural accelerations to levels below prescribed acceptable limits. The current design codes of practice governing footbridge design in Ireland are Eurocodes (i.e., [6-8]). These codes supersede the British Standard (i.e., [9]), which was one of the first codes to try and address the problem of pedestrian induced vibrations on footbridges. The procedures adopted in [6-8] and the previous Standard [9] in respect of serviceability considerations are remarkably similar, despite an approximately 30 year time separation in the first publication of the two documents; and notwithstanding the attention currently being given to this phenomenon. According to Eurocode 0 (i.e., [6]) the comfort criteria of the bridge deck is deemed to be satisfied if its fundamental frequency is greater than 5Hz in the vertical direction and greater than 2.5Hz in the horizontal (lateral) direction. Fanning and Healy (i.e., [5]) pointed out that if such limits were used exclusively they would preclude the construction of lightweight type structures, which many modern footbridges are. If the above limits are not met [6] then gives permissible acceleration limits for vertical, lateral, and crowd accelerations. However, Eurocode 1 (i.e., [7]) does not give a procedure to calculate the dynamic characteristics produced by pedestrians; but instead asks designer to develop them him/her self. These models are then checked against a dynamic load model for the bridge, which is again down to the designer to develop [7]. Unlike [7], Eurocode 5 (i.e., [8]) does give procedures to calculate the accelerations of the bridge in the vertical and lateral directions along with another for crowd situations. However, the models in [8] are only for simply supported beams or trusses of timber construction; structures of a more daring variety and of a material other than timber are left to the devices of the designer.

As dictated by the codes the designer is more often than not pressed into designing his/her own pedestrian models. Such loads models include force functions and stochastic load models developed using information from various sources. However, even though walking is second only to private car use as the most common form of locomotion in Europe and the USA ([10, 11] cited in [12]) there is still a dearth of data on it and its intuitive relationship with pedestrian loading. Most of the data that is available tends to be sourced in the biomechanical domain, but this often falls short of what structural engineers require in that it tends to focus more on the kinematic rather than the kinetic aspect of gait. This gap in information often causes pedestrian load models to be somewhat inaccurate, therefore, causing these models to be of limited relevance. Also absent from the various data pools is information relating to pedestrian structure interaction and how the various gait parameters and, hence, pedestrian loading are altered when subjected interaction factors occur, such as footbridge vibrations.

This paper examines the current design guides and codes of practice for footbridge design and how these approach the issue of vibration serviceability. Also presented is an overview of reported gait parameters and how these may influence pedestrian loading on footbridges. The paper also briefly describes trials conducted by the authors in which pedestrian loading at normal pacing velocities was examined involving over 100 trials.

II. CODES OF PRACTICE AND GUIDELINES

In general there are two approaches within design guidelines towards dealing with footbridge vibration serviceability, Table I. The first guideline approach requires the designer to avoid designing footbridges that have specific natural frequencies and is referred to as a '*Frequency Tuning Approach'*; i.e., the bridge is designed to avoid certain frequencies. While the second allows footbridges to be designed within specific frequency ranges as long as the dynamic response of the bridge is within acceptable limits for bridge users and may be considered as a '*Vibration Limit Approach'*; i.e., the dynamic response of the bridge to a dynamic load model is analysed. Both of these methods will be discussed further below.

A. Frequency Tuning Approach

Table I lists four design codes that use the *Frequency Tuning Approach*. Apparent form this is that Swiss code (i.e., [13]) and the Comite Euro-International du Beton code (i.e., [14]) both state the same values ranges to be avoided namely, 1.6 – 2.4Hz, and 3.2 – 4.8Hz. Archbold (i.e., [4]) pointed out that these ranges are based on walking rates between 1.6 and 2.4Hz, and therefore having a second harmonic between 3.2 and 4.8Hz. The Comite Euro-International du Beton code (i.e., [14]) states that joggers can cause vibrations in bridges with natural frequencies between 2.4 and 3.5Hz, which is intuitively another reason for the higher range given [4]. The Japanese code cited by [4] and [15] gives only one limit range, i.e., 1.5 to 2.3 Hz; as a consequence, ignoring the second harmonic associated with walking, and the first harmonic with running. The American Guide (i.e., [16]) has a minimum value of 3Hz for walkers only; and in the case of low stiffness, damping, and/or mass, for activities such as running and jumping the value is increased to 5Hz. Unlike the other *Frequency Tuning Methods* listed in Table I lower limits are 'marked absent' from the specification.

TABLE I. APPROACHES TO SERVICABILITY DESIGH

Approaches to Serviceability Design						
Frequency Tuning Approach		***Vibration Limit Approach***				
Design Code	***Avoidance range in vertical direction (Hz)***	***Design Code***	***Satisfactory fundamental frequency minimum value (Hz)***		***Limits on accelerations (m/s²)***	
			$\mathbf{V^c}$	$\mathbf{H^d}$	$\mathbf{V^c}$	$\mathbf{H^d}$
SIA 160 [13]	1.6 – 2.4 3.2 – 4.8	BS5400 [9]	5.0	1.5	$0.5\sqrt{f_o}$	*
AASHTO 1997 [16]	$>3.0^a$ $>5.0^b$	Eurocode 5^e [8]	5.0	2.5	0.7	0.5 or 0.2
CEB [14]	1.6 – 2.4 3.2 – 4.8	Eurocode 1^f [7]	5.0	2.5	0.7	0.5 or 0.2
Japanese code (cited in [4] and [15])	1.5 – 2.3	OHBDC [17]	4.0	4.0	**	*
		CSA [18]	4.0	4.0	**	*
		Bro 2004 (cited by [19])	3.5	*	0.5	*
		ISO 10137^g [20]	N.A.	N.A.	$0.6\sqrt{f_o}$ $1<f_o<4$Hz 0.3 $4<f_o<8$Hz	0.2
		Hong Kong [21]	5.0	1.5	$0.5\sqrt{f_o}$	0.15
		AS 5100.2 [22]	3.5	1.5	**	*

a. For bridges used solely for walking. b. For bridges where running and jumping may be possible. c. V = Vertical. d. H = Horizontal. e and f. Eurocodes 5 and f (i.e., [7, 8]), respectively, both direct reader to

Eurocode 0 (i.e., [6]) for comfort values. g. Values cited in [23]. * Limit not given in code. ** Limits given in graphical form in code.

Interestingly the frequency tuning methods in Table I does not give limiting frequency ranges in the lateral direction, where some of the most well known examples of excessive vibration have occur. For example, [1] explained that footbridges with lateral fundamental frequencies of 1.3Hz or less are particularly susceptible to horizontal pedestrian induced vibrations; as demonstrated with London Millennium Footbridge in 2000. A significant problem with using the *Frequency Tuning Approach* is that it does not consider acceleration limits, and therefore only bases the design on frequency ranges. Pimental et al. (i.e.,[24]) found that the frequency tuning approach can be restrictive because there are footbridges which are ‘serviceable’ although they have frequencies in the range recommended for avoidance[15].

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B. Vibration Limit Approach

One of the first attempts at solving pedestrian induced vibrations on footbridges was [9]. Numerous other codes have followed similar provisions to that of this standard in dealing with pedestrian induced vibrations, some of which are included in Table I. The first criterion of [9] is rarely satisfied in that most modern footbridges have vertical natural frequencies less than 5Hz in the vertical direction and 1.5Hz in the lateral [23]. The scientific compliance rules of [9] are based on work carried out by [25]. The first criterion established by [25] was the tolerance of a pedestrian to vertical vibrations [4]. The tolerance levels were obtained from results by [26] whilst determining in total 40 different peoples’ sensitivity towards amplitudes applied to a beam they were crossing; and [27] who conducted similar testing on an aluminum plant-this time involving 26 people [28]. The threshold curve was much higher in Smith’s (i.e., [27])than Leonard’s (i.e., [26]) test results [28]. According to [4, 28], [25] compromised by taking the mean of results found in [26, 27] defining the level of acceptable acceleration as in (1) :

$$a_{\text{Limit}} = 0.5\sqrt{f_o} \qquad (1)$$

A simplified procedure is then given to calculate the fundamental natural frequency f_o of the bridge and the actual acceleration of the bridge; but these formulas are only valid for single span, or two-or three-span continuous, symmetric superstructures, of constant cross-section, that are supported on simply supported bearings [9]. For values of fundamental frequency f_o greater than 4Hz there is a reduction factor that can be applied [9]. For more complicated structures than described above the maximum acceleration should be calculated assuming that the dynamic loading applied by a single pedestrian can be represented by a pulsating point load, F, (1,2) [9]. This is based on the sinusoidal load model in [25] (cited in [15]).

$$F = 180 \sin 2\pi f_o T \text{ (in N), where T is the time (in s)} \qquad (2)$$

$$V_t = 0.9 f_o \text{ (in m/s)} \qquad (3)$$

Where f_o can be taken as the fundamental frequency of the bridge and 0.9 equates to the pedestrians step length; V_t represents the assumed pacing velocity of the pedestrian. The pedestrian is assumed to have a weight of 700N, while 180N is considered by [25] as being the first harmonic of walking; which equates to 25.7% of 700N [15]. In regards providing a limit or method to calculate the horizontal acceleration [9] falls short. The only real reference it makes to horizontal loading is that it tells the designer to give special consideration to the possibility of excitation by pedestrians at a fundamental frequency below 1.5Hz in the horizontal direction, especially where mass and damping are low; and where the bridge is going to be used by large crowds. Indeed, it was only after the London Footbridge problem in 2000 [9] made any reference at all to horizontal type vibrations.

Footbridges are deemed to be satisfied if the vertical fundamental frequency is 5Hz in [6], which is the exact same value as [9]. However, the threshold for the horizontal fundamental frequency in [6] is even more stringent at 2.5Hz in comparison to 1.5Hz outlined in [9]. A further similarity is the acceptable acceleration limit; i.e., if 2Hz – which is the pacing frequency that relates to (2) – is subbed into (1) a value of 0.7m/s^2 is found; which is the vertical value limit given in [6]. As explained by [28] the Ontario Highway Design Code (i.e., [17]) provides the same provisions for the vibration serviceability of footbridge structures as the Canadian Highway Bridge Design Code (i.e., [18]). The two codes (i.e., [17, 18]) require a detailed dynamic analysis in the vertical direction of the bridge due to footfall loading, simulated by a moving sinusoidal force with amplitude of 180N, and a frequency equal to the fundamental vertical natural frequency or 4.0Hz; whichever is less. The limit acceleration is presented graphically in [17, 18]and according to [28] is less than [9]. Although no limit is given in terms of the lateral acceleration in either [18] or [17] they still require that the lateral frequency of the footbridge should not be less than 1.5 times the fundamental vertical frequency or 4.0Hz; whichever is less. The International Organization for Standardization’s code (i.e., [20]) provides different regions for different frequency ranges in terms of vertical dynamic vibrations, while the limit value in the horizontal region is fixed at 0.2m/s^2. ISO 10137 (i.e., [20]) explains that the design situation should be selected depending on the pedestrian traffic that will be using the footbridge, and it recommends considering checks on single pedestrians, groups consisting of between 8 and 15 people, and groups consisting of more than 15 people. The code (i.e., [20]) then highlights that the dynamic force produced by a person can be expressed in the frequency domain as a Fourier series in both the horizontal and vertical directions, and gives the two equations in Annex A [23]. An important point to note in regarding [20] is that the acceleration limits given refer to the root mean square (rms), instead of the peak values [23]. Similar to the other codes in this category the Swedish guideline Bro 2004 (cited in [19])

$$\alpha + \beta = \chi. \qquad (1) \qquad (1)$$

gives a simplified procedure to calculate the vertical acceleration, however for complex footbridges a detailed dynamic analysis is required by the designer – as with most of the other codes. The Australian code (i.e., [22]) requires, similarly to the other codes, to determine the dynamic response based on a pedestrian of 700N and with a pacing frequency of between 1.75 and 2.5Hz, and to check this against a dynamic amplitude limit presented graphically [28]. No limit is given for the horizontal acceleration even though consideration of such accelerations is required below 1.5Hz according this code [28].

Zivanovic et al. (i.e., [15]) explained that most of the vibration limit approaches are based on [9], which was developed by experiments conducted in the 1960s and 1970s. The same author (i.e., [15]) explained that in these eras higher harmonics were rarely considered, hence the DLF of 0.257 is not representative of the whole frequency range up to 5Hz. Another evident problem with the vibration limit codes is that they leave out limits and procedures; hence they leave it up to the designer to come up with a solution. One exception to the rule is [8], which gives limits and procedures for vertical, horizontal, and group induced vibrations; however, these are only for simply supported structures of constant cross section and of timber construction. Furthermore, the codes in Table I only give procedures for simply supported footbridges of constant cross sections, and for this reason most aesthetically daring footbridges are required to be designed by designers using their own force functions and load models; hence reliable data is necessary to input into these functions and models. Riccardelli and Pizzimenti (i.e., [29]) highlighted that most of the codes are based on results obtained from trials conducted on rigid floors, hence pedestrian structure interaction is not considered in the codes' formulas. Zivanovic et al. (i.e., [15]) even suggested some codes such as [20] are not based on published research pertinent to footbridge vibrations.

Zivanovic et al. (i.e., [15]) in their summary cautioned against using existing guidelines, explaining that they should be used carefully, with plenty of lateral thinking and along with some recently published research which could be relevant for design considerations.

III. GROUND REACTION FORCES

During walking a pedestrian imparts forces upon the ground in three orthogonal directions relative to their forward line of progression, namely; vertical, perpendicular, and parallel. Numerous papers refer to the perpendicular directed force as the lateral or medio-lateral force, while the parallel force is often referred to as the saggital or longitudinal force. Collectively the three forces are referred to as Ground Reaction Forces (GRFs), hence there is the vertical, medio-lateral, and longitudinal GRF; Fig. 1. In terms of pedestrian loading on footbridges the vertical and medio-lateral forces are of prime importance as these define the dynamic load model to be applied to a rigid surface: the saggital force is of least importance as the bridge is rather stiff in this direction [30].

A. *Vertical Ground Reaction Force*

Fig.1 illustrates the dominant magnitude of the vertical force relative to the saggital and medio-lateral forces. A normal walking profile is generally associated with two peaks and a trough. The first peak occurs at heel-strike and is associated with a braking force [31]. The trough occurs as the foot decelerates down to a midstance position, while the second peak occurs due to a push-off force [31]. Keller et al. (i.e., [32] whilst citing [33-36] explained that ground reactions forces are dependent on factors such as weight, gait speed, and gait style. The same authors (i.e., [32]) whilst citing [37, 38] stated that the vertical force shows the least variability between and within subjects, and stated (without explaining why) the vertical force, being the largest, is the easiest to quantify. In light of the relationship that is associated between a pedestrians gait and their vertical ground reaction a thorough understanding is, thus, required by the footbridge designer in order to develop accurate force functions and load models when trying to predict the likelihood of vibrations occurring on footbridges. Various attempts have being made at trying to predict the dynamic vertical force of a pedestrian, most are of the form of a sinusoidal force function such as the one below proposed by [39], (4):

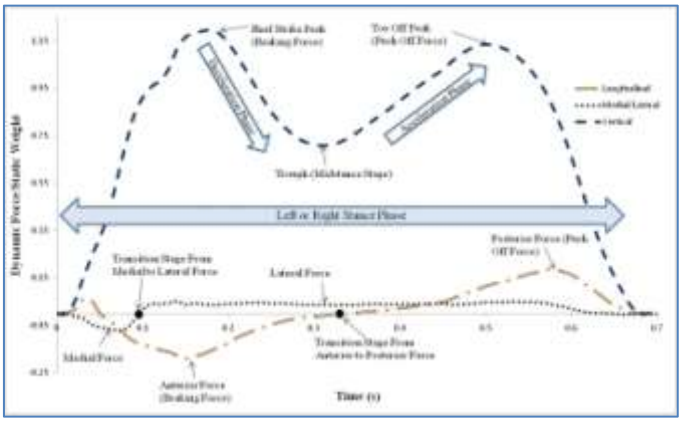

Figure 1. Typical trace of the three GRFs

$$F(t) = G + r_1 \sin(2\pi f_s t) \text{ (in N)} \qquad (4)$$

Where:

F(t) = the vertical force function (N)

G = weight of pedestrian (N)

r_1 = dynamic load factor (attempts by various authors have tried to find a relationship between this and pacing frequency f_s)

f_s = the pacing frequency (Hz)

t = time at specific points across the force (s)

B. *Lateral Ground Reaction Force*

Fig.1 also illustrates the relatively small magnitude of the medio-lateral force relative the saggital and vertical forces. Clear from Fig. 1 is that the magnitude of the medial force is quite similar to the magnitude of the lateral force. However, it can also be seen that the medial to lateral force transition point occurs quite early-on in the force profile; i.e., the lateral force is present for a longer duration than the medial force. According to [40] the medio-lateral force may be influenced by a pedestrians foot landing position, in both magnitude and direction. Other gait and normal parameters thought to affect the medio-lateral force include step width, pedestrian weight, and pacing frequency. Another worthwhile point is that the medio-lateral cycle length is twice that of the vertical force cycle length, hence the lateral pacing frequency is half that of the vertical one. This is because it takes two steps to produce one medio-lateral cycle, while it takes only one to produce the vertical cycle. Relative to the vertical force the medio-lateral force has a dearth of information published about it. Knowledge on the medio-lateral force is important in footbridge design as the bridge is rather flexible in this direction as demonstrated by the incidence that occurred on the London Millennium Bridge in 2000 [1]. Archbold (i.e., [4])proposed the following function (5) to simulate the lateral force applied by walking pedestrians on a fixed surface; done using a single sinusoidal force function:

$$F_L(t) = (-0.05f_s + 0.12)P_f G\sin(\pi f_s t) \text{ (in N)} \quad (5)$$

Where:

$F_L(t)$ = the Lateral force function (N)

G = weight of pedestrian (N)

Pf = FLP (foot landing position) factor (0.5, 1.0, or 2.0 for toe-in, neutral, and toe-out respectively)

(-0.05fs + 0.12) = r_L, lateral dynamic load factor based on a relationship with pacing frequency f_s

f_s = the pacing frequency (Hz)

t = time at specific points across the force (s)

IV. GAIT PARAMETERS

As explained earlier, codes of practice often place the onus on the footbridge designer to carry out their own detailed dynamic analysis of pedestrian loading. In order to predict the influence a pedestrian (s) may have on the dynamic properties of a footbridge the designer must acquire accurate force functions, numeric models and input data. In order to design such models and functions the designer must have an intuitive understanding of how a pedestrian's gait can influence their GRFs and, hence the dynamic properties of the footbridge. Gait is simply defined as a manner or style of locomotion rather than a process of locomotion itself [41], hence walking is the most common form of gait or pedestrian locomotion. Table II categories the gait parameters into their respective spatial and temporal categories.

TABLE II. SPATIAL AND TEMPORAL GAIT PARAMETERS

Spatial Gait Parameters	***Temporal Gait Parameters***
Step Length Gait Cycle Length Step Width Foot Landing Position	Pacing Frequency Pacing Velocity Stance Phase Swing Phase

A. Pacing Frequency

As defined in an earlier paper by the authors (i.e., [30]) it's the inverse of the time from the initial contact of the left foot with the ground to the initial contact of the right foot immediately thereafter, and corresponds to the rate of application of the vertical forces. In simpler terms it's the amount of steps/cycles a person takes in one second; hence it's measured in Hertz. And, as explained earlier the lateral pacing frequency is half the vertical one due to the differences in force cycle lengths. Pacing frequency is considered the most relevant of all gait parameters in terms of predicting a relationship with pedestrian dynamic action on footbridges. For example if the frequency of the bridge and pacing frequency of the pedestrian are known the possibility of resonance occurring can be easily checked. (4) and (5) also demonstrate how pacing frequency can be used to determine the dynamic loading in both the vertical and lateral sense. In [30] the authors surveyed the results of 20 walking trials and found that persons aged 20 – 60 years walking at normal pacing velocities had an average pacing frequency of 1.92Hz. The under 20 years group in [30] had a pacing frequency of 2.02Hz, while the over 60s had a pacing frequency of 1.91Hz; indicating pacing frequency may have a relationship with age [30].

B. Step Length

Step length can be defined as the distance from the left heel to the right heel or *vice-versa*. Gait cycle length on the other hand is left step length plus right step length. To say gait cycle length is twice left step length or twice right step length may hide the fact that there is a variation between some peoples left and right step lengths [42]. In the same survey as carried out for pacing frequency and presented in the same paper (i.e., [30]) the authors found that step length was 0.59m for persons under 20, 0.67m for mature adults, and 0.61m for persons over 60 years with standard deviations of 8%, 11%, and 9%; respectively. Interestingly, the force function in [25] presented in [9] is based on a step length of 0.9m; which maybe over conservative.

C. Pacing Velocity

Pacing velocity can be simply defined as distance over time in a given direction (forward line of progression in the case of walking). Intuitively, it has a direct relationship with pacing frequency and step length. Kirtley (i.e., [31]) explained the relationship is a linear one with pacing frequency and a logarithmic one with step length. And, as previously explained in another paper [42], by the authors of this paper, this means it can be increased at low speeds by increasing both pacing frequency and step length; but at higher speeds it can only be increased by increasing the pacing frequency. Bohannon and Williams (i.e., [12]) whilst surveying the results of 41 source articles on walking trials conducted at normal pacing velocities recorded the grand averages for the trials at different age groups. For men the average pacing velocity for those aged between 30 and 59 years was 1.43m/s, while for those aged between 20 and 29 years the average was 1.36m/s. For women the average was between 1.31m/s and 1.39m/s for the ages 20 -59 years. Interestingly, at a speed of 3.0m/s most females jog rather than walk if the case needs be, but must males tend to still walk at this speed [32]. Keller et al. (i.e., [32]) observed that vertical force tends to increase in a linear manner with increases in pacing velocity up to about 3.5m/s for both male and females.

D. Stance Phase and Swing Phase

Stance phase is the amount of time the foot remains on the ground during a gait cycle. While swing phase is the amount of time it remains off the ground. Kirtley (i.e., [31]) made clear that the shorter the stance phase the greater will be the vertical force [42]. What is unique to walking is the double stance phase where both feet are on the ground at the same time. In running there is a phase known as the double swing phase when both feet are off the ground at the same time; this does not occur during walking.

E. Step Width

Step width is defined as the distance between the centre lines of the two feet. Reported values of step width have proven to be far more variable than step length, with standard deviations up to 30% [30]. Further, there is less reported data on this particular spatial parameter [30]. Five reviewed references yielded values between 0.09m and 0.19m for adults, with no apparent link between subject height and step width [30]. Interestingly, values reported by [43] and [44] suggest that Korean adults exhibit greater step widths than others reported [30]. Bauby & Kuo (i.e., [45]) both linked step width to stride length reporting that the step width was approximately equal to 13% of the step length [30]. It may be a fair assumption to make that step width may have a bearing on the lateral force; for example, as a person starts to feel movements they will subconsciously tend to widen their step width to increases their balance, such a widening of the step width may only increase the horizontal force.

F. Foot Landing Position

Simpson and Jiang's (i.e., [40]) reported tests reveal that foot landing position influences the force applied by the pedestrian [30]. They categorised their test participants into categories of "toe-in", "neutral" and "toe-out" depending on their foot landing position during straight line walking [4, 30]. Values for foot landing position are reported in degrees, with positive representing toe-out and negative representing toe-in. Reported values for foot landing position range between $+14.3^0$ (toe-out) and -3.8^0 (toe-in) [40]. Kirtley (i.e., [31]) explained that the average foot landing position is $+15^0$ [42]. Foot landing position is sometimes referred to as angle of gait, angle of progression, or angle of deviation.

V. PREVIOUS RESEARCH

Previous research [42, 46, 47] has been reported by the authors, in which over 100 walking trials involving 27 healthy adults walking at a 'normal' velocity were conducted and later analyzed. A layout of the walking trial set-up used for this research is presented in Fig.2.

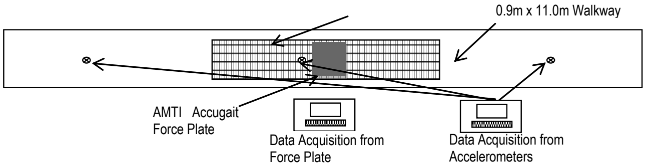

Figure 2. Schematic representation of walkway and test set-up (not to scale) [42, 46, 47]

The spatial and temporal gait parameters recorded for each trial were step length, cycle length, step width, foot landing position, and pacing frequency. Pacing velocity was determined from the product of pacing frequency and step length. Also, the ground reaction forces (GRFs) in the three orthogonal directions were measured for the instance of a footfall striking the force plate. The vertical GRF trace also enabled the determination of the single foot stance support phase.

A. Relationship Between Gait Parameters and Vertical Loading

Table III, provides a summary of some of the gait parameters measured during this work, which is presented in more detail elsewhere [42].

TABLE III. SUMMARY OF GAIT PARAMETERS RECORDED

Gait Parameters	***Mean Value***	***S.D.***[a]
Step Length	0.75m	9%
Pacing Frequency	1.88Hz	7%
Pacing Velocity	1.41m/s	11%

a. S.D. = Standard deviation

Analysis of the recorded data also revealed a number of relationships between gait parameters, which are again presented in detail elsewhere [42]. They are shown here via (6), (7), and (8).

$$l_s = 0.44h \tag{6}$$

$$v_s = 0.23h.f_s^2 \tag{7}$$

$$f_s = (v_s/0.23h)^{0.5} \tag{8}$$

(6) shows close agreement with an equation previously obtained by [48], (9).

$$l_s = 0.45h \tag{9}$$

Where:

l_s = step length (m)

h = person Height (m)

v_s = pacing velocity of participant (m/s)

f_s = the pacing frequency (Hz)

(8) may be useful for estimating pacing frequency as both pacing velocity and height are easily quantifiable.

Moreover, a relationship was found between the vertical dynamic load factor (DLF), r_n, first with pacing frequency and then with pacing velocity. Interestingly, the relationship between the pacing velocity and the DLF yielded a better correlationship than pacing frequency did [42]. This is surprising considering most researchers report the relationship between pacing frequency and the DLF [42]. Keller et al. (i.e., [32]) also found a relationship between pacing velocity and the DLF, but for a higher range of walking speeds [42]. When the average pacing frequency found in the trials for [42] was subbed in to (10) the DLF was shown to be 0.17 [42]. The same pacing frequency yielded a DLF value of 0.37 when used with the a similar equation developed by [4]. Furthermore, the DLF in [9] roughly equates to 0.257 [15]. This may indicate that walking on a rigid surface produces a lower dynamic load factor than that produced when walking on a flexible surface. This is the subject of ongoing research by the authors.

B. Relationship Between Gait Parameters and Lateral Loading

Some of the pertinent gait parameters related to lateral loading were measured during the trials and summarized in Table IV. Again, these results are presented in detail elsewhere [46, 47]. One of the main findings of the work was the fact that the lateral force trace could be accurately represented using three harmonics of the fundamental pacing frequency and load factors associated with each of these harmonics were established.

TABLE IV. SUMMARY OF RECORDED GAIT PARAMETERS RELATED TO LATERAL LOADING

Gait Parameters	***Mean Value***
Step Width	0.079m
Foot Landing Position	6.03^0
Pacing Frequency	1.88Hz

VI. CURRENT & FUTURE RESEARCH

The previous work carried out has focused on normal pacing velocities for mature, healthy adults only. Current studies are exploring a significantly greater range of walking velocities, providing greater ranges of both pacing frequency and other gait parameters to assess. These studies include examination of the following:

- Different age groups of participants.
- Larger sample group walking again on a fixed surface but this time using different velocities, namely, slow, normal, and fast; hence, determining how each speed affects the forces, and the force gait relationship.
- Pedestrians walking on flexible surfaces, allowing analysis of any human-structure interaction effects.

Results from these experiments will contribute to the development of robust load models for pedestrian loading on both rigid and flexible surfaces.

VII. CONCLUSIONS

This paper has carried out a review of codes and guidelines that are used to overcome vibration serviceability problems. The first set of codes and guidelines, reviewed, looked at the *Frequency Tuning Approach*. This approach keeps the bridge outside certain frequency ranges in order to safe guard against possible resonance occurring with the pacing frequency of a pedestrian. This is a rather conservative approach, as the limits defined would make it difficult for lightweight and slender footbridges to be built at all. They are also largely marked absent in providing limits for horizontal frequencies. The second approach, the *Vibration Tuning Approach*, allowed bridges to be built within certain frequency limits as long as their accelerations are acceptable to bridge users. This is an improvement over the first approach – but still falls short; for example, effective models and force functions in order to predict and simulate such vibrations are absent – especially in terms of horizontal vibrations. Any functions or models that are provided are generally for footbridges of constant cross section, simply supported and of limited span arrangements. The paper then describes the nature of human loading and the parameters that influence such loading, highlighting that there is a dearth of data about the relationship between both. Such data and information would be of benefit to the footbridge designer in terms of designing to overcome vibration serviceability problems induced by pedestrians. Finally, some recent experiments carried out by the authors have been described and current and future work outlined.

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