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Conditions to avoid synchronization effects in lateral vibration of footbridges

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Abstract. Lateral vibrations of footbridges may induce synchronization between pedestrians and structure itself, resulting in amplification of such vibrations, a phenomenon identified by lock-in. However, investigations about accelerations and frequencies of the structural movement that are related to the occurrence of synchronization are still incipient. The aim of this paper is to investigate conditions that could lead to avoidance of synchronization among pedestrians themselves and footbridge, expressed in terms of peak acceleration. The focus is on the low acceleration range, employed in some guidelines as a criterion to avoid synchronization. An experimental campaign was carried out, employing a prototype footbridge that was set into oscillatory motion through a pneumatic exciter controlled by a fuzzy system, with controlled frequency and amplitude. Test subjects were then asked to cross the oscillating structure, and accelerations were simultaneously recorded at the structure and at the subject´s waist. Pattern and phase differences between these signals were analysed. The results showed that test subjects tended to keep their walking patterns without synchronization induced by the vibration of the structure, for structural peak acceleration values up to 0.18 m/s^2, when frequencies of oscillation were around 0.8 to 0.9 Hz. On the other hand, for frequencies of oscillation below 0.7 Hz, structural peak accelerations up to 0.30 m/s^2 did not induce synchronization.

Keywords: footbridge; lock-in; pedestrian; synchronization; vibration

1. Introduction

The design of breathtaking footbridges, with long spans and built from lighter and stronger materials, may cause perceptible lateral vibrations induced by the crossing of pedestrians. Blekherman (2005) mentioned that the first case of excessive lateral vibrations that led to closing of a footbridge happened in 1958 in Kiev (Ukraine), in a suspension footbridge with a lateral natural

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frequency of 1.0 Hz and a main span of 180 m. Horizontal displacements reached 9 mm in crowd conditions.

However, the cases that called much attention began to appear by the end of the twentieth century. Fujino *et al.* (1993) investigated the phenomenon at Toda Bridge (T-Bridge, as called) in Japan in 1989, a suspended footbridge with a main span of 134 m and a secondary span of 45 m, which showed predominant lateral vibrations in the first mode (0.9 Hz) and also exceeding 10 mm of lateral displacement during a crowd event. By working with an automatic image processing tool, Yoshida *et al*. (2007) found later a synchronization ratio of 60% at T-bridge, meaning that 60% of the pedestrians were moving laterally during walking with a frequency that differed no more than 0.1 Hz to the frequency of the bridge. However, it should be noted that, in this case, synchronization was reported to be evaluated by the frequency match between frequencies of pedestrians and structure only. In additional tests in the same structure with a group of only 30 individuals (Nakamura and Kawasaki 2006), lateral displacements of the bridge close to 6.5 mm were reached, and the excessive lateral vibration was appointed as being caused by synchronization between the movement of the structure and pedestrians, a phenomenon designated by synchronous lateral excitation (SLE) or lock-in. Again, frequency matching between pedestrians and structure was the criterion employed to characterize the synchronization.

In another structure, the London Millennium Bridge (LMB), a footbridge with a 144 m central span and two secondary spans of 80 m (north span) and 108 m (south span), in 2000, SLE was reported in the southern span of the bridge reaching about 50 mm of lateral displacement at a frequency of 0.77 Hz, and reaching 70 mm of lateral displacement in the central span at a frequency of 0.95 Hz (Dallard *et al.* 2001).

Nakamura (2003), in turn, carried out tests on the so-called M-bridge, a suspension footbridge with a main span of 320 m, reported to present excessive lateral vibration. More insight into the phenomenon was provided, in this case, by following the movement of an instrumented pedestrian together with the bridge movement. Synchronization was found between pedestrian and bridge for a mode the frequency of which was 0.88 Hz and bridge amplitude of 24 mm. Regarding phase angles between pedestrians and structure, the phase of the pedestrian was reported to be between 120^o and 160^o ahead of the bridge. Large bridge amplitudes of 45 mm apparently led the pedestrian to loose balance. No signs of synchronization were reported for the modes with natural frequencies below 0.6 Hz.

Pedestrian tests at the footbridge Solferino em Paris, and also laboratory tests (Charles and Bui 2005, Danbon and Grillaud 2005), led to the conclusion that there was no synchronization among pedestrians up to a certain level of acceleration. The Solferino footbridge is 140 m long and had an original (without dampers installed) lateral natural frequency of 0.81 Hz (Sétra 2006). As for the tests (Charles and Bui 2005, Danbon and Grillaud 2005), lock-in was observed, although for a purposeful slow walk of the crowd. Values of acceleration up to 0.10 m/s^2 were still unable to induce synchronization. On the other hand, synchronization rates around 30% were reported above this threshold, leading to high levels of lateral acceleration.

The Clifton Suspension Bridge (CSB) in Bristol was another case study, having a main span of approximately 214 m. In 2003, significant lateral vibrations caused by pedestrian crossings were reported (Macdonald 2008). Measurements indicated values of accelerations and relevant displacements in the second (0.53 Hz) and third (0.76 Hz) vibration modes, respectively, reaching 0.13 m/s^2 (11.3 mm) and 0.11 m/s^2 (4.5 mm). According to MacDonald (2008), although the behavior of CSB was similar to the behavior observed in LMB in terms of excessive lateral excitation due to crowds, evidence of synchronization between pedestrians was not identified.

These same observations of non-occurrence of synchronization made by MacDonald (2008) had been observed in another footbridge, excited laterally by up to 150 pedestrians (Brownjohn *et al.* 2004). Peak acceleration of 0.17 m/s^2 corresponding to an amplitude of displacements of 5.5 mm was reached. However, this footbridge had a lateral natural frequency of 0.9 Hz, differing from the LMB in terms of the order of magnitude of vibrations.

Reported significant lateral vibrations were observed in a footbridge in Norway (Rönnquist *et al.* 2008), that presented a lateral natural frequency of 0.83 Hz and a free span of 92 m. Measurements during use were not reported. On the other hand, a much studied (during design and construction) footbridge was built in Coimbra (Caetano *et al.* 2010) since lateral vibration problems were anticipated and measures were taken prior to opening. Its overall length was 274.5 m and a measured lateral natural frequency of 0.91 Hz was identified for the empty structure. Controlled pedestrian tests prior to installation of tuned mass dampers indicated a peak acceleration of 1.2 m/s^2 and respective peak lateral displacement of 40 mm for a crowd of 145 pedestrians. Interestingly, it was reported that a sudden rise in accelerations occurred at about 0.2 m/s^2.

A synthesis of the aforementioned case studies is presented in Table 1. When not directly available from the references, peak accelerations were estimated from the information provided by considering a sinusoidal oscillation at the natural frequency of the footbridge, and are shown between parentheses. This aimed to provide a basis for comparison between the reported cases and guideline specifications.

It should be noted that, in some cases, synchronization was characterized by a match of frequencies of movement of pedestrians and footbridge only, which is questionable. Indeed, synchronization is characterized not only by the match of frequencies but also by a constant phase difference between the oscillatory motion of pedestrians and structure. On the other hand, the onset of the lock-in phenomenon is debatable; however, a certain level of acceleration is required to trigger synchronization, and a threshold value is sought to guide the design. For instance, a peak acceleration of 0.10 m/s^2 was proposed in the Sétra guideline (2006) (see Table 1).

Another group of investigations of the phenomenon took place in laboratory conditions, employing bespoke treadmills or similar apparatus, bringing more insight into the subject since varied test conditions could be employed. Based on tests with five subjects, Pizzimenti and Ricciardelli (2005) concluded that the pedestrian tended to synchronize to the treadmill motion for increasing oscillation amplitudes of the latter, and also when the frequency of lateral oscillation approached the walking lateral frequency.

In treadmill tests with seven subjects, Ingólfsson *et al*. (2010) showed that step frequencies and phase angles between test subject and structure remained largely unaffected by lateral motion at most frequencies (0.33 to 1.1 Hz) and amplitudes (4.5 to 48 mm). It is worth mentioning that when the pedestrian lateral frequency matched the lateral oscillation frequency of the treadmill, the phase between test subjects and structure did not remain strictly constant. Also, phases varied substantially for pedestrian lateral frequencies away from the frequency of lateral treadmill motion.

Another test with seven subjects and employing a shaking table (Sun and Yuan 2008) showed that the test subjects reacted to vibrations as small as 4 to 5 mm in amplitude when the frequency of the shaking table was 1.0 Hz and his/her lateral frequency was 0.95 Hz. The phase angle between test subject and shaking table was in the range from 120 to 180 degrees, and the test subject adjusted his pacing rate from time to time to reset the phase lag. However, when the amplitude of vibration was set to 20 mm, the pedestrian adjusted his lateral frequency to 1.0 Hz and the phase angle remained constant, around 140 degrees. They, thus, concluded that the pedestrian synchronized to the vibration in the latter case. This experiment clearly showed that there is a limit in which, under

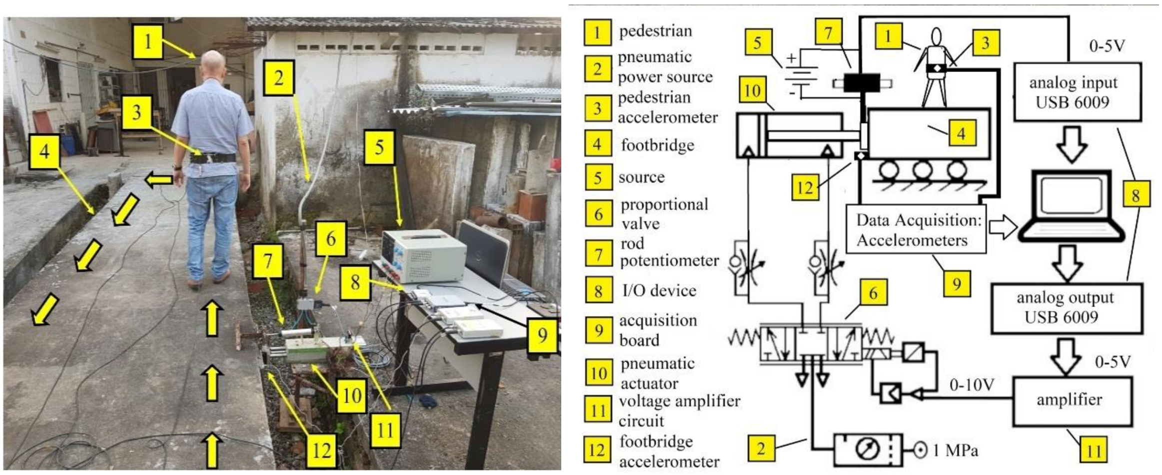
Table 1 Synthesis of case studies of reported lateral vibrations of footbridges

Reference	Lateral frequency (Hz)	Vibration amplitude (estimated peak acceleration)	Comments
Dallard *et al*. (2001)	0.77	50 mm ($1.16\ m/s^2$)	Synchronization reported
	0.95	70 mm ($2.46\ m/s^2$)	Synchronization reported
Nakamura (2003)	0.88	24 mm ($0.72\ m/s^2$)	Synchronization, with phase angles of pedestrians 120º-160º ahead of footbridge
	0.88	45 mm ($1.36\ m/s^2$)	Pedestrian lost balance
	0.6 and below	-	No synchronization
Fujino *et al*. (1993); Yoshida *et al*. (2007)	0.9	10 mm ($0.32\ m/s^2$)	Synchronization rate of 60% (based on frequency match only, between movement of pedestrians and structure)
Nakamura and Kawasaki (2006)	0.9	6.5 mm ($0.21\ m/s^2$)	Synchronization observed, but again based on frequency match only
Charles and Bui (2005); Danbon and Grillaud (2005); Sétra (2006)	0.81	$0.10\ m/s^2$	No synchronization up to this peak acceleration. Synchronization rates around 30% above this threshold
Blekherman (2005)	1.0	9.0 mm ($0.35\ m/s^2$)	-
Brownjohn *et al*. (2004)	0.9	5.5 mm ($0.17\ m/s^2$)	No synchronization
MacDonald (2008)	0.53	11.3 mm ($0.13\ m/s^2$)	No synchronization
	0.76	4.5 mm ($0.11\ m/s^2$)	No synchronization
Rönnquist *et al.* (2008)	0.83	-	-
Caetano *et al.* (2010)	0.91	40.0 mm $1.2\ m/s^2$	Synchronization, for accelerations above $0.2\ m/s^2$

certain conditions, synchronization takes place, and these reported phase angles were in line with the findings of Nakamura (2003) (see Table 1).

Still regarding phase angles between pedestrian and structure, Bocian *et al*. (2017) explored several different patterns. One of them was called a phase drift, which is a monotonic change of phase angles between the pedestrian and structure, related to an undisturbed pedestrian movement, who keeps his/her pacing rate irrespective of the frequency of vibration of the base. It is also worth mentioning another pattern, identified as persistent frequency locking, which corresponded to a synchronization of the pedestrian and structure, and was only achieved in their tests when the pedestrian lateral frequency matched the frequency of lateral oscillation of the test apparatus.

This idea of vibration limits to avoid SLE has been incorporated into some guidelines. The Sétra guideline (2006) defines a design lower bound threshold of $0.10\ m/s^2$ as the separation between random excitation and incipient synchronization, based on test campaigns at Solferino footbridge. Above that value, the tests indicated an increase of vibration towards synchronization, identified by an increase on the rate of correlation of movement among the pedestrians walking in a crowd.



(a) A test being carried out (b) A sketch of the equipment

Fig. 1 The prototype footbridge and details of the test equipment

Interestingly, other reported tests in Solferino footbridge with pedestrians walking fast showed that synchronization did not occur. It was concluded that when the pedestrian walking frequency was too far from the structural natural frequency, synchronization did not occur. However, no reference was made regarding the influence of the frequency in affecting the aforementioned threshold. The Hivoss document (2008a), in turn, mentions that potential synchronization may occur for persons walking with a step frequency within plus/minus 0.2 Hz of the vibration frequency of the deck. In the Hivoss guideline (2008b), for the appointed critical frequency range of lateral vibrations between 0.5 and 1.2 Hz, a threshold acceleration value above which SLE begins was set to 0.1 - 0.15 m/s^2. Again, no consideration was given of the influence of the frequency on this threshold.

From what has been shown, there is still an uncertainty in identifying conditions to avoid synchronization of pedestrians with the movement of the structure, in particular the definition of acceleration thresholds that take into account the frequency of movement. Indeed, recent studies have been devoted to investigate other aspects of the phenomenon (Cuevas *et al.* 2020, Jia *et al.* 2020, Chen *et al.* 2019, Jiménez-Alonso *et al.* 2019, Jia *et al.* 2018). Thus, the aim of this paper is, through an experimental campaign, investigate conditions that could lead to avoidance of synchronization among pedestrians themselves and footbridge, expressed in terms of thresholds of peak acceleration. To do that, a pneumatic exciter was employed to move a prototype footbridge in a given frequency range, when the structure is crossed by pedestrians. The description of the materials and equipment used and the methodology adopted in the tests to investigate those thresholds, together with the results obtained, are presented as follows.

2. Description of the experiment

2.1 Test structure

The same reinforced concrete test footbridge described in Silva *et al*. (2013) was used, with adjustments being made to attach a pneumatic actuator at midspan to ensure that the footbridge

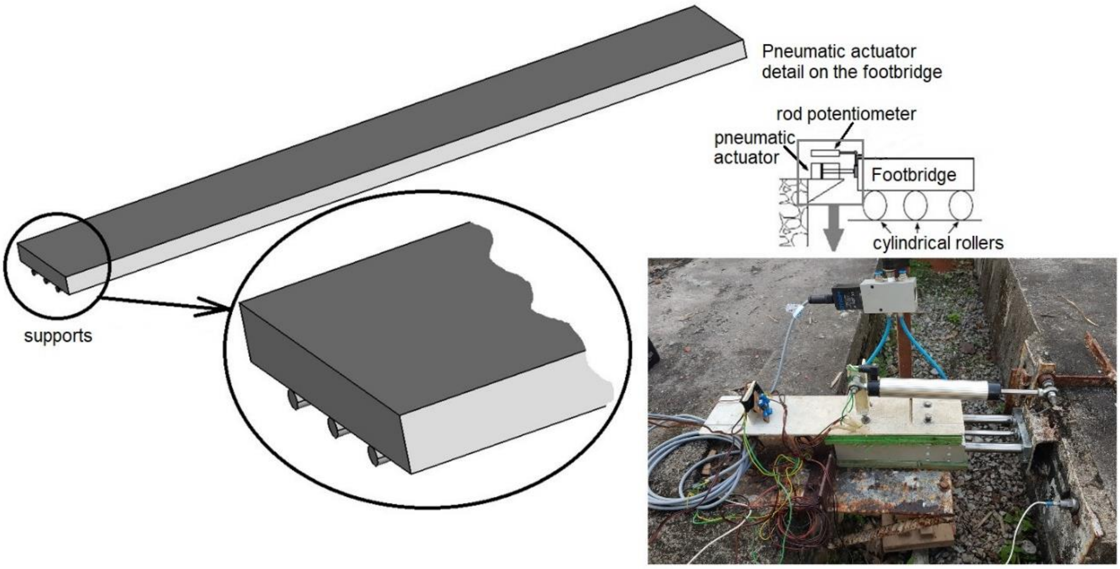


Fig. 2 Details of the support and pneumatic actuator

could be laterally excited (see Figs. 1(a)-(b)). The structure actually behaved as a rigid platform, and consisted of a 0.10 m thick slab supported laterally on two reinforced concrete beams, the dimensions of which were 0.17 m wide by 0.30 m high each. The slab and beam assembly had an inverted U-shaped section, except at the supports. There, the structure is massive with a rectangular cross section, being simply supported in 0.35 m long cylindrical rollers, which consisted of metallic tubes filled with concrete (Fig. 2). This setup facilitated the lateral movement exerted by the pneumatic actuator. Other relevant structural dimensions are: span of approximately 11.30 m, deck 1.80 m wide and a mass per unit length of 620.65 kg/m. The support conditions and the choice of the excitation point at midspan enabled a steady lateral movement of the structure.

2.2 Excitation system

A Festo servo-pneumatic system was employed as the footbridge exciter, considering its capacity to move the heavy structure. Basically, it consisted of a pneumatic actuator DFM-32-200-P-A-GF, and a MPYE-5-1/4-010-B 5/3-way proportional flow valve. The actuator can apply forces up to 482 N and the valve is limited to pressures of 1 MPa. The sole limitation of this system for this application was the limiting pressure the valve stands, and this will be discussed later on. In order to detect the actual position of the footbridge during the tests, a Festo MLO-POT-100-LWG rod potentiometer was employed, having a maximum elongation of 100 mm and a resolution of 0.01 mm. On the other hand, in order to measure accelerations, two accelerometers Endevco model 7754A with sensitivity of 1 V/g were used. An analog input and output board model National Instruments USB-6009 and a house-made voltage amplifier circuit complemented the system (see Figs. 1(b) and 2).

As for the control system, the choice of one based on fuzzy logic was appropriate due to its robustness in dealing with the inherent nonlinearities of a pneumatic system (friction, air compressibility), plus alterations at the movement of footbridge supports during the crossing, and

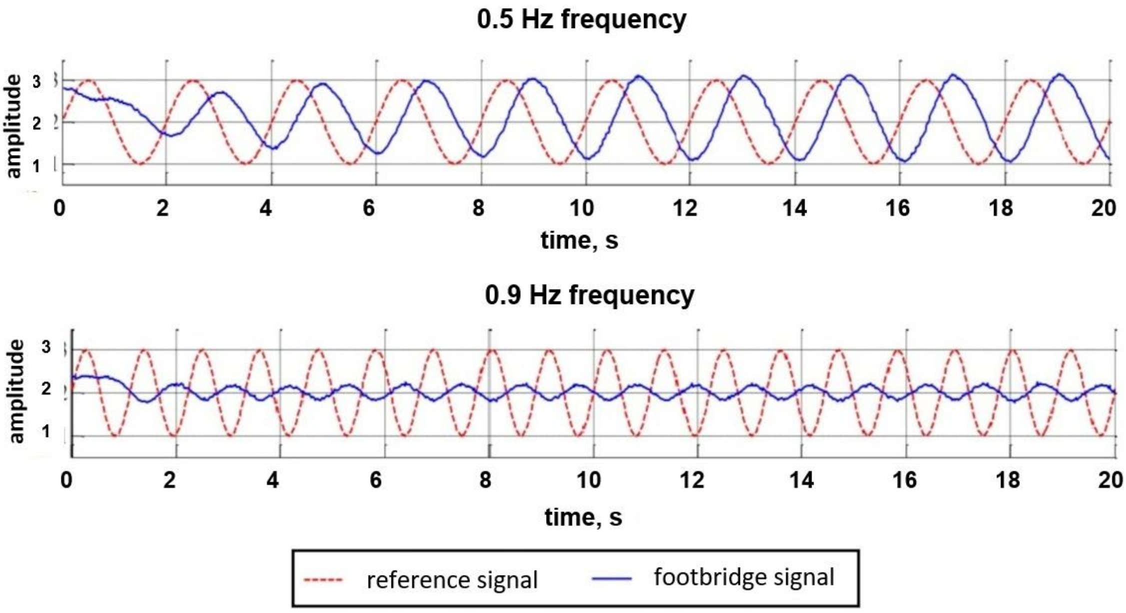


Fig. 3 Sine-wave reference signal and footbridge signal from the rod potentiometer, for different frequencies

also the presence of pedestrian-induced vibrations, which should be neutralized in order to keep the footbridge in motion at constant amplitude and frequency.

Trials were first performed to verify if the pneumatic actuator was able to move the footbridge according to a given reference signal generated by the control system. Sine-wave reference signals were used in the frequency range from 0.5 to 0.9 Hz (see Fig. 3). It was verified that the pneumatic actuator was able to keep the footbridge moving with the same frequency of the reference signal.

However, as the frequency of the reference signal approached the upper frequency of the tested range, there was an increase in the phase angle between the reference signal and the signal indicating the position of the footbridge. This means that a delay in the footbridge movement occurred, and this led to difficulties in reaching the peak displacements defined in the reference signal. This phase angle may be due to limitations of the working pressure that could be applied to the pneumatic components. This way, footbridge peak displacements around 20 mm were reached for the frequency of 0.5 Hz, whereas this reduced to around 6 mm for the frequency of 0.9 Hz (see Fig. 3 for a visualization of this effect). This corresponded to peak accelerations of 0.20 m/s^2 and 0.19 m/s^2, respectively. This gives a gross idea of the magnitudes of accelerations reached, since variation occurred for each test, due to inherent nonlinearities of the system. In spite of these limitations, the accelerations reached were compatible with the level of accelerations adopted in the guidelines to avoid synchronization, and thus, attended the focus of the paper. Values of peak acceleration obtained in each test are summarized in the Results section.

2.3 Test procedures with pedestrians

The accelerometers were fastened laterally through bolts, one at midpoint of the footbridge, and the other at the pedestrian's waist through a belt with appropriate support (see Figs. 1(a)-(b) for details). Carroll *et al*. (2013) demonstrated that this position at the pedestrian body is representative

Table 2 Pedestrian features and mean lateral frequency in each test

Excitation frequency of the footbridge (Hz)		P1	P2	P3	P4	P5	P6
	Age (years)	16	48	53	50	33	28
	Weight (kg)	53	74	73	107	53	56
	Height (m)	1.71	1.71	1.74	1.62	1.45	1.60
		Mean lateral frequency (standard deviation) (Hz)					
0.50		0.81(0.00)	0.88(0.00)	0.81(0.00)	0.88(0.00)	0.88(0.00)	0.91(0.04)
0.63		0.80(0.03)	0.84(0.06)	0.84(0.04)	0.83(0.03)	0.88(0.00)	0.86(0.03)
0.69		0.83(0.00)	0.88(0.00)	0.80(0.00)	0.81(0.03)	0.90(0.04)	0.81(0.00)
0.81		0.86(0.00)	0.83(0.04)	0.75(0.03)	0.83(0.03)	0.88(0.05)	0.83(0.03)
0.88		0.88(0.00)	0.84(0.04)	0.75(0.00)	0.81(0.00)	0.92(0.03)	0.86(0.03)
No excitation		0.94(0.00)	1.05(0.00)	0.87(0.00)	0.86(0.00)	0.97(0.00)	(*)

(*)not available

of the overall lateral movement of the pelvis, torso and head, and characterizes the lateral body movement when walking both on a fixed or movable support. However, in spite of the fact that the lateral movement captured by the accelerometer was also affected by the rotation of the pelvis, it served the purpose of this investigation, since the aim is to investigate frequencies and phase angles between pedestrians and structure only.

First, the pedestrian was positioned at one end of the footbridge. After the excitation system was activated, the pedestrian began to walk on the footbridge. Before acquiring signals, it was decided to extend the walking path, and the pedestrian continuously crossed the footbridge twice, going and returning to the starting point. To avoid an abrupt turning back, the pedestrian walked at one side of the deck and returned by the other side (see Fig. 1(a)). After completing this route twice, the pedestrian crossed the structure again and the signals were acquired for this last crossing. Thus, before starting the acquisition, the pedestrian would walk a distance of approximately 45 m on the oscillating footbridge. This aimed to provide a condition similar to a continuous vibration over long spans, since in actual footbridges with vibration problems the spans are much longer than that of the prototype structure. As it will be seen in the results, the response of the test subjects had similarities with those obtained from continuous walking in treadmills.

The tests were conducted with a group of six adults, four males (identified P1 to P4) and two females (identified P5 and P6), all wearing soft shoes. Each test was performed with each pedestrian crossing the footbridge alone at his/her desired pacing rate. The rationale for walking at free will is that the focus of the study is investigating synchronization between structure and pedestrians in normal conditions of usage. This way, the pedestrian pacing rate should not be artificially controlled.

The acquisition time of each signal was 16.384 s with a sampling rate of 125 Hz, and each pedestrian repeated, in general, the same test four times, to take intra-subject variability into account. This acquisition time was sufficient to include the whole crossing. Regarding the sampling rate, it was defined considering that for the highest test frequency of 0.9 Hz, it resulted in about 138 points for each vibration cycle, which is sufficient for an accurate detection of the sinusoidal shape of the signal. A total of 120 tests were carried out, including the aforementioned repetitions, plus 20 tests with five out of the six pedestrians crossing the footbridge when it was not set to vibrate.

Since the pedestrians were walking at free will, some variation of pacing rate is expected. This way, for each crossing of a given test, a spectrum was obtained from the accelerometer signal placed

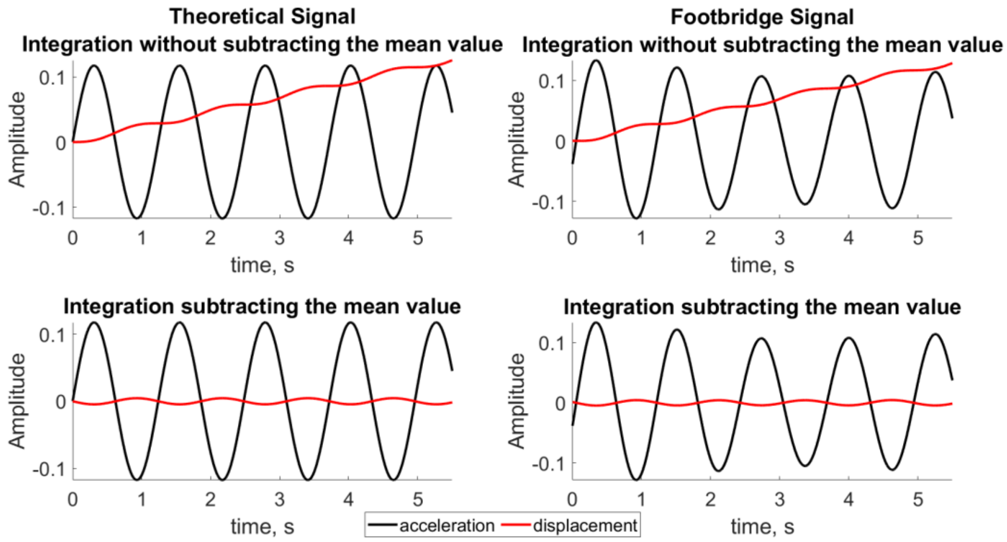


Fig. 4 Theoretical (left side) and footbridge (right side) signals: upper plots - integration without subtracting the mean value; lower plots - integration subtracting the mean value

at the pedestrian waist, from which the lateral frequency is identified by the spectral peak. The mean lateral frequency of each pedestrian (half of the pacing rate) and respective standard deviation during each test were obtained from these spectral peaks and are presented in Table 2, together with the lateral frequencies obtained in the same way for crossings with the excitation system turned off. It can be noticed that the pedestrian usually walked slowly in a vibrating surface, in comparison with his/her natural pacing rate. Personal features of each pedestrian are also included in Table 2, and there is no apparent relationship between them and the adopted pacing rates.

3. Analysis methodology

Based on previous works related to investigations of SLE in footbridges, a relevant aspect is to obtain not only frequencies but also the phase angle between the footbridge and pedestrian lateral movements, during the crossing.

In order to do that, spectra and respective band-pass filtered time-domains signals of the pedestrian and footbridge were obtained. Filtering aimed to make it easy to obtain the phase angle between these pair of signals. The definition of the frequency band of the filter was based on the spectrum of the original signal, to preserve the frequency content of interest.

From the filtered acceleration signal of the footbridge, integrations were made to obtain the displacement signal. For each integration, the mean value of the obtained integrated signal was subtracted from the signal itself, as a correction to avoid integration drifts. This was first checked by employing a theoretical sinusoidal acceleration signal having a non-zero mean value, and integrating it twice to obtain the respective displacement signal. Such a displacement signal was then compared with the theoretical expression of the displacement signal, and a match was achieved only when applying the aforementioned correction. In sequence, this procedure was checked by departing from a measured acceleration signal and the same behavior was observed (see Fig. 4).

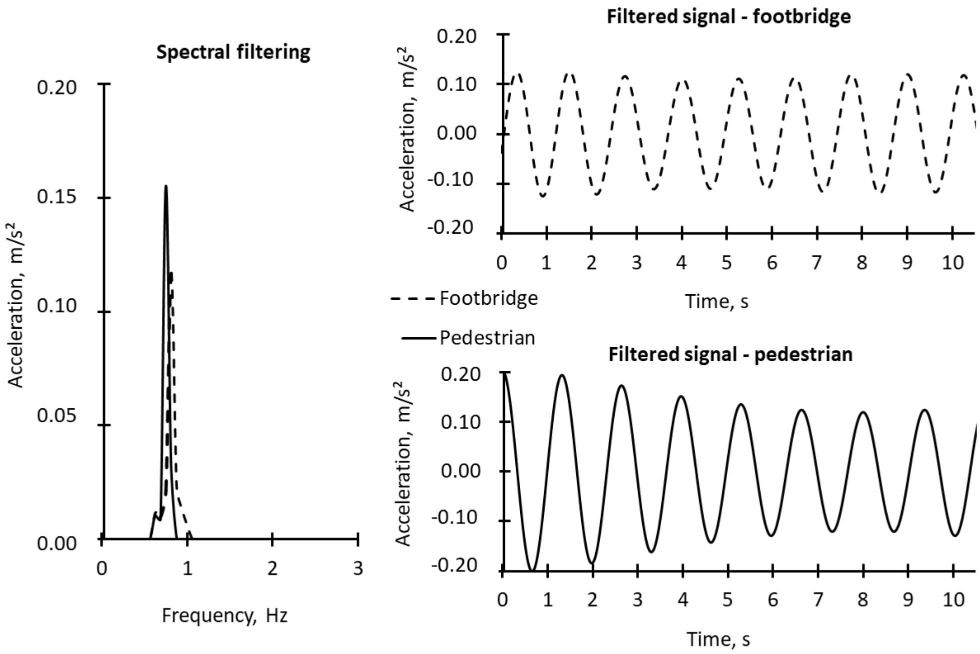


Fig. 5 Fourier spectra for a crossing of pedestrian P1 and footbridge and their respective filtered time domain signals

Subtracting the mean value of the signal was then revealed to be sufficient as a corrective measure. However, it should be noted that displacements were calculated just as a reference, since the analysis of phase angles was carried out using the acceleration signals.

In sequence, the filtered acceleration signals of the pedestrian and footbridge were superimposed, enabling the relative position between each pair of peaks of the signals to be observed. In the case of no occurrence of synchronization, the phase angle between pairs of consecutive peaks tends to vary significantly, monotonically or randomly throughout the signal. On the contrary, in case of synchronization, the phase angle tends to remain fairly constant.

Finally, it should be mentioned that all changes that occurred with the phase angles between pedestrian and footbridge were considered to be due to an interaction between them. This was based on a set of tests carried out with the same pedestrians crossing the footbridge, but without setting it to vibrate. It was observed in these tests that the pedestrians' movements presented regularity, with only minor changes in the lateral frequency and period of vibration from cycle to cycle.

Two cases are taken as examples to investigate the phenomenon: a case of frequency match, and another of frequency mismatch between the movements of pedestrian and structure. The detailed explanation of these cases aims to show how the experimental data were processed for identification or not of synchronization.

3.1 Case of frequency match

In Fig. 5, Fourier spectra and time response of the footbridge and pedestrian are shown, for a crossing in which the aforementioned frequencies of footbridge and pedestrian were close to each other. Small fluctuations can be noticed among the values of the peaks in the filtered signals. Since,

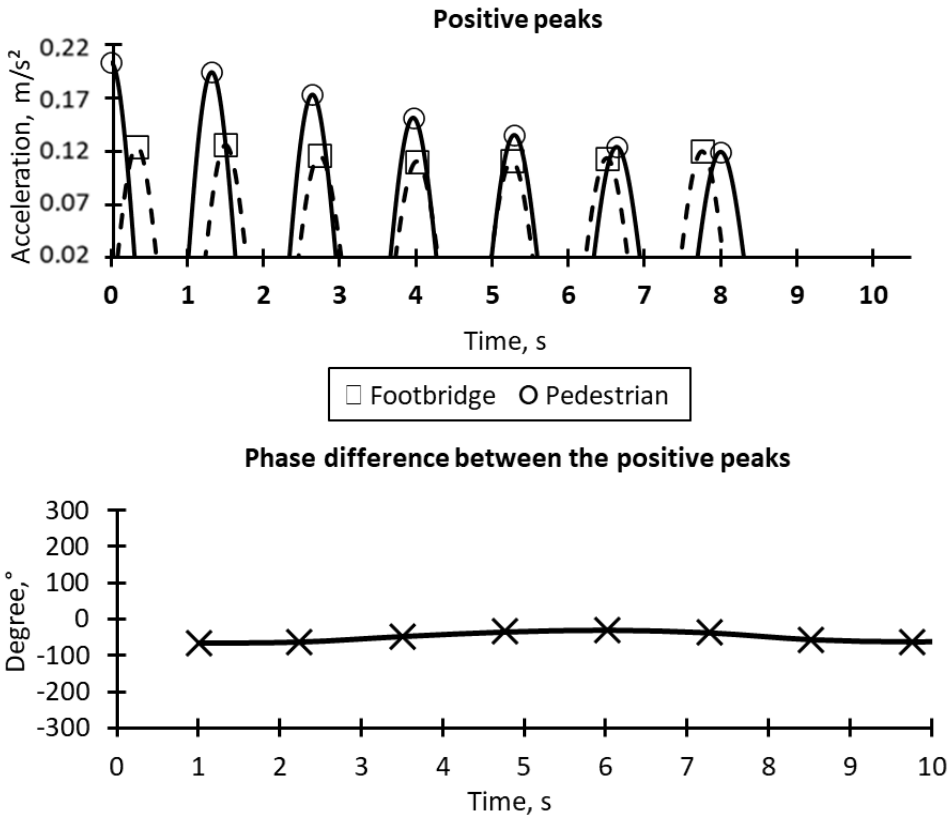


Fig. 6 Superposition of filtered signals and phase angles in case of frequency match - Pedestrian P1

in principle, the filtered signals should resemble a pure sinusoidal signal, reference values of peak displacement and acceleration for the footbridge were obtained by taking the mean of the peak values. Values of 4.9 mm and of 0.12 m/s² were obtained, respectively.

In Fig. 6 the overlapping of the two temporal signals of footbridge and pedestrian during this crossing is shown, to calculate the phase angles along the crossing. The accuracy in phase angle calculation is 0.6°, evaluated from the time interval employed to acquire the signals. The phase difference of the last nine pairs of peaks varied monotonically from -62° to -24°, due to a small difference between the frequencies of pedestrian (0.86 Hz) and excitation (0.81 Hz, see Table 2).

This behavior was similar to that obtained by Bocian *et al*. (2015), from tests in a treadmill moving with amplitude of 10 mm and frequency of 0.9 Hz, in which a virtual reality apparatus was employed to compensate limitations of visual cues of treadmill tests in laboratory conditions. The monotonic phase differences observed here show that this is a case of phase drift and not synchronization, in which the pedestrian maintained the original pacing rate. The frequency match between pedestrian and structure per se is not sufficient to characterize synchronization.

3.2 Case of frequency mismatch

A typical crossing in which frequencies of pedestrian and excitation are not so close like in the previous case is shown in Fig. 7. The lateral frequencies of footbridge and pedestrian were 0.81 Hz

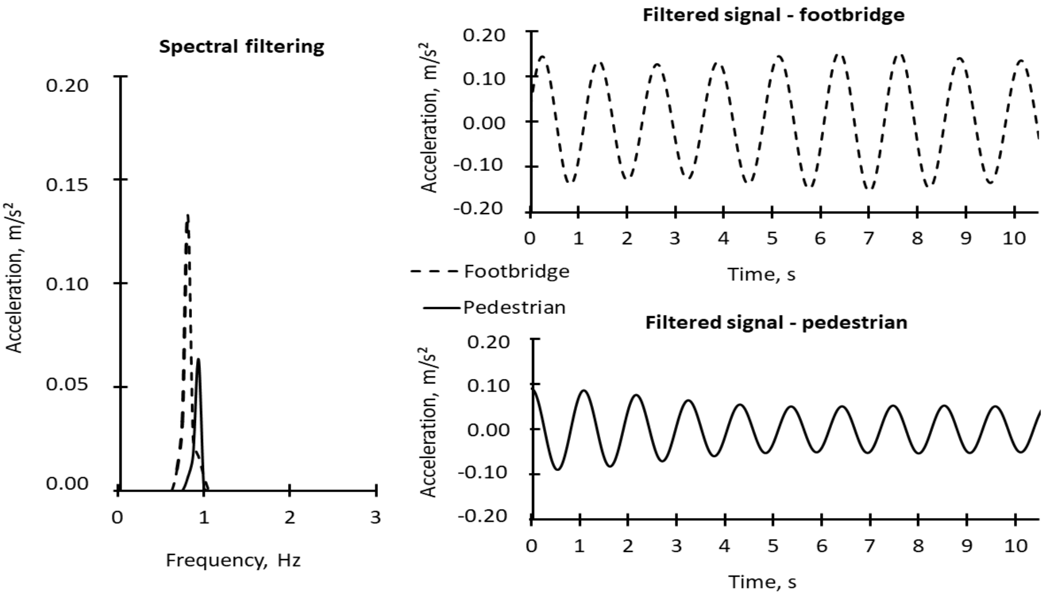


Fig. 7 Frequency spectra for a crossing of pedestrian P5 and footbridge and their respective filtered time domain signals

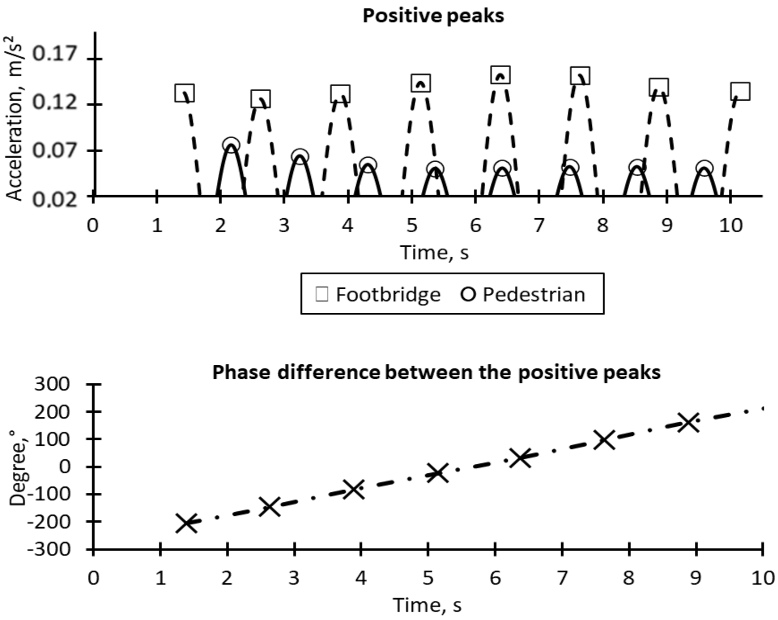


Fig. 8 Overlap of filtered temporal signals and phase angles in case of frequency mismatch - Pedestrian P5

and 0.94 Hz, respectively. The footbridge presented mean peak displacement and acceleration of 5.5 mm and 0.14 m/s², respectively. The variation of phase angles between the two signals is very visible in Fig. 8.

There was a much significant monotonic increase in phase angles between each consecutive pair

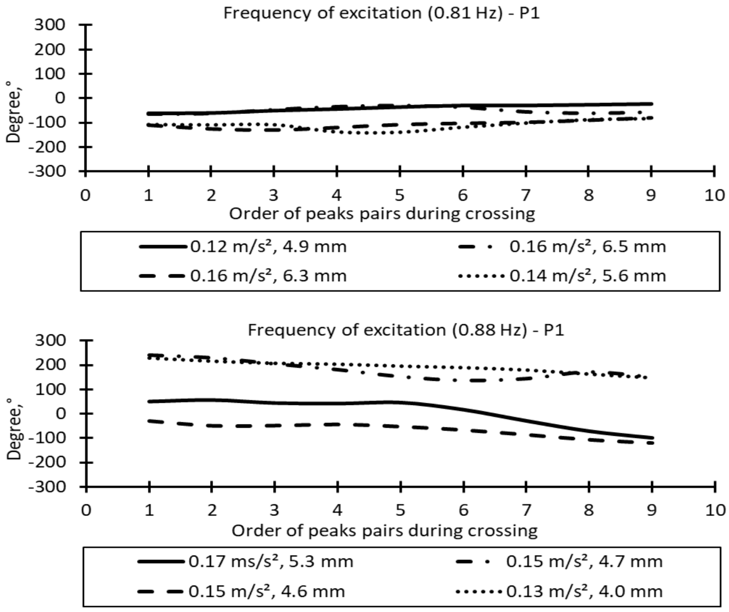


Fig. 9 Phase angles from crossings of pedestrian P1: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

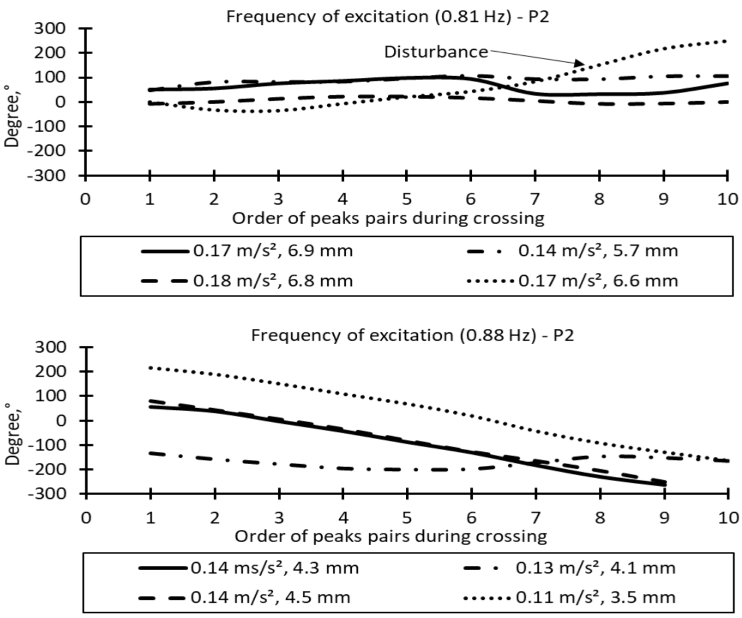


Fig. 10 Phase angles from crossings of pedestrian P2: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

of acceleration peaks. It was observed that the pattern of changes in phase was identical to the previous case, and phase drift was characterized. However, in this case not only phase changes were significant but also the lateral frequencies differed.

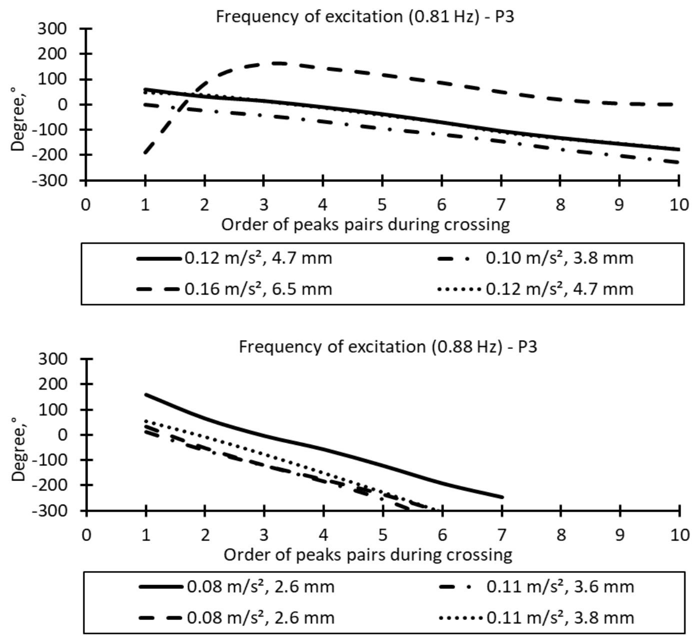


Fig. 11 Phase angles from crossings of pedestrian P3: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

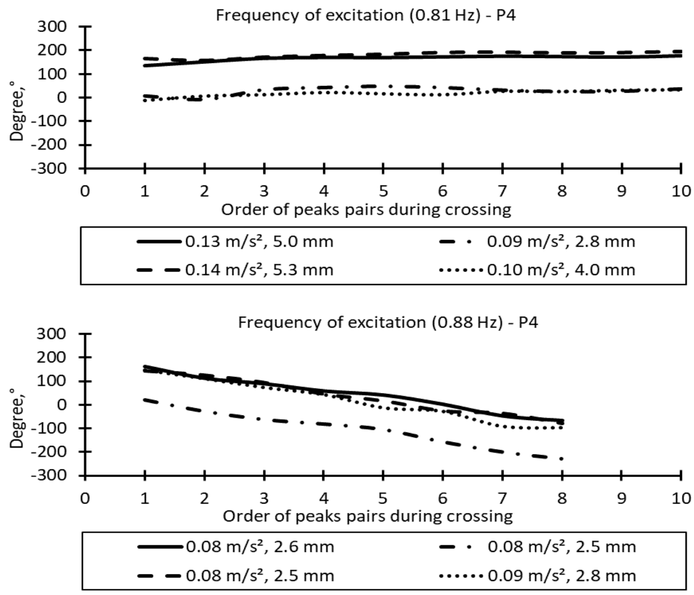


Fig. 12 Phase angles from crossings of pedestrian P4: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

4. Results and discussion

Considering a previous (or not) proximity between the lateral frequency of the pedestrian and

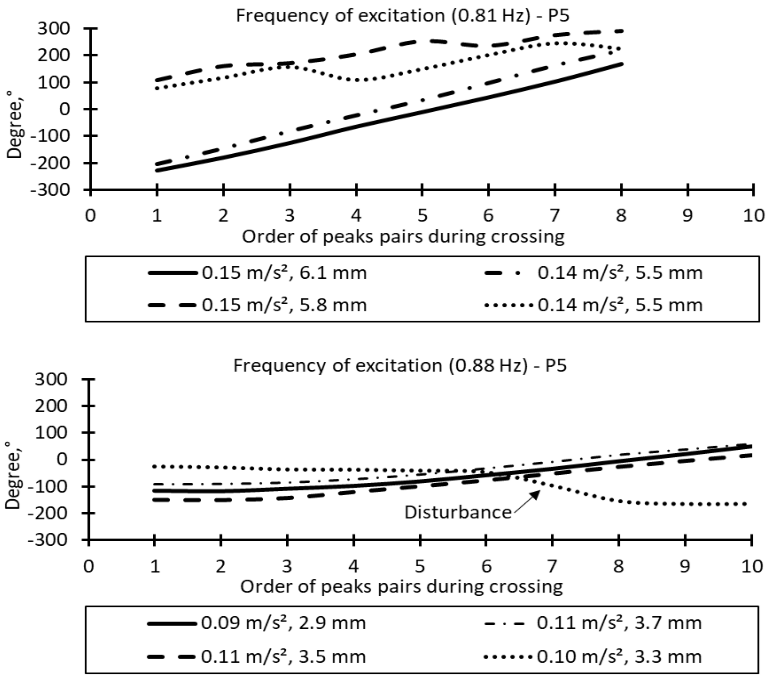


Fig. 13 Phase angles from crossings of pedestrian P5: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

the excitation frequency of the structure, the results were divided into two groups: lateral frequencies near and far from the excitation frequency.

Figs. 9-14 show the whole set of results for each pedestrian crossing the footbridge, for the cases in which frequencies of pedestrian and excitation were much close to each other. The legends indicate the average values of peak acceleration and displacement of the footbridge during each test performed. It is worth mentioning that a given pedestrian repeated the same test about four times; this is why each plot has more than one curve presented on it. The points in each curve were the phase angles obtained between the footbridge and the pedestrian.

It is worth noting that such angles varied in a large range among pedestrians (inter-subject variability, see for instance the values of the phase angles at the upper plots in Figs. 9, 12 and 14) and even for the same pedestrian (intra-subject variability, see for instance the upper plots in Figs. 12 and 14). This is evidence that the pedestrian did not actually locked-in with structural vibration, that is, the pedestrian kept sometimes in (or almost in) phase with structural movement simply because he/she was already walking with a pacing rate equal (or close) to the frequency of excitation of the structure. For the cases in which the frequencies of pedestrian and excitation did not match (all crossings in Fig. 11 and lower plot of Fig. 12), linear changes of phase along the cycles of vibration also indicated that the pedestrians kept his/her natural pacing rate in spite of the structural vibration. Here and there, there was incidence of cases of disturbance of the walking rhythm, indicated by abrupt changes in phase angle visually observed in the plots. Much evidence of this effect can be noticed at a crossing in the upper plot of Fig. 10 and another in the lower plot of Fig. 13.

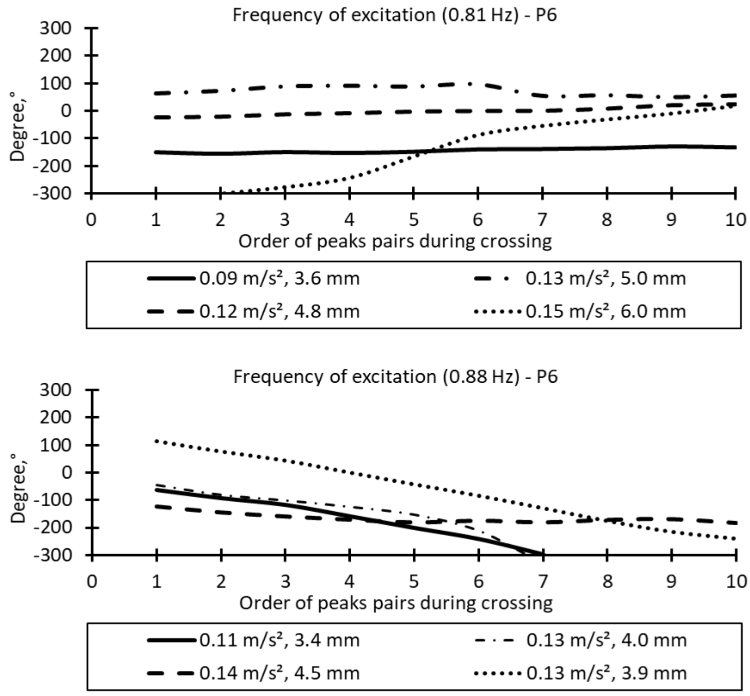


Fig. 14 Phase angles from crossings of pedestrian P6: upper plot for response at 0.81 Hz; lower plot for response at 0.88 Hz

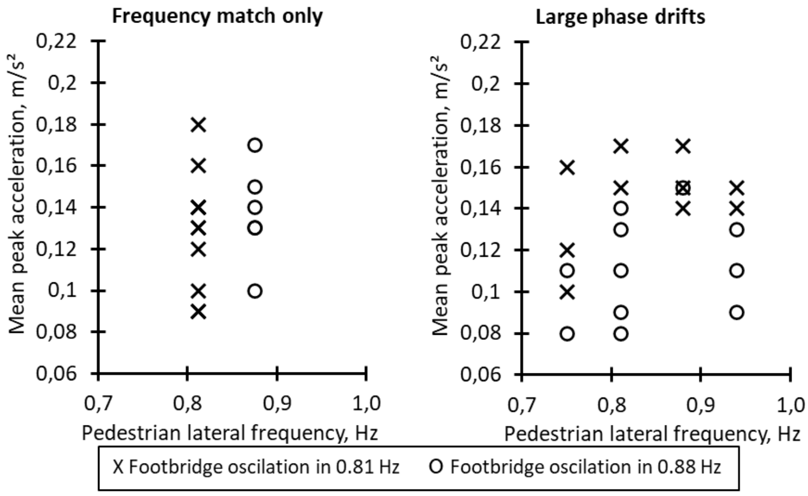


Fig. 15 Cases in which the footbridge was excited at 0.81 and 0.88 Hz

In Fig. 15, a collection of values is presented, in order to evaluate the magnitude of mean peak accelerations of the footbridge, for the structure excited at frequencies of 0.81 Hz and 0.88 Hz. For these frequencies, a match between frequencies of structure and of pedestrians occurred (see plot on the left side of the Figure), but without evidence of synchronization as previously discussed. These results, then, corresponded to no occurrence of synchronization in spite of frequency match.

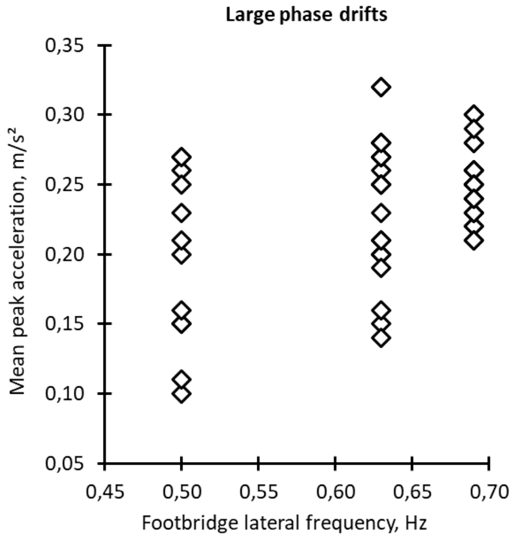


Fig. 16 Cases of no synchronization for frequency of excitation between 0.5 and 0.7 Hz

Variations in peak values among the tests were also due to difficulties in exciting the footbridge. However, the tests shown in Fig. 15 enable an upper limit of peak acceleration around 0.18 m/s^2 to be defined, with no lock-in for both the cases in which there was or not a frequency match between pedestrian and structure.

By following the same approach, Fig. 16 shows a synthesis of results in which no synchronization was observed. This occurred in the cases in which the structure was excited at frequencies below 0.7 Hz, even for higher values of acceleration. As previously discussed, only large phase drifts occurred, mostly with linear patterns of change of phase angle between successive cycles of vibration, indicating that the pedestrian kept his/her original pacing rate. Values of peak acceleration around 0.3 m/s^2 were reached in this frequency range for the investigated test cases, which are higher than the proposed limit to avoid lock-in of the Sétra (2006) and Hivoss guidelines (2008b). However, it should be noted that the Sétra threshold was obtained from tests with pedestrians walking in a crowd, whereas herein the pedestrians were walking alone. This is a limitation of this study and requires further investigation.

Finally, by observing again the results of phase angles in Figs. 9 to 14, there is randomness in the value of the phase angles between each pedestrian and footbridge. This means that it would be difficult for pedestrians to synchronize their movement with each other, so as to increase the net force exerted by a group and induce large structural displacements. Cases of synchronization observed in the literature show that pedestrians synchronize with each other (as they are locked-in to structural vibration). However, this would possibly be a next stage of the phenomenon, for higher values of acceleration, above the ones investigated here.

4.1 Research needs

It has been shown in this work that values of peak acceleration higher than those specified in guidelines as thresholds to avoid synchronization, could be reached without making single walkers to synchronize with structural movement. It is worth mentioning that studies that led to current guideline thresholds were obtained from tests in structures in which the frequency of lateral vibration were close to the usual frequency of pedestrian lateral movement.

Tests with high vibration levels are needed to identify the onset of synchronization for the whole frequency band of interest, bearing in mind that synchronization was observed in some actual footbridges for acceleration levels around 0.7 m/s^2. On the other hand, some footbridges in which synchronization was not reported presented lower acceleration values (see Table 1), although their lateral frequency did not match with frequencies of pedestrian lateral movement. In order to identify acceleration thresholds, as they may also depend on frequency, controlled tests are needed.

However, the phenomenon of synchronization is intrinsically related to pedestrians walking in groups or in a flow, as they synchronize not only with the structural movement but also among themselves. This is because visual cues and movement restrictions, and not only acceleration levels, may interfere with the phenomenon. The test subjects who took part in the experimental campaign of this work showed a consistent pattern of results. Such results are also consistent with other published works from walking in treadmills, but they were all obtained for single walkers; tests with pedestrians walking in a flow of varied densities are needed to consider the effect of the flow and restrictions to free walk.

5. Conclusions

This work addressed the problem of structural lateral vibrations, focusing on conditions that could lead to avoidance of synchronization among pedestrians themselves and footbridge. It should be noted that synchronization is a condition to be avoided in terms of design, since it implies that significant lateral vibrations will take place, as has been observed in actual footbridges.

A total of 120 tests were carried out with six pedestrians crossing a 11.3 m long test footbridge, laterally excited by a pneumatic actuator in a controlled way, in the frequency range between 0.5 to 0.9 Hz. Peak accelerations up to 0.3 m/s^2 were reached in these tests. In addition, 20 tests were carried out without artificially exciting the footbridge. The number of pedestrians was limited, but there was an observed consistent reduction of pacing rates when the test subjects were walking on a vibrating surface.

Synchronization did not occur in any of the investigated cases, even for the cases in which there was a frequency match between the lateral undisturbed frequency of the pedestrian and the frequency of structural oscillation. Such a match was observed in the range of frequencies between 0.8 and 0.9 Hz.

The results showed that synchronization can only be evaluated by investigating the pattern of changes of the phase angle between pedestrian and structure along the cycles of vibration. For the acceleration levels investigated, phase drifts from cycle to cycle of vibration occurred, indicating that the pedestrian was not influenced by the structural vibration, in the sense of not locking in with it. The values of the phase angle between pedestrians and structure were not constant, even for the same pedestrian when he/she repeated the tests. These occurred for acceleration levels between 0.10 m/s^2 and 0.18 m/s^2 for the frequency range from 0.8 to 0.9 Hz, and for acceleration levels up to 0.3 m/s^2 for frequencies of vibration below 0.7 Hz. In a few tests, erratic abrupt changes in phase angle revealed that the pedestrian was disturbed by the movement of the structure, but without synchronizing to it later on.

It is worth mentioning that guidelines like Sétra (2006) and Hivoss (2008b) adopt a single acceleration limit of 0.10 m/s^2 for the whole frequency range of interest regarding lateral vibrations, in order to separate safe and unsafe sides in terms of potential of synchronization between pedestrians and structure. The results showed that such acceleration limit could be increased for the frequency range below 0.7 Hz. In such a range, frequency drifts were much intense between pedestrians and structure. However, some words of caution are necessary:

- Tests with high vibration levels are needed to identify the onset of synchronization for the whole frequency band, bearing in mind that synchronization was observed in some actual footbridges for acceleration levels around 0.7 m/s^2.
- the results obtained here were consistent among themselves and also with other published works from walking in treadmills, but the results were for single walkers; tests with pedestrians walking together are required to capture the effect of the flow and restrictions to free walk.

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