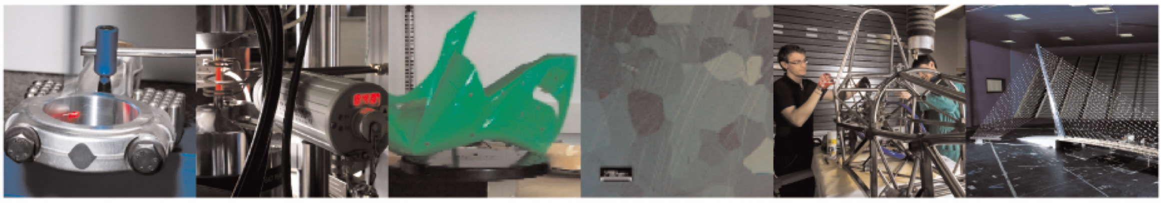


# Vision-Based Method to Measure the Synchronization Level of Jumping Crowds

Turrisi S.;Zappa E.;Cigada A.

This is a post-peer-review, pre-copyedit version of S. Turrisi, E. Zappa and A. Cigada, "Vision-Based Method to Measure the Synchronization Level of Jumping Crowds," in IEEE Transactions on Instrumentation and Measurement, vol. 72, pp. 1-9, 2023, Art no. 5012109, doi: 10.1109/TIM.2023.3267536

# Vision-based method to measure the synchronization level of jumping crowds

Simone Turrisi, Emanuele Zappa, *Senior Member, IEEE,* and Alfredo Cigada, *Member, IEEE*

***Abstract*—The prediction of the dynamic loads produced by groups of people is a crucial aspect for the design of stadiums or entertaining venues. This is because the coordinated motion of lively crowds may induce severe vibration levels in the structure, which can become critical for both human comfort and structural safety. However, the available information on this topic are very limited. Human loads often rely on deterministic models which do not consider the interaction and the coordination achieved by the participants or try to account for them through empirical assumptions. Therefore, they could find very little correspondence in realistic scenarios. This paper aims to close this gap by introducing a vision-based technique able to directly measure the crowd loading and quantify the synchronization level between the individuals. Starting from a sequence of images of a jumping crowd, Digital Image Correlation (DIC) is used extract the vertical velocity of different regions occupied by the participants; then, the vertical force time record is estimated. Finally, the comparison between the actual force signals and their envelopes allows to estimate the crowd synchronization over time. The method has been successfully validated with two field tests on the grandstands of the Giuseppe Meazza stadium in Milan, demonstrating its ability to reliably estimate the synchronization level reached by the participants.**

***Index Terms*—Digital Image Correlation, Computer Vision, Crowd Synchronization, Vibration Serviceability, Structural Health Monitoring.**

## I. INTRODUCTION

THE correct design of facilities intended to host a large number of people must undoubtedly consider the presence of the crowd and its interaction with the structure [1]. For structures like stadiums or concerts venues, this requires to properly characterize the dynamic loads induced by the audience since they may create extreme vibration responses. This phenomenon is particularly relevant when, during a concert, the music beat tend to synchronize the motion of the audience around one of the resonant frequencies of the structure. Under these circumstances, steady state conditions are reached and the structural response is significantly amplified.

The importance of these topics has pushed the researchers to investigate the people behaviour when jumping or bouncing on civil structures [2], [3]. Although the load model has been well understood in case of a single individual or small groups [4]–[6], the generalization to a large crowd is not straightforward. This is because one has to consider the stochastic nature of the crowd behaviour, the lack of synchronization between the individuals and the non-stationary jump conditions. In 2004, Ellis and Ji [7] develop a numerical model for jumping crowds and consider variations of contact ratio, frequency and phase lag based on the measurements obtained on two floors with groups up to 64 people. These models were also used to study the synchronized crowd activities in the BRE Digest 426 [8]. Later on, Parkhouse and Ewins [9] carried out an extensive research where the Dynamic Loading Factors (DLFs) and the Synchronization Factor (SF) are presented for groups from 5 to 200 participants. These groups are simulated by combining the load time histories of 60 individuals jumping alone on a load pate to different metronome beats.

Nowadays, only a few experimental measurements of dynamic loads and synchronization levels are available to design engineers in case of large crowds [10]–[12]. First, this is related to the difficulty of implementing efficient approaches that work in presence of highly crowded areas and real-world scenarios. Second, the high costs and the intrusiveness of the setup to measure the force signals limited the application to laboratory or controlled environments.

This paper introduces an innovative technique able to directly measure the crowd loads due to jumping and to quantify the level of synchronization between the participants. The method uses a standard camera and a computer for image processing, therefore it is cheap, easy to implement and convenient to track large number of people. From the evidence of previous studies that successfully apply Digital Image Correlation (DIC) to measure dynamic quantities [13], [14], the technique is here adopted to estimate the crowd induced dynamic loads as the sum of the contributions of different areas, called subsets, associated to the crowd position. Then, the level of synchronization between the jumpers is calculated for each oscillating period of the crowd signal by the comparison between the actual crowd force and its envelope curve. The most relevant contribution of this work with respect to the existing state-of-the-art methods is to introduce the possibility of providing a time-varying measurement of the crowd synchronization level, and thus of the load distribution over time, based on real evidence. This would improve the reliability of the actual crowd load models and therefore it would be a valid support during the design and the assessment of critical structures.

---

Manuscript received MM DD, YYYY; revised MM DD, YYYY; accepted MM DD, YYYY. Date of publication MM DD, YYYY; date of current version MM DD, YYYY.

The Associate Editor coordinating the review process was ... (*Corresponding author: Simone Turrisi*)

S. Turrisi, E. Zappa, and A. Cigada are with the Department of Mechanical Engineering, Politecnico di Milano, Milan 20156, Italy.

Color versions of one or more of the figures in this article are available online at ...

Digital Object Identifier ...

## II. VISION-BASED MEASUREMENT OF THE CROWD SYNCHRONIZATION LEVEL (CSL)

This section introduces a new approach to evaluate the synchronization level of a crowd jumping or bobbing on a grandstand, starting from the people's motion, as estimated thanks to a sequence of images acquired by a standard video camera. Digital Image Correlation (DIC) is first used as optical method to track the vertical velocity of the participants and then to estimate their accelerations. In a second step, these signals are manipulated via the Hilbert transform (HT) so as to provide relevant indications about the coordinated motion reached by people over time. The main steps of the proposed method are discussed below.

### A. Subset-based estimation of the force records

Given a sequence of frames reproducing a crowd jumping activity, Digital Image Correlation (DIC) is used to compute the time history of the vertical velocity of each subset $dv_p$, with $p = 1, \cdots, n$ and $n$ is the total number of subsets assigned to the region of interest, occupied by the crowd. Then, the vertical acceleration of each subset is obtained through numerical differentiation, i.e. $a_p = dv_p(t)/dt$.
An equal fraction of the global crowd mass is assigned to each subset ($m_p = m_c/n$), thus allowing to estimate the force time history of each subset as in Eq.1:

$$F_p = m_p a_p + m_p g \tag{1}$$

where $m_p g$ indicates the gravitational contribution. In order to make comparisons and signal visualization easier, each force time record is normalized with respect to the subset mass. Next, the force of the crowd $F_c$ is computed as the average of the contributions of each subset force:

$$F_c = \frac{\sum_{p=1}^{n} F_p}{n} \tag{2}$$

This steps is in agreement with the same approach proposed by the authors in previous works [12], [15], where the crowd load were estimated with low uncertainty also in realistic scenarios.

### B. Compute the CSL via Hilbert Transform

The Hilbert Transform (HT) is used to compute the analytic signal from a real data sequence [16]. The analytic signal $x = x_{real} + jx_{imag}$ has a real part $x_{real}$ which is the original data, and an imaginary part $x_{imag}$ which contains the Hilbert Transform. The imaginary part is a version of the original real sequence with a 90° phase shift. Therefore, the Hilbert-transformed series has the same amplitude and frequency content as the original sequence, but phase information changes. The HT is typically adopted to calculate the instantaneous amplitude (or envelope) of a time series, expressed as the amplitude of the complex Hilbert transform. For a pure sine wave, the instantaneous amplitude and frequency are constant, while the instantaneous phase reflects how the local phase angle varies linearly over a single cycle. For mixtures of sinusoids, these attributes are expressed as short term averages.

In this work, the Hilbert Transform is applied to the force record of each subset to obtain the complex valued analytic signal $F_A = F_{p,real} + iF_{p,imag}$ . Since the HT performs better with narrow-band signals, the subset forces are first bandpass (BP) filtered into a series of $h$ bands, centered around the main harmonics $f = f_1, f_2, \cdots, f_h$. For each of the $h$ signals, the HT is computed separately, then the magnitude of the analytic signal is extracted (Eq. 3a). The envelope, or equivalently, the instantaneous amplitude of the generic subset force us expressed by Eq. 3b. By averaging the envelope plots of all the subsets, it is possible to obtain the envelope of the normalized crowd force as in Eq. 3c.

$$F_E|_{BP(f_j)} = |F_A|_{BP(f_j)}| \tag{3a}$$

$$F_E = \sum_{j=1}^{h} F_E|_{BP(f_j)} \tag{3b}$$

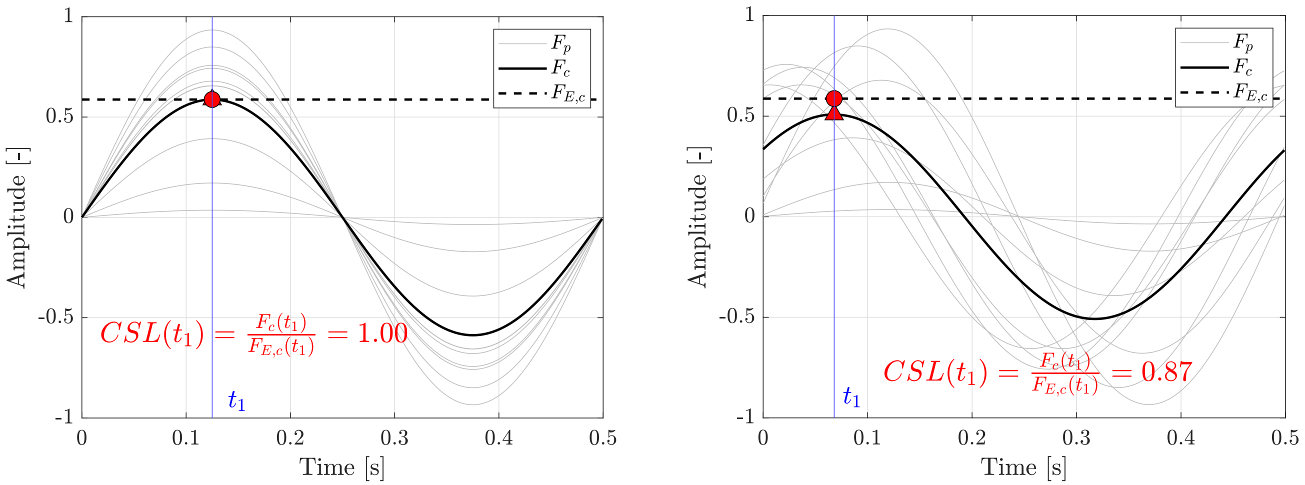
$$F_{E,c} = \frac{\sum_{p=1}^{n} F_{E,p}}{n} \tag{3c}$$

The latter can be seen as the actual crowd force amplitude when all the subsets, and thus all the individuals, are perfectly synchronized. This is because with the envelope we just keep the istantaneous amplitude, neglecting any information about the relative phases.
It should be noted that each subset force signal $F_p$ must be low-pass filtered in such a way that the resulting crowd force $F_c$ of Eq. 2 has an harmonic content which is consistent with the one of the crowd envelope curve $F_{E,c}$. Now, the Crowd Synchronization Level (CSL) may be defined as the ratio between the crowd force $F_c$ and the corresponding envelope $F_{E,c}$ at the time instant $t_k$ associated to the $k^{th}$ peak amplitude of $F_c$:

$$CSL_{t_k} = \frac{F_c(t_k)}{F_{E,c}(t_k)} \tag{4}$$

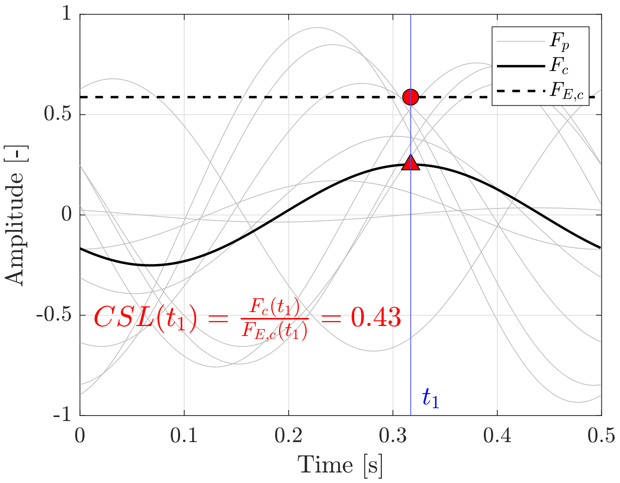
Fig. 1 provides a simple example to let the reader better understand the method proposed to calculate the CSL. For this purpose, ten subsets are considered and their normalized force time histories $F_p$ are numerically generated to resemble purely harmonic sine waves (j=1) with a carrier frequency equal to 2 Hz. The extension to an higher number of harmonic components is straightforward, provided that all the steps presented above are properly followed.

For each subset time history, a random amplitude between 0 and 1 is assigned. For what concerning the phase of the signals, instead, three different situations are simulated. In the first case (upper panel), the phase angles are set to 0 radians for all the subsets time series. In the second case (middle panel), it is assigned to each subset record a random phase value between 0 and $\pi/3$ radians. The third condition (bottom panel) is similar to the previous one, but it is considered a range between 0 and $2\pi$ radians. The crowd force $F_c$ is then calculated as the average of the subset time series (black solid line), while the crowd envelope $F_{E,c}$ is calculated as the average of all the subset-related envelope curves $F_E$. By analysing the first jumping period, which goes from 0 to 0.5 seconds, $t_1$ indicates the time at which the peak amplitude is



(a) Phase shift = 0 rad

(b) Phase shift = (0,$\pi/3$) rad



(c) Phase shift = (0,$2\pi$) rad

Fig. 1. Numerical example to explain the calculation of CSL with the proposed method for three different ranges of phase shift between the subset force time series.

reached in $F_c$. The ratio between the amplitude of the crowd force signal and the crowd force envelope at this specific point provides the CSL for that jumping period.

An interesting consideration emerges from a closer look of Fig. 1. Given the same amplitude of the subset force signals, a wider spread of the phase angles produces a lower amplitude in the crowd force $F_c$. On the contrary, the crowd envelope $F_{E,c}$ does not change. This permits to directly link the synchronization between the jumping signals with the definition proposed for the CSL.

## III. EXPERIMENTAL VALIDATION

Two experimental campaigns were carried out to assess the validity and the applicability of the above method, whose details and results are discussed below.

### A. *Jumping tests with 183 volunteers*

A first study involved a crowd made of 183 volunteers which performed a sequence of jumping activities on a cantilever grandstand of the Giuseppe Meazza stadium in Milan. Tests were done following the beat of either a metronome or famous pop/rock songs which fall in a range of comfortable jumping frequencies, i.e. between 2 and 3 Hz. To get the best performance from the group, the duration of each test was no more than 35 seconds and a short break was done between one test and the following. The sequence of jumping tests is listed in Tab.I, together with some relevant information.

A standard reflex camera (Canon EOS 750D) was used to acquire a movie of each test. The camera had a resolution of 1920 x 1080 px$^2$ and a sampling frequency of 25 frames per second. At the same time, grandstand vibrations were measured through a high-sensitivity piezo accelerometer (PCB 393B12) with a sampling frequency of 125 Hz. The accelerometer was installed on the tip of the cantilever, in

TABLE I
SEQUENCE OF JUMPING TESTS FOR THE FIRST EXPERIMENTAL STUDY.

| Test ID | Song/Metronome | $f_{\text{beat}}$[Hz] | Duration |
|---|---|---|---|
| 01 | Metronome | 2.67 | 25.64 |
| 02 | Metronome | 2.00 | 23.44 |
| 03 | Song | 2.06 | 29.12 |
| 04 | Song | 2.15 | 31.64 |
| 05 | Song | 2.17 | 22.36 |
| 06 | Song | 2.23 | 31.60 |

Fig. 2. Experimental setup and field of view for the jumping tests with 183 volunteers.

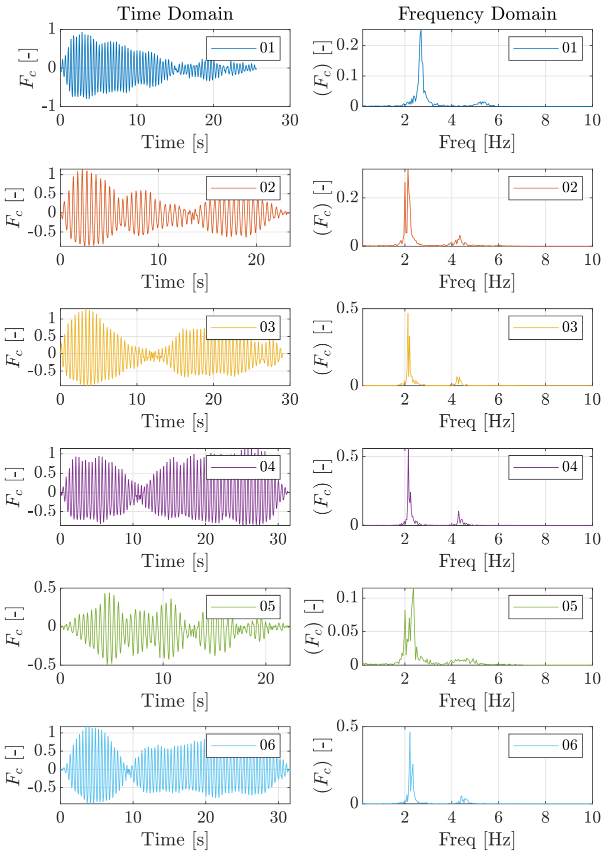


Fig. 3. Crowd force estimated with DIC for the six jumping tests in time domain (left) and their amplitude spectra (right).

proximity of the crowd position. Fig. 2 provides an overview of the experimental setup used in the activities.

Digital Image Correlation has been applied to the acquired movies to estimate the normalized force of the subsets in the region occupied by the crowd as well as the normalized force of the overall crowd. For DIC processing, a subset size of 15 px and a step size of 5 px were used, while the conversion factor was equal to 14.7 mm/px. These values fall in the optimal ranges suggested in [15], where the uncertainty related to DIC estimates for this kind of applications is minimized. The time series of crowd forces obtained for the different tests are depicted in Fig. 3 (left panel), together with the magnitude of their spectra (right panel). The time domain representation highlights a time varying amplitude in the crowd force signal, which is proportional to the synchronization of the participants during jumping. The plot in frequency domain, instead, reveals the presence of two main frequency components, where the first harmonic (equal to the beat frequency) is predominant with respect to the second. This aspect has been also confirmed by other researches which tried to model the behaviour of real crowds on civil structures [11], [12].

Fig. 4a provides the illustrative example of Test ‘02’ to explain the procedure adopted to estimate the CSL. The whole time history of the normalized crowd force $F_c$ estimated by DIC is represented by a blue solid line, while the relative envelope $F_{E,c}$ is represented by a blue dashed line. The constant term associated to the gravitational contribution has been subtracted from the original force signals since only the dynamic component due to people jumping is relevant to calculate the CSL. Moreover, subset force signals have been bandpass filtered two times to compute the envelope curve according to the methodology explained in Section II-B, first between 1 and 3 Hz and then between 3 and 6 Hz. This is because, as clearly visible from the spectra of Fig. 3, the main harmonic components of the signals fall in these ranges.

The obtained CSL values are interpolated with a cubic smoothing spline, so as to generate a curve having the same sampling frequency of the signals measured with DIC. The zoomed view of Fig. 4b between 2 and 4 seconds, instead, highlights the points related to the peak values of the crowd force and of the envelope curve for each jumping interval. The ratio of these two quantities returns the CSL for that period.

The same approach has been repeated for all the analysed tests and results are shown in Fig. 5. The points representing the estimated CSL over time are overlapped to the force and envelope curves using black circles. It is worth remembering that the envelope represents a measure of the crowd loading under the hypothesis of perfect synchronization. Accordingly, the amplitude of this signal is low at the beginning and at the end of each test, where people start and stop jumping respectively. In the center, the amplitude of the crowd envelope $F_{E,c}$ remains constant for the fact that the participants continued jumping with the same energy. On the other side,

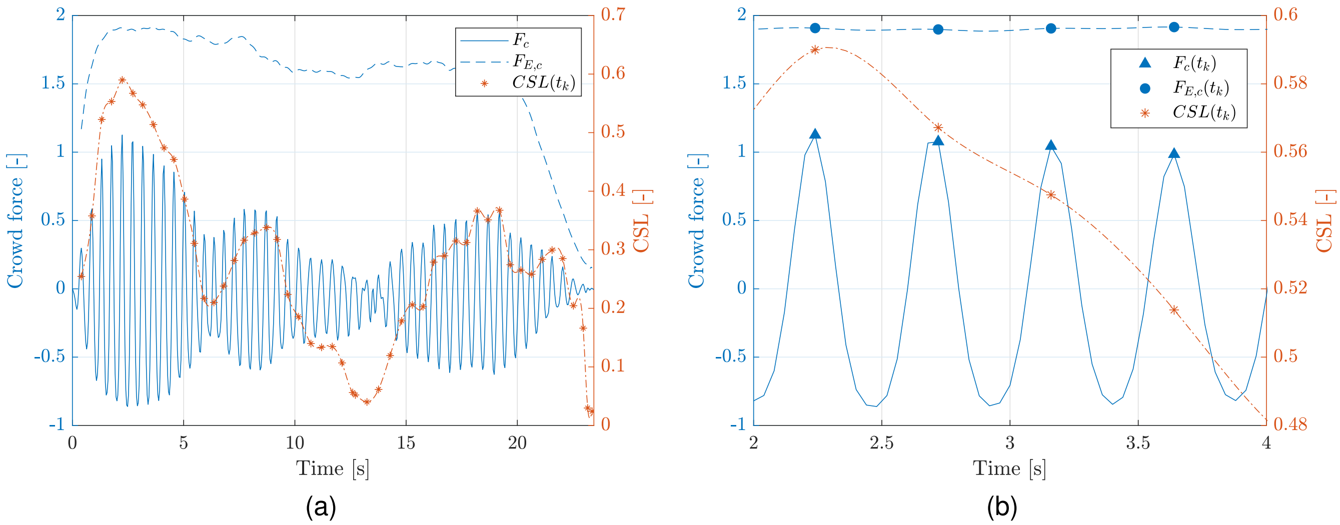


Fig. 4. Test ‘02’: a) normalized crowd force $F_c$, crowd envelope $F_{E,c}$ and Crowd Synchronization Level (CSL). b) Procedure to calculate the CSL between 2 and 4 seconds.

the amplitude of the crowd force $F_c$ quickly varied due to the phase delay between the subset time histories used in the averaging procedure. In this sense, the estimated values of the CSL intrinsically provide a realistic representation of the coordinated motion achieved by the participants. For example, in Test ‘03’ the CSL passes from 0.60 to 0 in about ten seconds, to then rise again and stabilize around 0.40.

Finally, the CSL curves are extracted for all the tests and compared with the vertical acceleration of the grandstand, with the intention of finding a potential relationship between the input excitation and the system response. To this regard, the acceleration data have been low pass filtered and down sampled to match the same sampling frequency, and thus the same frequency content of the CSL curves (0-25 Hz). The comparison is carried out considering the five-second RMS of the above mentioned signals. This allows to take into account the not perfect synchronization between the two measurement systems as well as the time delay between people jumping and grandstand accelerations due to transient conditions. Anyway, the possibility to evaluate the CSL every few seconds is a very good achievement for SHM purposes. The obtained results are reported in Fig. 6. First, it is possible to notice how the estimated CSL varies within the same test due to the degree of coordination reached by the participants. Second, for each test most of the CSL values are concentrated in the range between 0.10 and 0.50, testifying a fairly ability of the jumping volunteers to coordinate among themselves. Finally, there exists a direct proportionality between the CSL and the acceleration response, which can be approximated pretty well by a second order polynomial fitting curve. Although the dominant frequencies of the tests fall in a very similar range of values, one should keep in mind that the grandstand response is clearly influenced by the transfer function of the structure. Therefore, different dynamic amplifications and phase delays may occur in the acceleration signals. For this reason, the main goal is just to provide a qualitative proof of the goodness of the CSL estimates through the similar trend assumed with respect to the system response. This is because the more synchronized the people are, the higher the input loading is and thus the more severe the grandstand accelerations are.

### B. Real stadium event

The second studies applied the method during a real football match held at the G. Meazza stadium. To estimate the CSL, a full stand of the stadium was investigated as shown in Fig. 7. This section is the one assigned to the home fans, which are known to create the highest excitation, and thus the highest vibrations during the game. Structural accelerations of the cantilever tip were collected during the entire match by the accelerometers of the permanent vibration monitoring system of the stadium [17]. A digital video camera (SONY HDR-CX405) was used to record the time sequences when the supporters jumped following the rhythm of some choruses. The sampling frequency of the camera was equal to 25 Hz.

Two movies were selected for the following analysis, being the ones where the people motion due to jumping was the most noticeable. These are referred to as Test ‘07’ and ‘08’. DIC was adopted to estimate the subset forces, the crowd force and so the CSL for each test, following the same procedures and parameters presented in the previous experimental campaign. This time, a subset size of 13 px, a step size of 5 px and a scaling factor of 18.5 mm/px were used for DIC computations. Once again, these parameters were selected in order to respect the optimal ranges proposed in [15]. Fig. 8a illustrates the field of view for Test ’07’, where the region of interest (ROI) used for DIC analysis is highlighted in blue colour. Fig. 8b instead plots the standard deviation of the estimated vertical velocity for each subset. From this, it is possible to observe how the supporters from the left region are more active with respect to those from the right side, but there are also a considerable number of people who participate little in the jumping motion or even stand still.

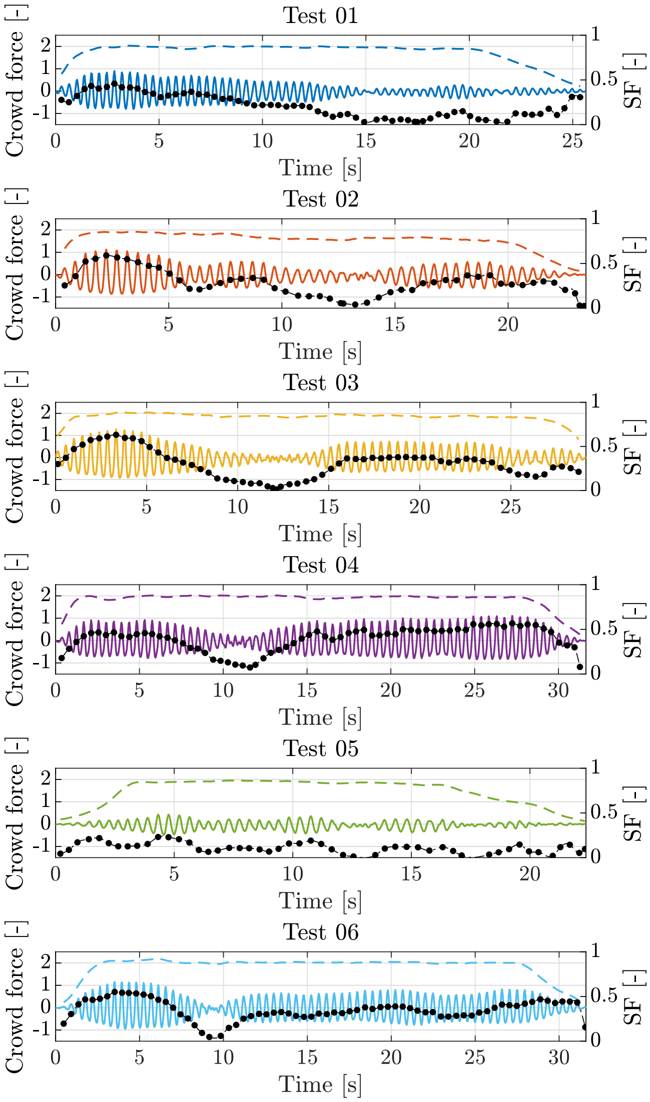


Fig. 5. Normalized crowd force $F_c$ (coloured solid line) and the relative envelope $F_{E,c}$ (coloured dashed line) used to calculate the crowd synchronization level CSL (black line) during the six jumping tests.

These aspects have been investigated more in detail, by analysing the left half and the right half regions of the original ROI separately. Fig. 9 shows the normalized crowd force $F_c$ and the corresponding envelope $F_{E,c}$ computed for the two considered regions. Both signals from the left side are characterized by an higher amplitude; they suggest that here the fans are more active with respect to the ones of the right side. There exists also a time delay between the normalized crowd forces of the two regions, which highlight the presence of a different jumping pace and synchronization. Peak levels are reached in different moments within the two time series of the crowd forces and therefore also the estimation of the CSL occurs at different time instants. The obtained CSL curves illustrated in Fig. 9 are in agreement with the previous considerations, being the estimated synchronization level of the left group always higher than the right one.

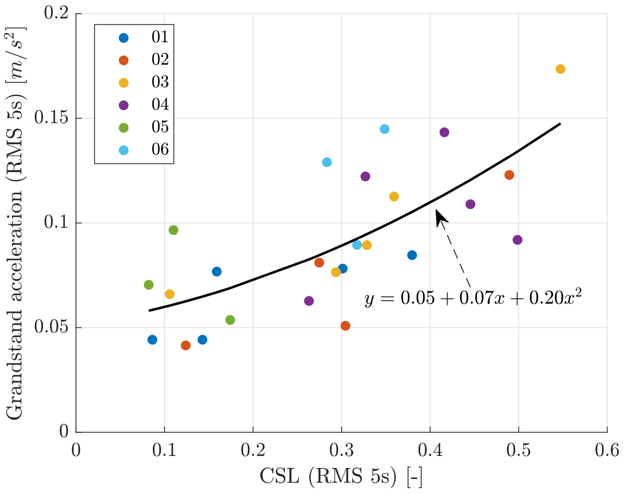


Fig. 6. CSL plotted versus grandstand acceleration (five-seconds RMS) for the six jumping tests.

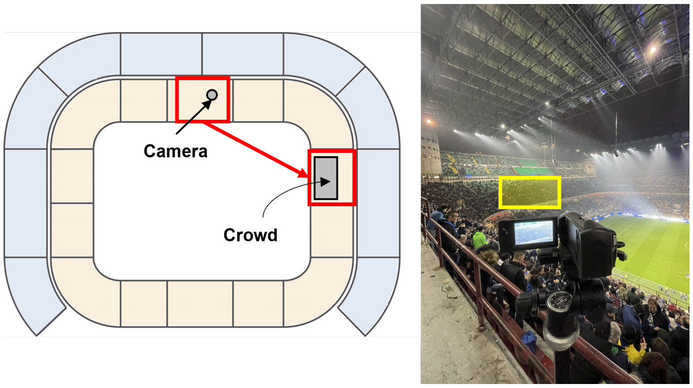
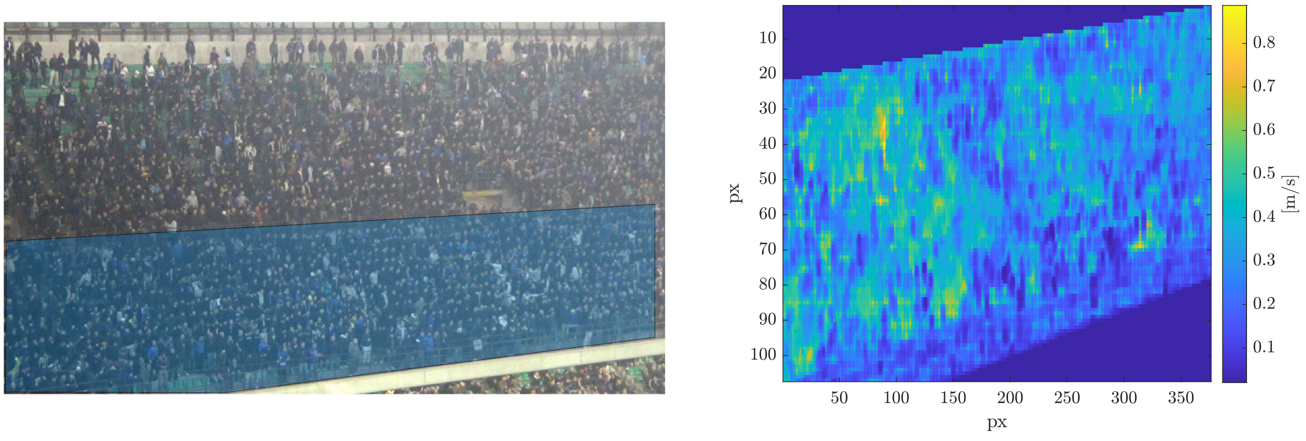


Fig. 7. Experimental setup and field of view used for the football match at the G. Meazza stadium.

The main results for the Test ’07’ and Test ’08’ are presented in Fig. 10. In general, both the amplitude of the normalized crowd force and the crowd envelope (thus also the CSL) are lower if compared to the curves of the first experimental campaign. Due to the high number of people, it is more likely to find individuals that do not jump synchronously or that even remain still. Moreover, the densely crowded scene and the contact with the neighbours prevented from a natural and energic jumping. Once again, the computed CSL values actually resemble the variations of the group synchronization over time. By comparing the CSL plots of Fig. 9 and Fig. 10 for Test ’07’, you will see how the CSL values computed from the whole ROI are lower with respect to the ones calculated separately for the two small groups. This is somewhat expected, since in the first case the adopted method considers the force time series of all the subsets and thus it is more likely to find high differences in the force amplitude and phases. This contributes to an overall reduction of the



(a) (b)

Fig. 8. Test ‘07’: a) Field of view and ROI considered for DIC analysis. b) Standard deviation of vertical velocity estimated with DIC for the considered ROI.

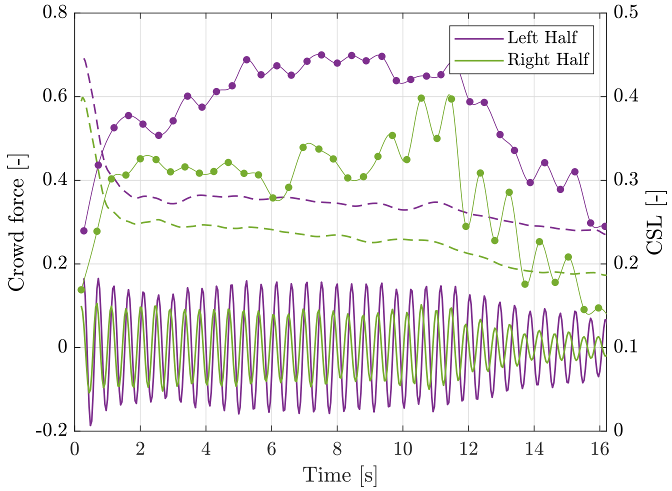


Fig. 9. Test ‘07’: Normalized crowd force $F_c$ (coloured solid line), crowd envelope $F_{E,c}$ (coloured dashed line) and CSL (coloured line with round markers) computed for the left half and the right half regions of the analysed ROI.

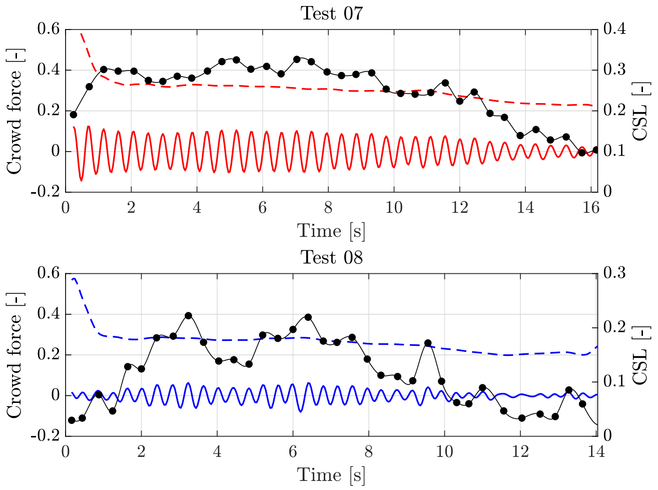


Fig. 10. Normalized crowd force $F_c$ (coloured solid line) and the corresponding envelope $F_{E,c}$ (coloured dashed line) used to calculate the crowd synchronization level CSL (black line) for the two movies recorded during the football match.

CSL values when calculated using the averaging procedure described above.

The relationship between the CSL and the grandstand acceleration is investigated too. Because of the limited duration of the time series, the RMS values were computed every two seconds. The plot of Fig. 11 highlights the presence of a clear correlation between the two quantities. Due to the few available sample points, linear regression was not statistically significant in this case and therefore the fitting curve has not been calculated. Finally, the relatively low vibration levels measured on the grandstand (RMS $< 0.35 m/s^2$) confirms the low coordination reached by the group.

## IV. CONCLUSIONS

This work proposes a vision-based measurement technique to estimate the loads induced by a jumping crowd on a civil structure as well as the level of synchronization of the participants. Given a sequence of images depicting the crowd activity, the method relies on the use of Digital Image Correlation (DIC) to retrieve the dynamic loads of different pixel regions associated to the crowd position, called subsets. After that, the overall force is computed by averaging the contributions of each subsets. The envelope of each subset time history is computed too and then averaged to obtain the envelope of the crowd force. At this point, it is possible to calculate the Crowd Synchronization Level (CSL) for each time instant $t_k$, defined as the ratio between the peak amplitude of the actual crowd force $F_c(t_k)$ and the relative envelope $F_{E,c}(t_k)$. The efficacy of the technique has been validated with two experimental campaigns held on the grandstands of the G. Meazza stadium. In the first study, six tests were carried out by 183 volunteers asked to follow different jumping

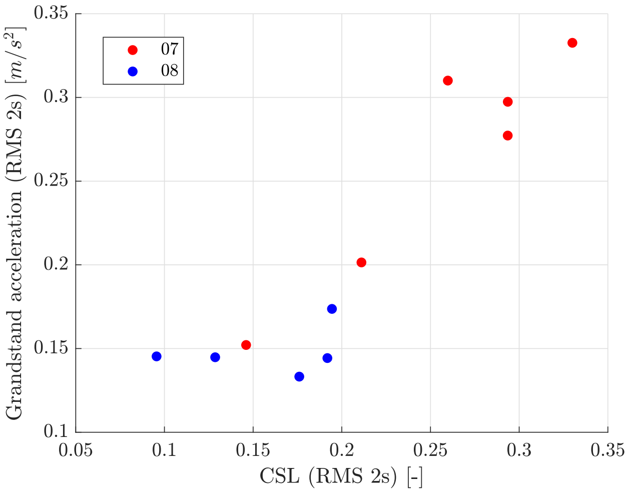


Fig. 11. CSL plotted versus grandstand acceleration (two-seconds RMS) for the two movies recorded during the football match.

beats. In the second study, two movies from a real football match were considered, focusing the analysis on the motion of the supporters of the local team. In both cases, the method demonstrated to provide reliable estimates, even in presence of low resolution images and crowded areas.

The major advantage of this approach is the ability to provide a quantitative measure of the crowd induced loads and its level of synchronization, based on what is actually happening in the grabbed scene. Since most of the existing codes for the design and the assessment of civil structures rely on parameters derived from analytical models or numerical simulations, these findings represent an important step towards the definition of more realistic crowd load models.

## REFERENCES

[1] ISO/TC 98/SC 2, “Bases for design of structures - serviceability of buildings and walkways against vibrations. International Organization for Standardization,” 2007.

[2] T. Ji and B. R. Ellis, “Floor vibration induced by dance-type loads. Theory,” *Struct. Eng. London*, vol. 72, no. 3, pp. 37–44, 1994.

[3] J. G. Parkhouse and D. J. Ewins, “Vertical dynamic loading produced by people moving to a beat,” in *Proceedings of the 2004 International Conference on Noise and Vibration Engineering (ISMA)*, pp. 821–835, 2004.

[4] R. E. Harrison, S. Yao, J. R. Wright, A. Pavic, and P. Reynolds, “Human Jumping and Bobbing Forces on Flexible Structures: Effect of Structural Properties,” *J. Eng. Mech.*, vol. 134, no. 8, pp. 663–675, Aug. 2008.

[5] N. A. Alexander, J. H. G. Macdonald, and A. R. Champneys, “Numerical investigation of a simple model of human jumping on an oscillating structure,” *Procedia Eng.*, vol. 199, no. December, pp. 2844–2849, 2017.

[6] J. Fangliang and W. Dingjun, “A random crowd load model for human-induced vibration analysis,” in *2011 International Conference on Electric Technology and Civil Engineering (ICETCE)*, pp. 4751–4754, Apr. 2011.

[7] B. R. Ellis and T. Ji, “Loads generated by jumping crowds: Numerical modelling,” *Structural Engineer*, vol. 82, no. 17, pp. 35–40, 2004.

[8] B. R. Ellis and T. Ji, “BRE Digest 426: the response of structures to dynamic crowd loads,” 2004.

[9] J. G. Parkhouse and D. J. Ewins, “Crowd-induced rhythmic loading,” *Proc. Inst. Civ. Eng. Struct. Build.*, vol. 159, no. 5, pp. 247–259, Oct. 2006.

[10] A. Cigada and E. Zappa, “Analysis of Jumping Crowd on Stadium Stands Through Image Processing to Security Purposes,” in *2006 IEEE International Workshop on Measurement Systems for Homeland Security*, vol. 159, no. 5, pp. 56–61, Oct. 2006.

[11] O. Celik, C. Z. Dong, and F. N. Catbas, “A computer vision approach for the load time history estimation of lively individuals and crowds,” *Comput. Struct.*, vol. 200, pp. 32–52, 2018.

[12] S. Turrisi, E. Zappa, and A. Cigada, “Experimental validation of a vision-based technique to estimate the crowd loading on stadium grandstands,” *IEEE Open J. Instrum. Meas.*, vol. 1, pp. 1–12, 2022.

[13] A. Lavatelli and E. Zappa, “A Displacement Uncertainty Model for 2-D DIC Measurement Under Motion Blur Conditions,” *IEEE Trans. Instrum. Meas.*, vol. 69, no. 6, pp. 2826–2836, Jun. 2020.

[14] A. Lavatelli, R. Balcaen, E. Zappa, and D. Debruyne, “An Experimental Investigation on Uncertainty in Measuring Vibration Deflection Shapes With Digital Image Correlation,” *IEEE Trans. Instrum. Meas.*, vol. 66, no. 3, pp. 451–459, Mar. 2017.

[15] S. Turrisi, E. Zappa, A. Cigada, M. R. Vivanco, and N. C. Avin, “Effect of image acquisition and processing parameters on the estimation of crowd-induced dynamic loading on stadium grandstands,” in *IEEE Instrum. Meas. Technol. Conf.*, May 2021.

[16] H. Boche and M. Protzmann, “A new algorithm for the reconstruction of bandlimited functions and their Hilbert transform,” *IEEE Trans. Instrum. Meas.*, vol. 46, no. 2, pp. 442–444, Apr. 1997.

[17] S. Turrisi, E. Zappa, A. Cigada, and T. Hötzer, “Large structures natural frequencies estimation using a limited number of sensors,” in *IEEE Instrum. Meas. Technol. Conf.*, May 2021.

**Simone Turrisi** received the B.Sc., M.Sc. and Ph.D. degrees in Mechanical Engineering from Politecnico di Milano, Milan, Italy.
Currently, he is a Research Fellow with the Department of Mechanical Engineering, Politecnico di Milano, Italy. His research interests include the development of advanced measuring solutions and data processing techniques for mechanical and civil applications.

**Emanuele Zappa** (Senior Member, IEEE) is a Full Professor in Mechanical and Thermal Measurements with the Politecnico di Milano, Milan, Italy.
His scientific activity is mainly in the field of mechanical and image-based measurements. He is also an Associate Editor in Chief of the IEEE Transactions on Instrumentation and Measurement.

**Alfredo Cigada** (Member, IEEE) is a Full Professor of Mechanical and Thermal Measurements with the Politecnico di Milano, Milan, Italy.
His main research topics deal with the development of new measurement systems for structural health monitoring of civil structures and cultural heritage.