applied sciences

IMPACT FACTOR 2.5

CITESCORE 5.5

Article

Innovative Experimental Assessment of Human–Structure Interaction Effects on Footbridges with Accurate Multi-Axial Dynamic Sensitivity Using Real-Time Hybrid Simulation

Bryan Castillo, Johannio Marulanda and Peter Thomson

Special Issue
Advances in Foot Biomechanics and Gait Analysis

Edited by
Prof. Dr. Rubén Sánchez-Gómez

MDPI

https://doi.org/10.3390/app14198908

applied sciences

MDPI

Article

Innovative Experimental Assessment of Human–Structure Interaction Effects on Footbridges with Accurate Multi-Axial Dynamic Sensitivity Using Real-Time Hybrid Simulation

Bryan Castillo *, Johannnio Marulanda and Peter Thomson

School of Civil and Geomatic Engineering, University of Valley, Cali 760001, Colombia;
johannio.marulanda@correounivalle.edu.co (J.M.); peter.thomson@correounivalle.edu.co (P.T.)
* Correspondence: bryan.castillo@correounivalle.edu.co

Abstract: This study evaluates the dynamic performance of a reference footbridge under human–structure interaction (HSI) effects using real-time hybrid simulation (RTHS). The footbridge, designed with precise multi-axial dynamic sensitivity, is tested under pedestrian gait velocities of 1.20, 1.50, and 1.80 m·s^{-1}. The RTHS framework involves an analytical continuous model of the footbridge as a numerical substructure and real human gait loads as the experimental substructure. The results reveal significant dynamic coupling between pedestrian-induced loads and the responses of the structure. Lateral vibrations exhibit a fundamental frequency of approximately 1.0 Hz, whereas vertical vibrations peaked near 2.0 Hz. Dynamic synchronization, particularly at higher gait velocities, amplified the structural vibrations, with lateral loading increasing by up to 300% in the middle span. Vertical loads show substantial amplification and attenuation depending on gait velocity and footbridge location. Lateral accelerations display a dispersion of approximately 15.0%, whereas vertical accelerations showed higher variability, with dispersions reaching up to 20%. The RTHS technique demonstrates high fidelity and accuracy, with global errors below 2.95% and delays of less than 2.10 ms across all evaluated directions. These results emphasize the critical importance of accounting for HSI effects in the design of pedestrian footbridges because human-induced vibrations can significantly impact structural serviceability and user comfort. This study offers important insights into optimizing footbridge design to mitigate the risks of excessive vibrations and ensure both safety and functionality under typical pedestrian loads.

Keywords: human–structure interaction; footbridge; human-induced loads; human gait; vibration; real-time hybrid simulation

Citation: Castillo, B.; Marulanda, J.; Thomson, P. Innovative Experimental Assessment of Human–Structure Interaction Effects on Footbridges with Accurate Multi-Axial Dynamic Sensitivity Using Real-Time Hybrid Simulation. *Appl. Sci.* **2024**, *14*, 8908. https://doi.org/10.3390/app14198908

Academic Editors: Arkady Voloshin and Claudio Belvedere

Received: 9 September 2024
Revised: 21 September 2024
Accepted: 25 September 2024
Published: 3 October 2024

1. Introduction

In contemporary urban development, there is growing emphasis on prioritizing pedestrian traffic, leading to the creation of civil structures designed specifically for walkable use. This shift aims to enhance walkability and promote sustainable urban living [1]. However, the dynamic interaction between human-induced activity loads and the response of civil structures frequently limits serviceability owing to the development of excessive structural vibrations. Dynamic coupling between gait pedestrians and structural responses has been extensively discussed in the literature concerning civil structures, such as stairs [2–4], grandstands [5–9], slabs [10–12], and footbridges [13–24]. The latter type of structure has become the most affected urban civil structure regarding vibration serviceability limits due to the increase in technical and aesthetic requirements, their condition of spanning large distances, and the ongoing integration of advanced materials that are more robust and lighter during and after the construction process. Grouping of these conditions allows for design optimization, resulting in relatively low mass and damping. Consequently, footbridges are becoming increasingly slender and flexible, increasing their dynamic sensitivity to excessive vibrations owing to human activity [13,17,25]. Normally, vandalism-induced human loads have the greatest dynamic effect on the response of footbridges [18,26]. However, owing to their intensity and wide frequency range, human-induced gait loads have the highest recurrence and potential to limit the structural serviceability due to the vibrations generated. In addition, the human gait frequency content is typically close to the dynamic properties of these types of structures, which poses a latent risk of synchronization phenomena affecting both footbridges and pedestrian traffic.

The adaptive [17,27,28], random [29,30], and nonstationary conditions [17,29,31] of human-induced gait loads have generated an interrelation phenomenon with structural vibrations known as structure-to-human interaction (S2HI) [17,32–34]. Concurrently, the dynamic properties of footbridges are influenced by the presence of these anthropic loads, and the participatory mass and damping provided by human loads are significant for these dynamically sensitive structures; this relationship is known as human-to-structure interaction (H2SI) [23,35–37]. In addition, dynamic effects between the gait pedestrians themselves have been observed and are denoted as human-to-human interaction (HHI) [38–40]. These interaction aspects are referred to in the literature as human–structure interaction effects (HSI) [13,18,20,27,41–44]. These effects on footbridges represent an advanced case of dynamic synchronization and have become one of the most intriguing topics within the structural scientific community in recent years.

Traditionally, human-induced gait load effects on footbridge dynamic responses have been numerically evaluated by assuming the behavior of these anthropic loads on vibrating surfaces without complete interrelation effects with the structural response, which underestimates the dynamic coupling effects and leads to a tendency to condition serviceability due to the low estimation of structural vibrations [21,31,45–49]. Likewise, S2HI effects have been assessed on surfaces with lateral movement using instrument treadmills, which allows unidirectional or multidirectional analysis of the vibration effects on human-induced gait loads [17,32–34,50]. Although experimental tests allow better measurement of the human gait response due to controlled conditions and predefined protocols, limitations have generally been reported in the development of variability conditions under HHI effects and individual human gait disturbances [9,14,17,51,52]. In order to reduce the impact of laboratory conditions, in the last two decades, several footbridge benchmarks have been built, evaluated, and described in state-of-the-art structural engineering to submit benchmarking problems of international reference, which have been highlighted for conditioning the structural design to fundamental frequencies close to the frequency content of the human gait [25,41,42,49]. However, the construction process and variability of the materials used have led to shifts in the target fundamental frequencies, limiting their effectiveness in studying the HSI effects. In addition, the cost-effectiveness, maintenance, and obsolescence of this type of footbridge development after the research has been completed represent another important constraint.

Studies on functional urban footbridges are ideal study prototypes because of their natural geometry, large-scale dimensions, actual service loads induced by pedestrian flows, and environmental perception around the structure, which affect pedestrian gait behavior. Fujino et al. [53] conducted a pioneering study on a large-scale footbridge under typical pedestrian loading conditions (Toda Park Footbridge, Japan). They quantified the influence of HSI lateral effects for more than 20.0% of pedestrians, observing coupling with the fundamental frequency of the structure (≈0.91 Hz) and subsequent serviceability limitations due to structural vibrations. Similarly, excessive lateral vibrations caused by human-induced loads have been reported during the openings of the Millennium Bridge (London), Solferino Bridge (Paris), and Changi Airport Bridge (Singapore). Large-scale tests on these structures have gradually demonstrated dynamic alterations in the lateral structural vibration behavior due to HSI effects, as extensively documented by Dallard et al. [54], Živanović et al. [13], Dziuba et al. [55], Ingólfsson et al. [27], and Brownjohn et al. [56]. Numerous cases have been reported in the literature on HSI effects, modeling, and anthropic load testing related to footbridges, including the Wuhan Yangtze Bridge, China [57], and the Le Ponte del Mare, Pescara, Italy [58], among others. Additionally, slabs, and stairs. This dynamic feedback condition increases the requirements of analytical models, which generates greater uncertainty in the estimation of human gait-induced loads and dynamic structural responses.

In fact, human gait analytical models have limitations in simulating and evaluating the dynamic behavior of the HSI effects on footbridges. Therefore, in this study, each TS gait was assumed to be an experimental substructure with active anthropic loads ($F_{k,j}$, $k \rightarrow$analysis direction {vertical (blue), lateral (red), or friction (green)}, and $j \rightarrow$selected foot {left or right}), which were induced in the reference footbridge, as detailed in Section 3.5. Likewise, the dynamic structural response ($\ddot{a}_{s,total}$, total structural acceleration) feedback of the experimental TS gaits, which modifies human-induced gait loads on the structure, generates a dynamic interaction in real-time, as schematically shown in Figure 2. This methodology allows the measurement and incorporation of real human gait-induced loads under dynamic HSI effects, which increases the accuracy of the structural response simulation and acquires anthropic loads. In addition, each TS used a safety lifeline to ensure the integrity and sense of security during the gait tests and was instrumented with a pair of insole pressure sensors (Stridalyzer Insight developed) by ReTiSense [17]. Moreover, active motion markets were positioned in the body joints to measure the tridimensional displacements using two motion capture systems: sagittal and coronal planes, as experimentally shown in Figure 3 (top). This indirect and direct measurement allows to generate a comprehensive dataset about HSI effects on reference footbridge.

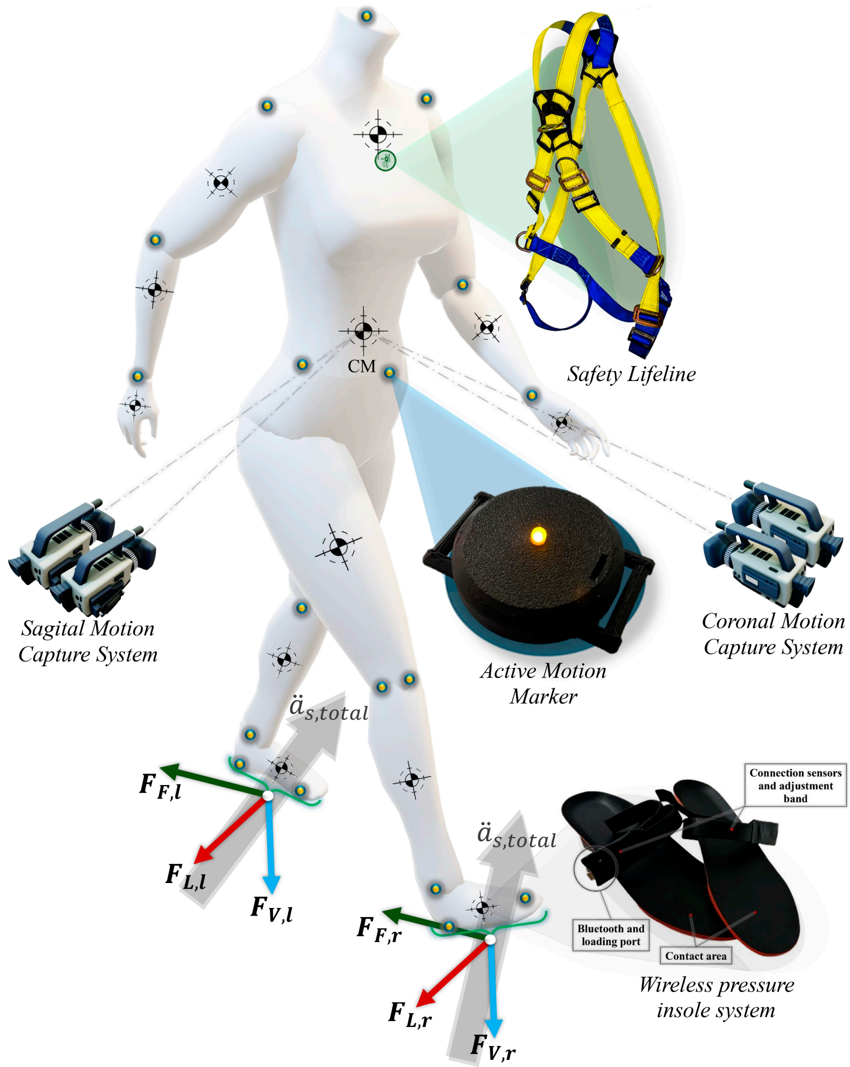

Figure 2. Experimental substructure: multi-experimental human-induced loads.

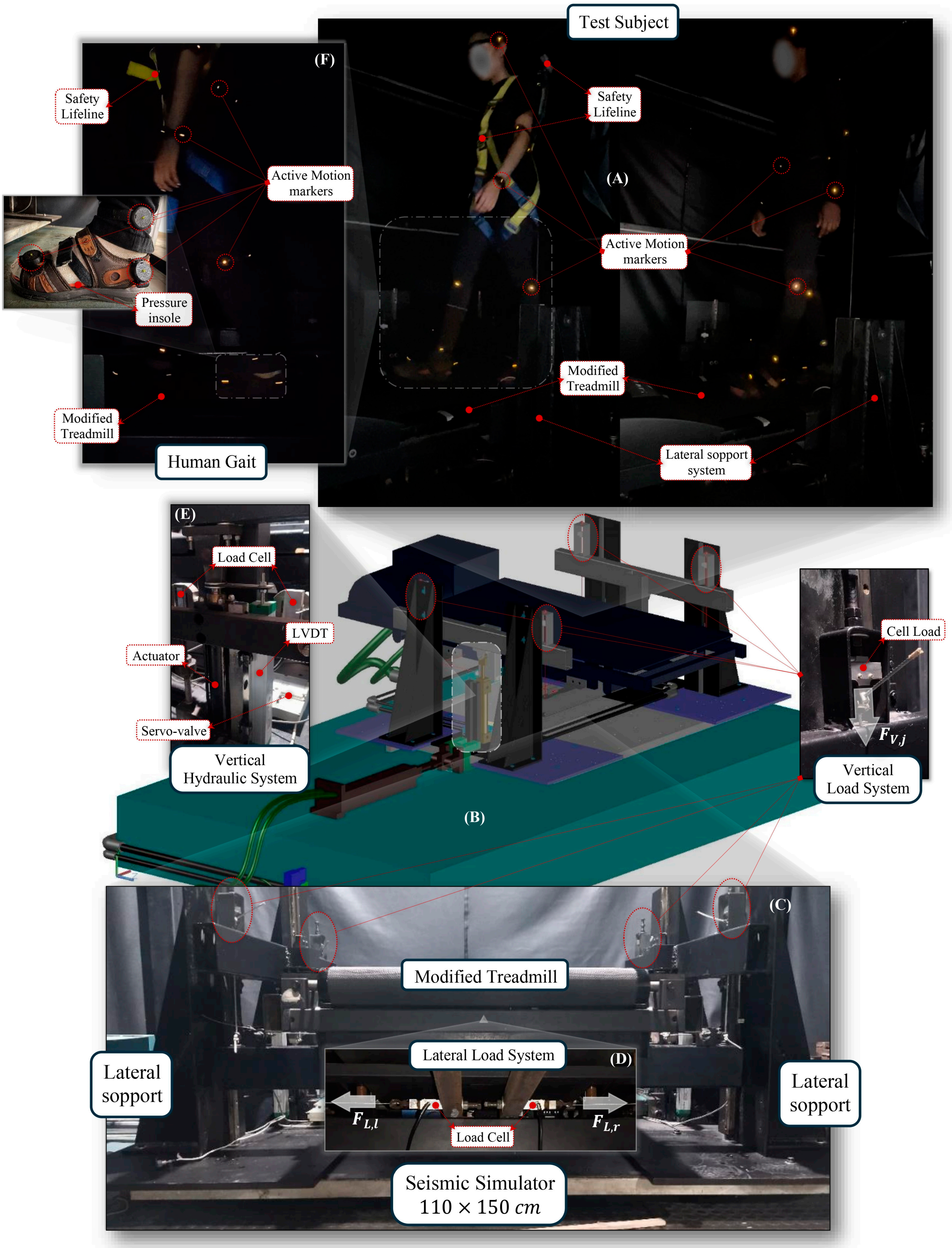

Figure 3. Description of the HSI-MTF. (**A**) Test subjects during gait tests; (**B**) three-dimensional scheme of the HSI-MTF; (**C**) front view of the HSI-MTF; (**D**) lateral load system of the HSI-MTF; (**E**) vertical hydraulic system of the HSI-MTF; and (**F**) additional measuring devices.

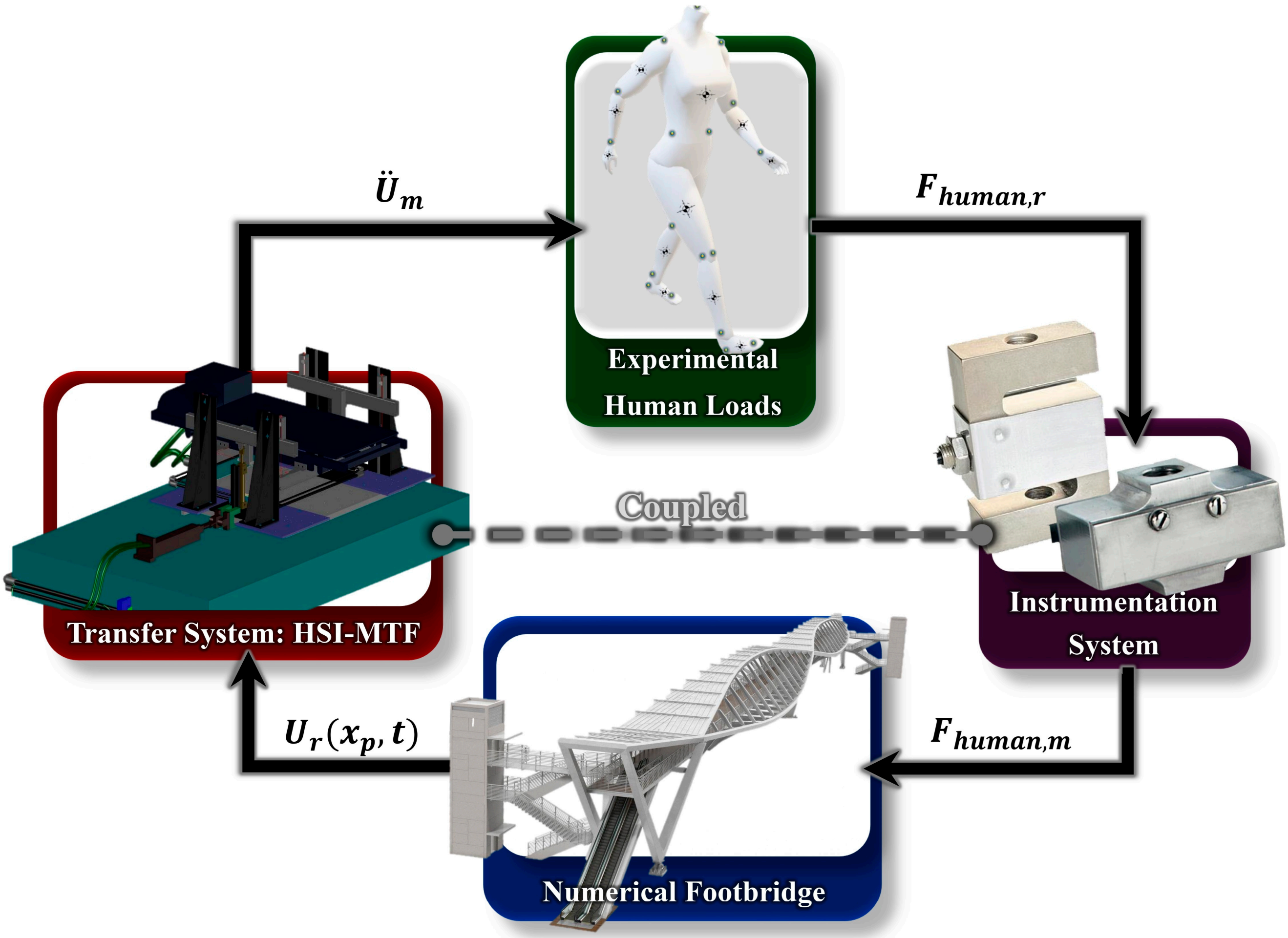

Figure 4. Closed dynamic loop to evaluate HSI effects on civil structures.

3.5. Experimental Input: Evaluation of HSI Effects

Gait tests were carried out in this study for each TS, which consisted in the dynamic evaluation of HSI effects due to crossing of crowd-induced gait loads over the reference footbridge to three constant typical gait velocities: 1.20 m·s^{-1}, 1.50 m·s^{-1}, and 1.80 m·s^{-1}. In addition, each TS-induced experimental gait load acted on the centroid of the reference footbridge, which constituted the numerical prototype, using HSI-MTF as the transfer and instrumentation system, as described in Section 3.3.

4. Results and Discussion

4.1. Human-Induced Gait Load Performance on the Reference Footbridge

Dynamic interactions between human activities and lightweight structural responses have been reported and have significantly increased in recent years, which constitutes a risk to condition the structural serviceability due to the coupling of dynamic changes in human gait behavior and structural vibrations. Therefore, in this section, the evaluation of pedestrian-induced gait loads in direct connection with reference footbridge responses is divided into two main assessment directions: lateral and vertical loads.

4.1.1. Lateral Loads

The lateral gait loads induced by all TSs on a rigid surface were evaluated for 30.0 s. The induced lateral load (L_L) was normalized with respect to the weight (W_0) of each ST, yielding an average normalized lateral load of approximately 2.0% and a maximum of 2.9%. These human gait loads induced by TSs are presented in Figure 5 (top left) for a 3.0 s

72. Chen, P.-C.; Dong, M.-W.; Chen, P.-C.; Nakata, N. Stability analysis and verification of real-time hybrid simulation using a shake table for building mass damper systems. *Front. Built Environ.* **2020**, *6*, 109. [CrossRef]
73. Maghareh, A.; Dyke, S.J.; Silva, C.E. A Self-tuning Robust Control System for nonlinear real-time hybrid simulation. *Earthq. Eng. Struct. Dyn.* **2020**, *49*, 695–715. [CrossRef]
74. Sarebanha, A.; Schellenberg, A.H.; Schoettler, M.J.; Mosqueda, G.; Mahin, S.A. Real-time hybrid simulation of seismically isolated structures with full-scale bearings and large computational models. *Comput. Model. Eng. Sci.* **2019**, *120*, 693–717. [CrossRef]
75. Brailsford, S.C.; Eldabi, T.; Kunc, M.; Mustafee, N.; Osorio, A.F. Hybrid simulation modelling in operational research: A state-of-the-art review. *Eur. J. Oper. Res.* **2019**, *278*, 721–737. [CrossRef]
76. Ligeikis, C.; Christenson, R. Assessing structural reliability using real-time hybrid sub-structuring. *Int. J. Lifecycle Perform. Eng.* **2020**, *4*, 158–183. [CrossRef]
77. Williams, M.S.; Blakeborough, A.; Houlsby, G.T.; Williams, D.M. Development of a real-time hybrid dynamic testing system. In *Seismic Design and Practice into the Next Century*; Routledge: Abingdon, UK, 2022; pp. 373–379.
78. Insam, C.; Rixen, D.J. Fidelity assessment of real-time hybrid substructure testing: A review and the application of artificial neural networks. *Exp. Tech.* **2022**, *46*, 137–152. [CrossRef]
79. Tian, Y.; Shao, X.; Zhou, H.; Wang, T. Advances in real-time hybrid testing technology for shaking table substructure testing. *Front. Built Environ.* **2020**, *6*, 123. [CrossRef]
80. Wagg, D.; Neild, S.; Gawthrop, P. Real-time testing with dynamic substructuring. In *Modern Testing Techniques for Structural Systems*; Springer: Vienna, Austria, 2008.
81. Blakeborough, A.; Williams, M.S.; Darby, A.P.; Williams, D.M. The development of real–time substructure testing. *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci.* **2001**, *359*, 1869–1891. [CrossRef]
82. Mahin, S.A.; Shing, P.-S.B.; Thewalt, C.R.; Hanson, R.D. Pseudodynamic test method—Current status and future directions. *J. Struct. Eng.* **1989**, *115*, 2113–2128. [CrossRef]
83. Najafi, A.; Spencer, B.F. Validation Of Model-based Real-time Hybrid Simulation For A Lightly-damped And Highly-nonlinear Structural System. *J. Appl. Comput. Mech.* **2021**, *7*, 1252–1265. [CrossRef]
84. Castillo, B.; Riascos, C.; Franco, J.M.; Marulanda, J.; Thomson, P. Assessing Spatiotemporal Behavior of Human Gait: A Comparative Study between Low-Cost Smartphone-Based Mocap and OptiTrack Systems. *Exp. Tech.* **2024**. [CrossRef]
85. Ardakani, E.S. Dynamic Interaction of Walking Humans with Pedestrian Structures in Vertical Direction Experimentally Based Probabilistic Modelling. Ph.D. Thesis, University of Sheffield, Sheffield, UK, 2014.
86. Condori Uribe, J.W.; Salmeron, M.; Patino, E.; Montoya, H.; Dyke, S.J.; Silva, C.E.; Maghareh, A.; Najarian, M.; Montoya, A. Experimental benchmark control problem for multi-axial real-time hybrid simulation. *Front. Built Environ.* **2023**, *9*, 1270996. [CrossRef]
87. Tell, S.; Andersson, A.; Najafi, A.; Spencer, B.F., Jr.; Karoumi, R. Real-time hybrid testing for efficiency assessment of magnetorheological dampers to mitigate train-induced vibrations in bridges. *Int. J. Rail Transp.* **2022**, *10*, 436–455. [CrossRef]
88. Christenson, R.; Dyke, S.J.; Zhang, J.; Mosqueda, G.; Chen, C.; Nakata, N.; Laplace, P.; Song, W.; Chae, Y.; Marshall, G. *Hybrid Simulation: A Discussion of Current Assessment Measures*; US National Science Foundation (NSF): Alexandria, VA, USA, 2014.
89. Farrar, C.R.; Worden, K. *Structural Health Monitoring: A Machine Learning Perspective*; John Wiley & Sons: Hoboken, NJ, USA, 2012; ISBN 1118443217.
90. Deng, Z.; Huang, M.; Wan, N.; Zhang, J. The current development of structural health monitoring for bridges: A review. *Buildings* **2023**, *13*, 1360. [CrossRef]
91. Zhang, J.; Huang, M.; Wan, N.; Deng, Z.; He, Z.; Luo, J. Missing measurement data recovery methods in structural health monitoring: The state, challenges and case study. *Measurement* **2024**, *231*, 114528. [CrossRef]
92. Koh, B.H.; Dyke, S.J. Structural health monitoring for flexible bridge structures using correlation and sensitivity of modal data. *Comput. Struct.* **2007**, *85*, 117–130. [CrossRef]