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Assessing Displacement Estimation from Velocity vs. Acceleration: Effectiveness and Limitations for SHM Applications

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Abstract

Accurate displacement measurements are critical for the health monitoring of civil structures. Displacement time series can be retrieved in many ways, such as via time integration of acceleration or velocity series. These integration processes, however, are known to be susceptible to significant inaccuracies, since time integration amplifies noise and baseline drift, leading to cumulative errors. Various procedures and data processing algorithms can be used to mitigate such errors. In this context, a research project was initiated with the aim of analysing some of the aforementioned approaches, using experimental data retrieved from tests performed on full-scale structural components, to show potential and criticalities of different data processing techniques. Specifically, tests were performed on reinforced concrete beams instrumented with co-located accelerometers, velocity seismometers, and displacement transducers, and subjected to different loading protocols. During tests, sensors recorded the complete transient response, which served to assess the methodologies used to obtain displacement from time integration of acceleration or velocity. This work presents preliminary results of the aforementioned investigation. Discussions are provided on the comparison between displacement values measured by displacement transducers and those obtained by time integrations, considering effectiveness as well as limits of the adopted sensors and data processing approaches. Preliminary findings provide a basis and may offer some guidance on improvements required for achieving reliable displacement-based monitoring procedures.

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Keywords: SHM; Displacements; Time integration; Noise removal; Filtering; Experimental Validation.

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1. Introduction

In the practice of managing existing structures, dynamic motion data are used for structural health monitoring (SHM), model updating, and safety assessment purposes (Farrar and Worden 2012). Different sensors and techniques are used to measure accelerations, velocities or displacements, and based on the structure typology, location, vibration characteristics, and loading conditions, there are specific sensors or techniques that may be more suitable, while others may be actually unfeasible or even impossible to be adopted. For example, acceleration and velocity measurements are obtained using inertial sensors, which do not require an external reference frame, as they are based on the relative motion of an internal mass. In contrast, displacement measurements typically require a fixed reference or external datum (Havskov and Alguacil 2016).

Theoretically, displacement, velocity and acceleration time series are physically related through mathematical relationships, meaning it should be indifferent which quantity is measured and which ones are then retrieved from the measured one. In practice, however, both differentiation and integration involve aspects which lead to generation of errors (Hudson 1963).

Differentiation is characterized by an inherent loss in accuracy of the obtained results, regardless of the procedure by which it is performed (Hudson 1963). This is relevant in many cases, such as when it is necessary to determine ground acceleration time series induced by strong seismic events. In such cases, direct measures of accelerations are usually performed (Hudson 1963) with devices specifically developed for such purpose in order to obtain the desired information with a satisfactory accuracy.

Integration, on the other hand, although theoretically suited to provide more accurate results than differentiation, leads to a different class of issues. Let $a_m(t)$ and $v_m(t)$ be, respectively, the *measured* acceleration and velocity time series (t being the time variable). By using time integration, the value of displacement at time τ *retrieved by integration*, indicated as $u_{\text{int}}(\tau)$, becomes a function of the measured acceleration or velocity series, as expressed by equation (1) or (2), respectively. Displacement and velocity at time $\tau=0$ are indicated as u_0 and v_0, respectively.

$$u_{\text{int}}(\tau) = u_0 + v_0 \cdot \tau + \int_0^\tau \int_0^\tau a_m(t)\, dt dt \tag{1}$$

$$u_{\text{int}}(\tau) = u_0 + \int_0^\tau v_m(t)\, dt \tag{2}$$

Measured acceleration $a_m(t)$ and measured velocity $v_m(t)$ series are unavoidably affected by some errors, and so differ from the true ones. Such errors can include, for example, scale factors, biases, and random errors (Gindy et al. 2008; Kim and Sohn 2020; Needham 1994; Smyth and Wu 2007). Given that amplification of errors through integration may be lower in the case of a single integration, i.e., using velocity measurements, the latter is appealing.

To address the aforementioned issue of errors' propagation in approaches involving time integration, different approaches can be used. If the physical mechanism causing the errors would be known, corrections could be tailored for each specific case. Without the availability of specific information, traditional approaches usually involve a combination of baseline corrections and high-pass filtering (Boore et al. 2002). Such approach is particularly used to estimate ground motion displacements from measured acceleration series (Chiu 1997; Lin et al. 2018). Finally, in recent decades new approaches emerged to better reconstruct the transient response of structures by combining information from different data series of motion components. In particular, various methods have been proposed which adopt approaches categorized under the general umbrella term of "data fusion" methodologies, many of which are based on the use of Kalman estimators (Gindy et al. 2008; Kim et al. 2016; Kim and Sohn 2020; Smyth and Wu 2007; Xu et al. 2019; Zhu et al. 2020).

Considering the context described above, this work presents preliminary results of a research project aimed at analysing different processing techniques for retrieving displacement time series, using acceleration and velocity data measured during experimental tests performed in a laboratory environment. In the following, details are given regarding the experimental campaign, as well as the considered data processing methodologies. Examples of preliminary results are provided and discussed, also highlighting effectiveness as well as limitations of the adopted approaches.

2. Methodology

2.1. Preliminary analytical and numerical investigation

The experimental study presented in this work builds upon the findings of a preliminary analytical and numerical investigation conducted by some of the authors (Imani Moghaddam and Russo 2025). In that initial phase, time integration procedures were tested on noise-free synthetic data series, which were produced using analytical and numerical approaches for solving the structural motion over time of a case study structure. Specifically, the damped free vibration of a simply supported reinforced concrete beam was used as a case study. Synthetic time histories for acceleration, velocity and displacement were obtained using a closed-form analytical solution as well as using the Newmark's method, achieving similar results. The obtained synthetic acceleration and velocity series were integrated to estimate the displacement time-histories. The results of that study consistently demonstrated that displacements obtained from single integration of velocity data exhibited significantly higher accuracy (with errors typically below 1%) compared to those obtained from double integration of acceleration (with errors up to 7%). Those findings highlighted the theoretical advantages of velocity-based methods in a controlled, noise-free environment and established a critical benchmark for the present experimental validation phase, which aims to assess these techniques using real sensor data subject to physical noise and instrumental limitations.

2.2. Experimental program

An experimental campaign was conducted on two full-scale, simply supported reinforced concrete (RC) beams, selected from a set of three custom-cast specimens. The two beams, hereafter referred to as Beam 1 and Beam 2, were designed with different dimensions and reinforcements layouts to investigate the effects of varying structural properties. The detailed schematics, including length, cross-section and reinforcement layouts for Beam 1 and Beam 2, are presented in Fig. 1 and Fig. 2, respectively.

To capture the beam's complete transient response, a dense array of co-located sensors was installed at three key locations along the span L between supports: the midspan (L/2), the first quarter (L/4), and the third quarter (3L/4). At each of these locations, the instrumentation included an accelerometer, a portable seismometer for velocity measurements, and a wire-based Linear Variable Differential Transformer (LVDT) to directly measure vertical displacement. The complete experimental setups, showing the beams, support conditions, and sensors distribution, are depicted in Fig. 1 and Fig. 2. A detailed view of the sensors cluster at midspan is presented in Fig. 1d.

The loading protocol involved two test types, designed to keep the beams sections within their uncracked, linear-elastic working range. A vertical point load was applied at the midspan using a servo-hydraulic actuator, with a target displacement value lower than the calculated cracking limit for both specimens. This study presents one representative test type for each beam, to highlight different aspects of the dynamic response.

A fast unloading test is presented for Beam 1, designed to analyse the response of the beam being unloaded from a previously loaded stage. The load was released at the maximum possible speed allowable by the servo-hydraulic actuator. A controlled-rate loading-unloading test is instead presented for Beam 2, which focused on the response during a slow, symmetrical, loading and unloading process. The beam was loaded to a target displacement and then unloaded, both at a constant, low displacement rate.

Time histories were recorded by all sensors for a duration of about 360s. Data from the loading device, the displacement transducers and the accelerometers were acquired using a sampling frequency of 600Hz, while data from velocity seismometers were acquired at a sampling frequency of 1024Hz.

3. Data analysis and preliminary results

In performed analyses, LVDT displacement series at midspan was adopted as the “target” result, to be replicated by integrating velocity from seismometer or acceleration from accelerometer. Midspan velocity and acceleration were also estimated by differentiation of LVDT displacements, to be compared with those obtained from other sensors.

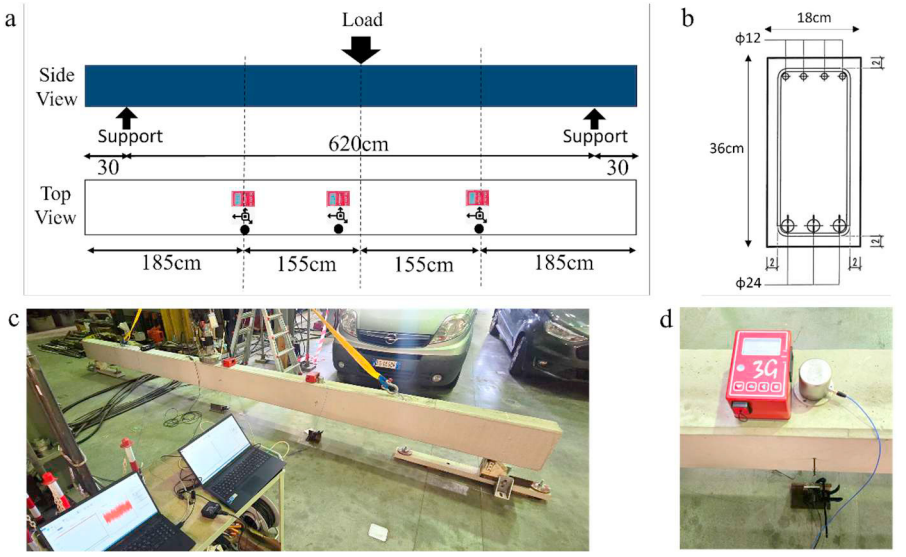


Fig. 1. Details and setup for Beam 1: (a) longitudinal side and top view; (b) cross-section dimensions; (c) overall view of the simply supported beam with sensors locations; (d) detailed view of the co-located sensors cluster at midspan.

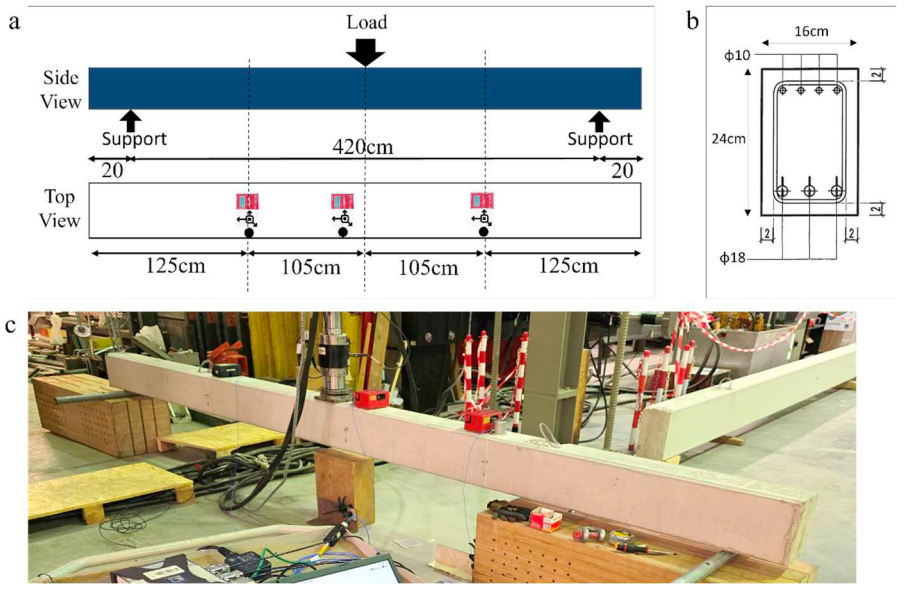


Fig. 2. Details and setup for Beam 2: (a) longitudinal side and top view; (b) cross-section dimensions; (c) overall view of the simply supported beam with sensors locations.

First, to focus on loading phase, short duration series were cut from complete raw time series. Then, Fast Fourier Transform (FFT) for such short data series were computed. Prior to time integration or differentiation, short data series were cleaned by applying filtering techniques and by removing biases. Their integration in time was performed using trapezoidal rule, while their differentiation was carried out using central difference scheme. Two kinds of filter were adopted in data processing, namely, a low-pass filter defined through a threshold frequency and a Savitzky-Golay filter defined through the degree of the fitting polynomial and the length of the filtering frame. Drift removal was performed by evaluating the mean value of the data within a certain time interval, and then subtracting that value from the whole data series.

3.1. Case study 1: fast unloading

The first load case reported herein was carried out on Beam 1 and involved a fast unloading from a previously induced loaded condition. In Fig. 3 are presented the short duration (cut) raw data series for midspan accelerometer, seismometer, and LVDT, respectively, while in Fig. 4 their FFTs are reported. Fig. 5 to Fig. 7 illustrates the processing chain applied to those data series to retrieve the other quantities of the structural motion. For these analyses, filtering was performed by applying first a low-pass filter with a 10Hz threshold, and then a Savitzky-Golay filter of degree 2 with frame length of 0.1s. Drifts were removed after filtering, considering the averaging interval 0s ÷ 0.3s. Integration of acceleration leads to velocity and displacement histories which are similar, though not completely overlapping, to those obtained from LVDT. On the other hand, velocity from seismometer seems low in intensity, and final results do not satisfactorily approximate the target, highlighting that sensor sensitivity and settings may be better optimized and processing chain improved.

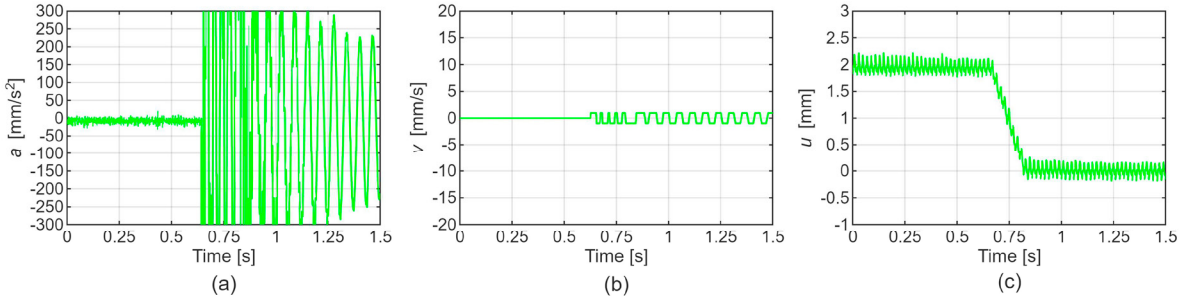


Fig. 3. Cut portions of raw data series recorded at beam midspan in case study 1 by (a) accelerometer; (b) seismometer; (c) LVDT.

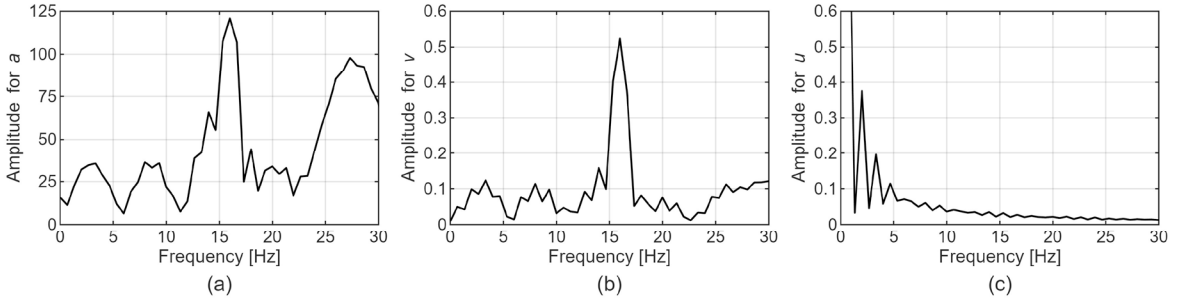


Fig. 4. FFT for cut portions of raw data series recorded at beam midspan in case study 1 by (a) accelerometer; (b) seismometer; (c) LVDT.

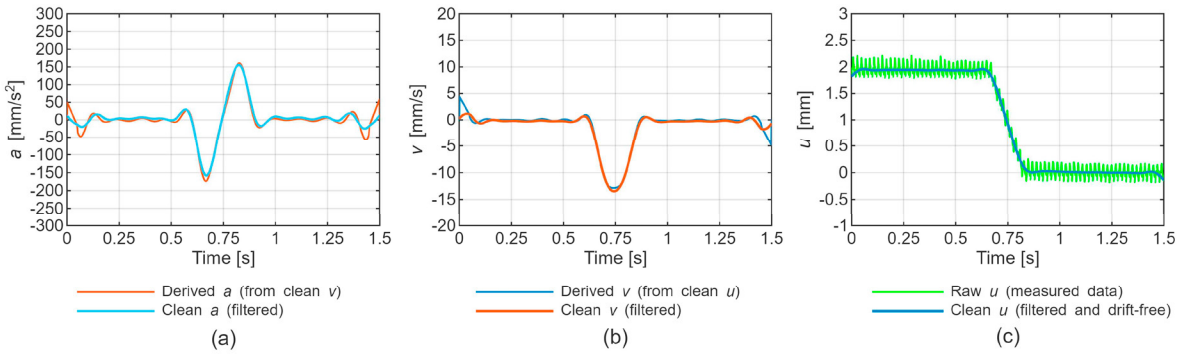


Fig. 5. Results of processing of displacement from LVDT at midspan in case study 1: (a) acceleration; (b) velocity; (c) displacement.

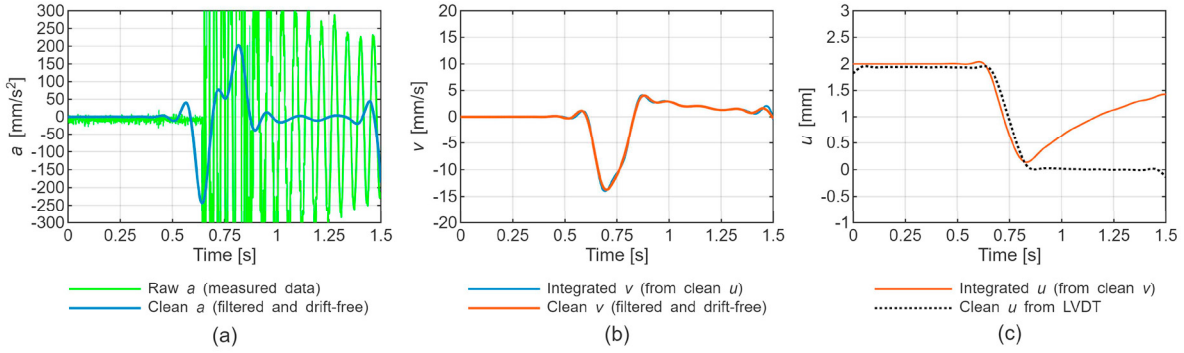


Fig. 6. Results of processing of acceleration series from accelerometer at midspan in case study 1: (a) acceleration; (b) velocity; (c) displacement.

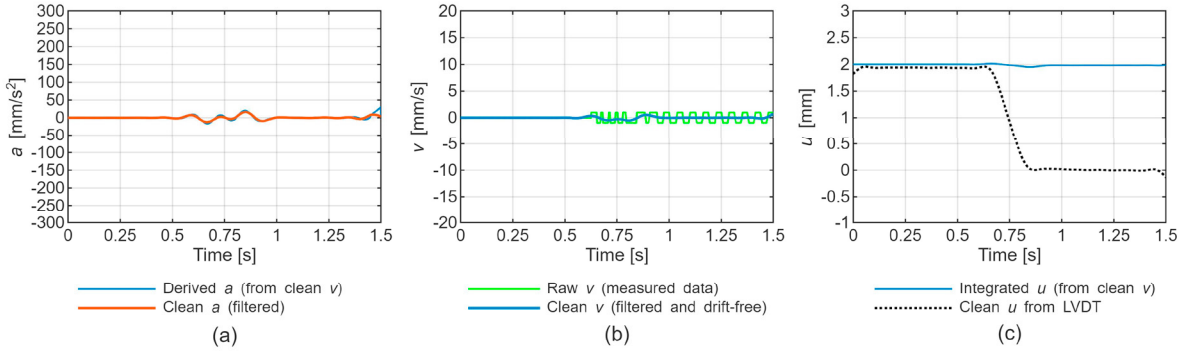


Fig. 7. Results of processing of velocity series from seismometer at midspan in case study 1: (a) acceleration; (b) velocity; (c) displacement.

3.2. Case study 2: quasi-static loading and unloading

The second case involved a quasi-static loading-unloading process on Beam 2. In Fig. 8 and Fig. 9, raw data series recorded at midspan and their FFTs are reported, respectively. Fig. 10 to Fig. 12 illustrate the processing chain applied to short duration (cut) raw data series, as well as the obtained results. Filtering was performed by only applying a low-pass filter with a 1Hz threshold. Drifts were removed after filtering, using the averaging interval 0s ÷ 50s for LVDT displacements, and 0s ÷ 180s for acceleration (from accelerometer) and velocity (from seismometer). Double integrating acceleration leads to a displacement series with a distinguishable loading-unloading path, while seismometer velocity has almost no content at low frequencies and has low intensity, and further tests and analyses are ongoing to improve the results.

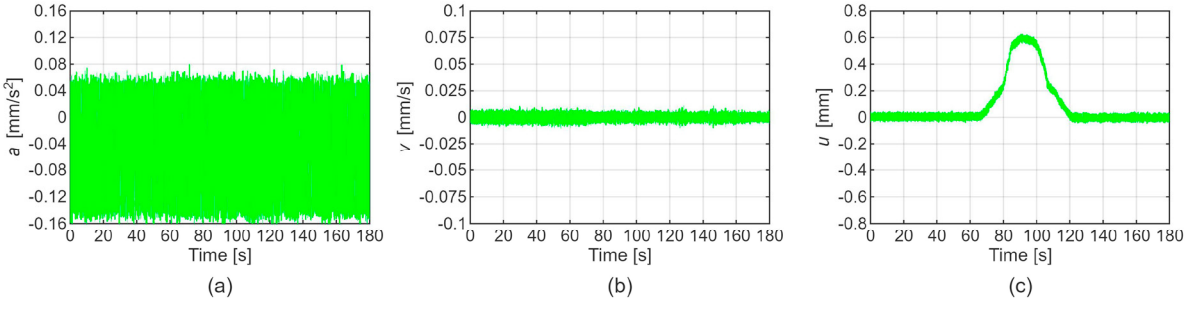


Fig. 8. Cut portions of raw data series recorded at beam midspan in case study 2 by (a) accelerometer; (b) seismometer; (c) LVDT.

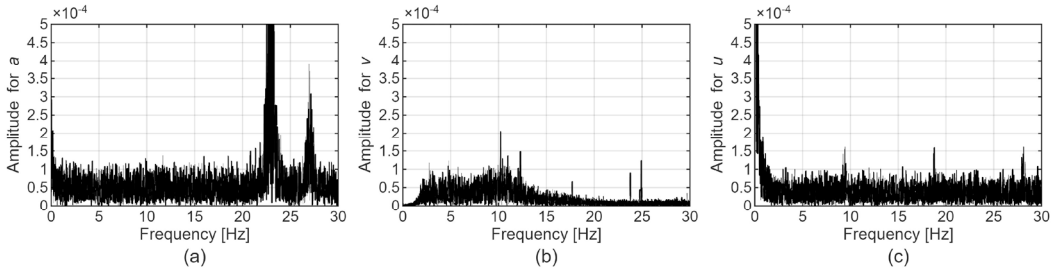


Fig. 9. FFT for cut portions of raw data series recorded at beam midspan in case study 2 by (a) accelerometer; (b) seismometer; (c) LVDT.

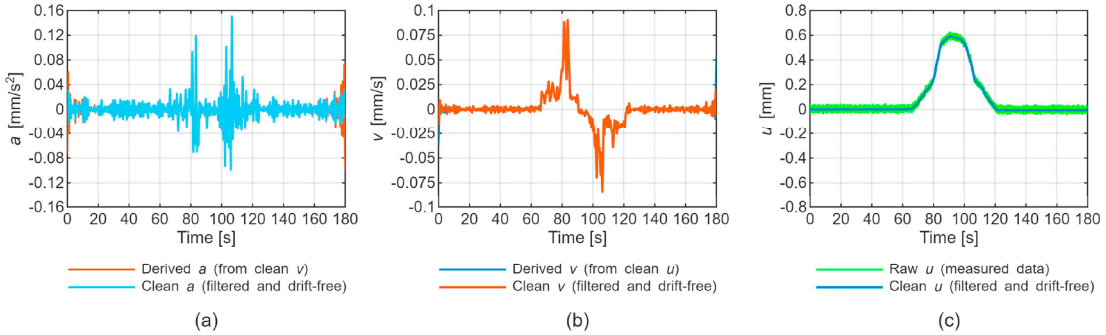


Fig. 10. Results of processing of displacement series from LVDT at midspan in case study 2: (a) acceleration; (b) velocity; (c) displacement.

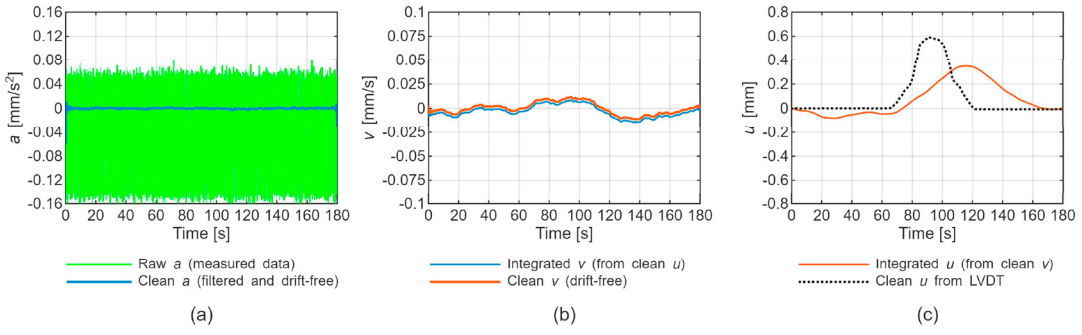


Fig. 11. Results of processing of acceleration series from accelerometer at midspan in case study 2: (a) acceleration; (b) velocity; (c) displacement.

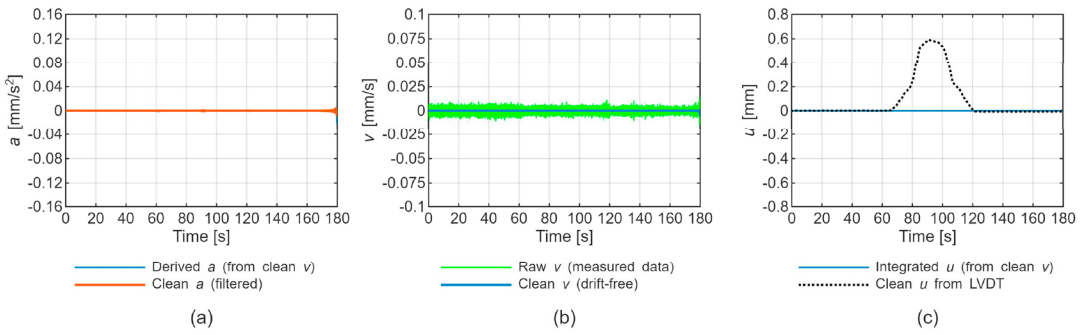


Fig. 12. Results of processing of velocity series from seismometer at midspan in case study 2: (a) acceleration; (b) velocity; (c) displacement.

3.3. Discussion

Preliminary results highlighted a challenge in estimating displacement from velocity data measured in the analysed case studies. This issue may be linked to a combination of seismometer's low frequency recording threshold of 0.1 Hz (Moho 2017) and the very low loading rate imposed by test protocols. Specifically, in case study 2 the FFT of raw velocity confirmed a lack of signal content for frequencies below 1 Hz. The latter range, as a matter of fact, involves a relevant part of the frequency content corresponding to the loading process. Such instrumental filtering effect may be a primary cause for the underestimation of the integrated displacement's amplitude. This finding underscores the critical importance of matching a sensor's operational range with the expected frequency content of the structural response.
Ongoing research is focused on addressing these challenges, through systematic investigations of various aspects. Among these, parametric analyses can be conducted on the effect of various filtering techniques, baseline correction schemes, and numerical integration methods, to determine whether different data processing approaches could improve the final results. In addition to this, future tests using refined experimental protocols could be designed and carried out to further address the observed limitations. This may include utilizing different kinds of dynamic loading protocols with higher frequency content, or employing different types of sensors better suited for quasi-static and low-frequency measurements.

4. Conclusions

This work reported preliminary experimental and data analysis results on the estimation of displacements using acceleration and velocity time series, as part of a broader project on the validation of different SHM techniques. Data obtained from co-located accelerometers, seismometers, and displacement transducers were analysed to assess data processing techniques as well as time integration of acceleration or velocity to estimate displacements. Acceleration-based estimates of displacements were effective for observing general trends of the structural motion, though contained some distortions. Conversely, velocity-based displacement estimations still require improvements in acquisition settings and data processing approaches, and further tests and analyses are currently in progress.

References

Boore, D. M., C. D. Stephens, and W. B. Joyner. 2002. *Comments on Baseline Correction of Digital Strong-Motion Data: Examples from the 1999 Hector Mine, California, Earthquake*. *Bulletin of the Seismological Society of America*.

Chiu, H.-C. 1997. “Stable Baseline Correction of Digital Strong-Motion Data.” *Bulletin of the Seismological Society of America*, 87 (4): 932–944.

Farrar, C. R., and K. Worden. 2012. *Structural Health Monitoring: A Machine Learning Perspective*. Wiley.

Gindy, M., R. Vaccaro, H. Nassif, and J. Velde. 2008. “A state-space approach for deriving bridge displacement from acceleration.” *Computer-Aided Civil and Infrastructure Engineering*, 23 (4): 281–290.

Havskov, J., and G. Alguacil. 2016. *Instrumentation in Earthquake Seismology*. 2nd ed. Springer International Publishing.

Hudson, D. E. 1963. “The measurement of ground motion of destructive earthquakes.” *Bulletin of the Seismological Society of America*, 53 (2): 419–437.

Imani Moghaddam, H., and S. Russo. 2025. “Innovative Displacement Calculation Techniques: A Comparative Analysis of Velocity and Acceleration Data Integration for Structural Monitoring.” In: *Proceedings of the 14th International Conference on Structural Analysis of Historical Constructions - SAHC 2025*. Lausanne, Switzerland.

Kim, K., J. Choi, G. Koo, and H. Sohn. 2016. “Dynamic displacement estimation by fusing biased high-sampling rate acceleration and low-sampling rate displacement measurements using two-stage Kalman estimator.” *Smart Structures and Systems*, 17 (4): 647–667.

Kim, K., and H. Sohn. 2020. “Dynamic displacement estimation for long-span bridges using acceleration and heuristically enhanced displacement measurements of real-time kinematic global navigation system.” *Sensors (Switzerland)*, 20 (18): 1–18.

Lin, Y., Z. Zong, S. Tian, and J. Lin. 2018. “A new baseline correction method for near-fault strong-motion records based on the target final displacement.” *Soil Dynamics and Earthquake Engineering*, 114: 27–37.

Moho. 2017. “Tromino User’s manual.” *Moho Science and Technology*. Venice, Italy.

Needham, R. L. 1994. “Calibration of strapdown system accelerometer dynamic errors.” Master Thesis, Massachusetts Institute of Technology.

Smyth, A., and M. Wu. 2007. “Multi-rate Kalman filtering for the data fusion of displacement and acceleration response measurements in dynamic system monitoring.” *Mechanical Systems and Signal Processing*, 21 (2): 706–723.

Xu, X., M. Luo, Z. Tan, M. Zhang, and H. Yang. 2019. “Measured accuracy improvement method of velocity and displacement based on adaptive Kalman filter.” *Sensor Review*, 39 (5): 708–715.

Zhu, H., K. Gao, Y. Xia, F. Gao, S. Weng, Y. Sun, and Q. Hu. 2020. “Multi-rate data fusion for dynamic displacement measurement of beam-like supertall structures using acceleration and strain sensors.” *Structural Health Monitoring*, 19 (2): 520–536.