

Research Article

Advanced Imaging-Based Metrology for Precise Deformation Monitoring: Railway Bridge Case Study

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In this article, two advanced imaging-based metrology methods, the multipoint method and the tele-wide-angle method, are introduced to the field of structural health monitoring. Both provide the means to significantly improve either the measurement uncertainty or the field of view compared to classical imaging-based methods. The multipoint method utilizes a computer-generated hologram to replicate a single object point to a predefined spot pattern in the image. Spatial averaging of the spot positions improves the measurement uncertainty. The second method, called tele-wide-angle, uses a diffraction grating to considerably enlarge the field of view of a tele objective lens. Both methods are investigated regarding the achievable measurement uncertainty at distances between 34 and 50 m. The standard deviations of the error range between 0.027 and 0.034 mm for the multipoint method and 0.008 and 0.02 mm for the tele-wide-angle method. In the second part of the article, both measurement systems are employed in a field study, measuring the deformation of a railway bar arch bridge. An inductive displacement transducer and several accelerometers are installed to validate the measured displacements and dynamics.

Keywords: hologram; metrology; multipoint; optical measurement; railway bridge; tied arch bridge

1. Introduction

The most important civil infrastructures in road and railway networks are bridges. However, the aging of these structures and the effects of environmental factors, such as extreme weather and seismic events, can lead to degradation and deterioration, potentially compromising their safety and performance. Structural health monitoring (SHM) is a crucial tool for ensuring the safety and longevity of bridges by providing real-time data on their condition and identifying potential issues before they become critical.

Today, many bridges are being monitored with the objective of acquiring data pertaining to their fatigue strength and of providing an early warning in the event of structural failure. This monitoring consists mainly of

vibration and deformation measurements. In order to analyze the structural deformation, it is necessary to measure the displacement of one or, ideally, several points on the structure simultaneously. Those measurements can serve as a basis for estimating structural load carrying capacities, in order to decide if large maintenance measures need to be taken [1, 2]. Furthermore, the knowledge of deformation is important to calibrate and update the parameters of a digital bridge model and also to evaluate the serviceability of a bridge.

The abovementioned factors not only apply to aging bridges. Especially the progress in the field of high-speed trains and the need for heavy load transportation are leading to increased requirements for existing bridges built at the end of the last century, as this kind of stress was not

considered in the design process. One way of dealing with these challenges can be to install a monitoring system in combination with an early warning system [3]. Another possibility is the implementation of actuators, to actively reduce deformations, as it is described in [4]. Either way, there is a real demand for the accurate sensing of displacements in large structures.

1.1. Overview of Displacement Measurement Techniques in SHM. Traditional contact sensors, such as linear variable differential transformers (LVDTs), offer both a high measurement rate and high accuracy (approximately 0.01 mm). In [5], two LVDTs were used to gauge the longitudinal and transverse movements of a timber railroad bridge at one point. However, LVDTs are often inapplicable, due to the necessity of a physical connection to the ground beneath the bridge as a reference point. When a comprehensive displacement measurement at multiple points is required, the installation effort is becoming exceedingly laborious, and for high bridges, it is not possible at all.

Indirect displacement measurement methods include fiber-based sensors [6, 7], as well as strain gauges and accelerometers [8, 9]. In case of strain gauges and fiber sensors, the obtained strain data must be converted, for example, by using a FEM model of the structure to reconstruct its displacement. Furthermore, fiber sensors are facing the practical issue of weatherproof packaging and lasting attachment. In case of accelerometers, displacement is obtained by mathematically integrating the signal twice. Especially this can be problematic for signal periods longer than 10 s and small displacements (below 1 mm), as the accumulated measurement error is leading to low-frequency drifts [8]. This error can be reduced by applying a high-pass filter to the signal. However, static and long-term displacements will also be filtered out.

In the context of noncontact measurement techniques, interferometers are the most accurate option. They only require a fixed location, from which the structural deformation at multiple points can be measured. An example of this is provided in [10], where a radar interferometer is applied to measure the deformation of a railway arch bridge. However, these systems are costly and not feasible for continuous measurements. Furthermore, their application can be complicated, as a fixed location beneath the bridge is required. This restriction can be overcome, as shown in [11], where a laser Doppler vibrometer mounted to an unmanned aerial system is used to measure bridge displacement at one point. Various publications report the use of the Global Positioning System (GPS). It is frequently applied to measure large amplitudes of long-span bridges [12, 13], since its accuracy is in the range of centimeters. During the last decade, terrestrial laser scanners [14] and total stations [15–17] have received growing significance in SHM. In this context, light detection and ranging (LiDAR) devices have been used as a tool for 3D-point cloud generation [14]. However, the scanning principle results in either low lateral resolution (small field of view (FOV)) or low measurement rates.

Computer vision-based systems are receiving increasing attention in the field of SHM due to the low cost of the equipment and the ability to achieve high temporal resolution and lateral accuracy. Additionally, they provide the capability to remotely measure the displacement at multiple positions simultaneously, with minimal restrictions regarding the type of structure, provided that a fixed point with a clear view of the structure is available. Measurement studies have been reported including short-span bridges [2, 15, 18], long-span bridges [3, 12, 19, 20], stadium structures [21], and buildings [22, 23]. Common methods are digital image correlation (DIC) with artificial [9, 24] and natural targets [3], orientation code matching [25], and various centroiding approaches [19, 20]. An overview of state-of-the-art computer vision-based measurement methods for SHM can be found in [26]. In [27], an imaging-based displacement measurement method based on correlation is presented. The presented method achieves a normalized root mean squared error of 0.72% under controlled conditions. Unlike the measurement methods presented, correlation methods rely on extended patterns making it impossible to measure the displacement of a defined point on the structure. In their study, Oh et al. [28] presented a vision-based system to measure the dynamic response of a structure. This was achieved by using displacement time histories.

While computer vision-based sensors are demonstrating satisfactory performance in a majority of scenarios, they are also confronted with specific challenges pertaining to changing lighting conditions (in the case of DIC), environmental vibrations (in the context of single-point photogrammetry), and accuracy. In particular, when measuring small vibrational amplitudes, such as those observed in the case of short-span bridges, a compromise between sensitivity and FOV is typically required. This can be achieved by selecting a large focal length for the objective lens, which enhances sensitivity but limits the visible region of the structure, or by choosing a shorter focal length, which reduces lateral sensitivity.

1.2. Contribution of This Study. The focus of this study is the application of two recently developed imaging-based displacement measurement methods, namely, the multipoint (MP) method and tele-wide-angle (TWA) method, to the field of SHM. Both methods offer the possibility to increase the accuracy of displacement measurement for a wide FOV.

The capability of the proposed measurement systems is demonstrated in a field study at a short-span railway bridge near the city of Hamburg. The studied bridge is a tied arch bridge, which is a quite common type around Hamburg. Those bridges face the problem that for certain load conditions, a sinusoidal oscillation mode is formed, affecting its structural fatigue strength. The bridge is monitored during the passing of several trains and the measurement data are analyzed in terms of displacement and dynamic response. In addition to the proposed optical measurement systems, further sensors are installed on the bridge for verification.

2. Advanced Optical Measurement Principles

One major advantage of imaging-based measurement techniques is their inherent ability to remotely measure the movement of multiple objects simultaneously. Therefore, with a wide FOV, unwanted environmental vibrations affecting the camera system can be suppressed, by calculating the relative position between the moving target points and a fixed point, which is not attached to the observed structure.

The following subsections describe two methods that are focusing on either increasing the accuracy of a small f system (MP) or increasing the FOV of a large f system (TWA). Both make use of a computer-generated hologram (CGH). CGHs are optical elements that—like, for example, lenses or curved mirrors—deflect light into certain directions. The deflection depends on the local structure of the CGH, the wavelength, and the local angle of incidence of the light falling onto the CGH. The deflection is caused by diffraction. Therefore, the CGH (and thin holograms) in general might be thought of consisting of a complex superposition of local gratings with periods in the micrometer range that leads to the desired deflection. Such thin holograms can be recorded on holographic film but, today, typically the grating structure is optimized by a computer and then fabricated photolithographically. By this complex grating-like approach, it is also possible to redirect an incoming light ray into multiple directions. This way we can generate something like a fan-out element, or in other words, generate multiple images of an object. For a more detailed introduction to CGHs, we refer to [29].

Of course it would be also possible to generate multiple copies by multiple reflections, but this would lead to rather complicated or multireflection beam splitting paths that would be very difficult if not impossible at all to realize in a stable enough way for the desired accuracy [30]. Also, refraction-based methods based on aperture division are conceivable. But again, the aperture division leads to potential errors or a reduced FOV [31].

2.1. Holographic MP Method. The accuracy of classical imaging-based position measurement is inherently limited by the wave nature of light and its associated statistical behavior (photon noise). If a photon, which starts from a perfect mathematical object point, is imaged onto a sensor, the place where it impinges can only be described statistically. This measurement uncertainty of the intensity distribution can be characterized by the Airy distribution with a standard deviation of

$$\sigma_{\text{Airy}} = 0.21 \frac{\lambda}{\text{NA}}, \quad (1)$$

where λ is the wavelength and NA is the numerical aperture of the objective lens [32]. This means that a photon will hit a circular area of radius σ_{Airy} with a probability of 68% (1 σ probability). If the number of photons is increased by factor N_{ph} , the measurement uncertainty is reduced by factor $\sqrt{N_{\text{ph}}}$ [33]. In other words, the more photons are captured from the object, the more accurate its position can be

estimated. However, the maximum number of photons per pixel is limited by the quantum well capacity of the imaging sensor. Temporal averaging (averaging intensities of multiple sequential images) is one way to increase the total photon number. Nevertheless, error contributors like discretization (pixeled sensor) and fixed pattern noise are not affected. Furthermore, the temporal resolution is diminished and fast moving objects can be blurred. The measurement uncertainty related to the spot position is often specified in fractions of a pixel in order to establish comparability between different image sensors. The achievable accuracies are between 0.1 pixels and 0.01 pixels [34–36].

The idea of the MP method is spatial averaging. A lithographically fabricated phase-only CGH is used to replicate the single spot in the image plane to a predefined pattern of N spots, a so called cluster [37]. A scheme of this method is illustrated in Figure 1. Here a lens with a short focal length f' is used, so that the object is fully visible on the sensor. The CGH replicates a single object point to a cluster of $N = 9$ spots. If the object point moves, all replications move by the same amount (lens aberrations neglected). $N = 9$ spots are chosen for this study because it offers a compromise between improved measurement uncertainty and good signal-to-noise ratio (SNR) of each spot. For applications with brighter emitters, more spots can be used (see [38]). The CGH is optimized using a direct binary search algorithm (for details, see [39]) and is placed in front of the imaging lens. Without spot replication of the MP method, the position information of one object point is stored in just a few pixels on the sensor. By making the object point brighter (active light emitters) and simultaneously using the CGH for cluster generation, the number of photons that carry useful position information can be increased by a factor of N . By averaging the spot centers, the accuracy can be theoretically improved by $\sqrt{N}$ because in addition to the increased number of collected photon error contributors like discretization, photon noise and sensor noise are not correlated between the spot copies. This improved accuracy was experimentally validated in various applications, such as vibration measurement [40], 2D and 3D position measurement [38, 41], and midsize structures [42].

2.2. Holographic TWA Method. The focal length f is an important factor influencing the capabilities of an imaging-based measurement system. As the focal length increases, the object appears larger on the sensor, enabling the detection of smaller movements. However, the FOV is shrinking and only a small part of the object can be observed. Additionally, a measurement system with large focal length becomes vulnerable to environmental vibrations. In [20], a 600 mm tele lens is used to measure the movement of a 3D target attached to a long-span suspension bridge. The authors try to suppress environmental vibrations in the camera mounting by the use of a stiffness girder with rubber washers and polystyrene foam.

The idea of the TWA method is to have the advantages of a long focal length and combine it with a CGH to replicate the FOV [43]. In contrast to the MP hologram, the TWA CGH consists of a phase-only sinusoidal diffraction grating. The diffraction angle γ is calculated as

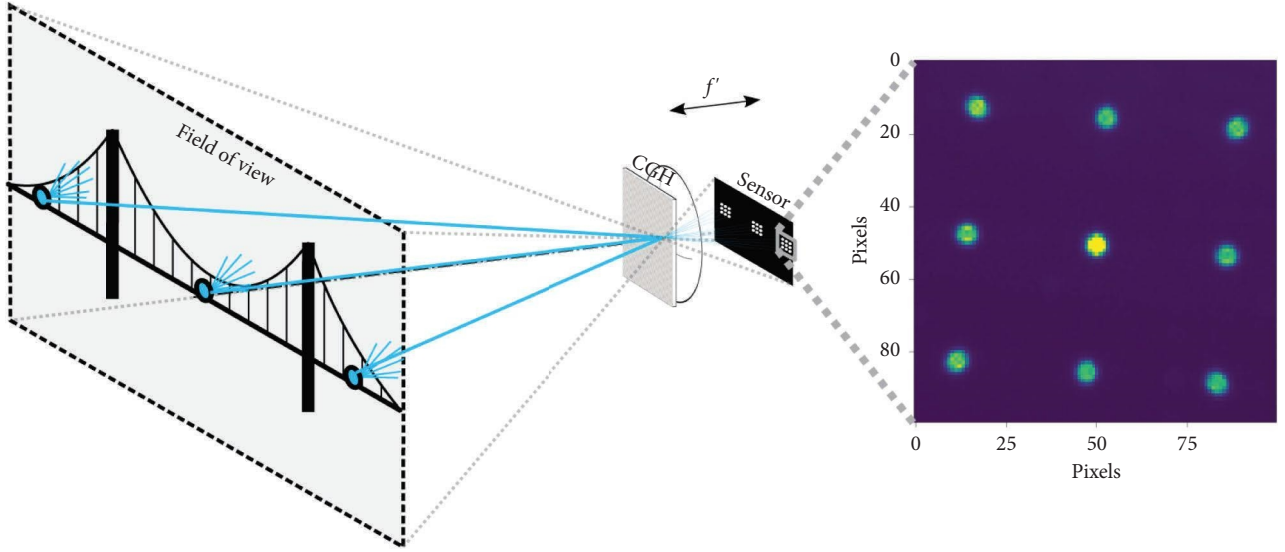


FIGURE 1: Scheme of the multipoint method. Three light emitters are imaged onto a camera sensor using a lens with focal length f' . The field of view is defined by the sensor size and f . A CGH in front of the lens replicates a single object point to a cluster of $N = 9$ spots. Averaging all spot centroids improves position detection accuracy.

$$\sin(\gamma) = \frac{m\lambda}{p} + \sin(\alpha), \quad (2)$$

where λ is the wavelength of the light, p is the period of the diffraction grating, and m is the diffraction order. α is the angle of incidence of the incoming light. The grating amplitude (phase shift) is chosen in a way that in theory it should create two strong first diffraction orders, two weak second diffraction orders, and a very weak zeroth diffraction order. This seems to be counterintuitive, as the zeroth diffraction order is needed for the real FOV. However, as expected from experience with the CGH manufacturing process, slight deviations from the designed parameters due to manufacturing tolerances led to a strong zeroth diffraction order. Hence, the emitter in the “real” FOV must be dimmed, so that all spots on the sensor have the same maximum intensity value for a fixed integration time.

In Figure 2, the same bridge object is shown as in Figure 1. In this scheme, a tele objective lens with a long focal length f' is used. The real FOV is defined by a linear relation between the sensor size, focal length f' , and the object distance and covers only a small region in the middle of the bridge. Light from the emitters outside the real FOV will not hit the sensor. The diffraction at the CGH is used to generate two symmetric virtual FOVs covering the emitters at the sides of the bridge. In case of the right emitter (seen from the measurement system), the -1 . diffraction order and for the left emitter, the $+1$. diffraction order is used. As the emitters' wavelengths are in the visible spectrum, a band-pass filter is used to allow only light from the emitters to pass through.

It is important to notice that the position of the virtual FOVs is defined by the grating period p of the CGH. Therefore, the measurement conditions (object distance and emitter positions on the object) have to be known in order to

set p . In addition, the emitter positions in the virtual FOVs have to be chosen in a way that the spots on the sensor do not overlap.

The successful application of the MP and the TWA method is dependent on the amount of light emerging from the object points. As the incoming light is divided by the CGH into the replicated spots, a useful SNR per spot can only be achieved using active light sources. External illumination together with retro reflective structures applied to the test object might also be possible but has not been tested yet.

2.3. Optical Measurement Setup. The measurement setup is shown in Figure 3. It consists of a MP-system (1 to 3) and a TWA-system (4 to 6), both mounted to the same optical rail system (7). The MP system comprises an objective lens (2) (Edmund optics #86-571, $f' = 16$ mm) and a camera (3) (Ximea XiC MC023MG-SY, 2.3 Mpix, pixel pitch $d_p = 5.86 \mu\text{m}$, 165 fps). The MP CGH (1) is designed to create a cluster of $N = 9$ spots (arranged on a 3×3 grid) with a grid distance of around 35 pixels on the image sensor. The CGH is glued to a threaded retaining ring and screwed in the filter mount of the objective lens.

The TWA consists of a fixed focal length tele lens (5) ($f = 300$ mm) and the same camera (6) as the MP-system. A band-pass filter (FLH532-4, $\lambda = 532$ nm, FWHM = 4 nm) is attached to the adapter between lens and camera, in order to block ambient light. The period p of the diffraction grating (4) is $1.8 \mu\text{m}$, so that the virtual FOVs roughly cover the edges of the MP FOV. For the light emitters, small high power LEDs (9) (Nichia NCSG219B-V1, 139 lm, extra collimating lens attached) are mounted in a waterproof housing (8), which is connected to a magnetic base (11) using a ball joint (10). This enables flexible attachment to the bridge and alignment in the direction of the camera system.

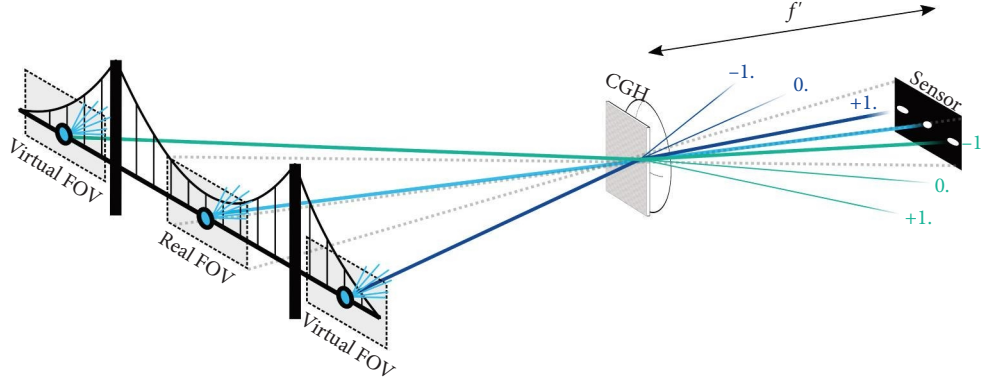


FIGURE 2: Scheme of the holographic TWA method. Compared to Figure 1, the focal length f' of the tele lens is considerably larger, leading to a higher sensitivity, but also a smaller FOV. In order to be able to measure the light emitters outside the real FOV, a CGH is used to generate virtual FOVs using diffraction. The CGH divides light from each emitter in +1., 0., and -1. diffraction order.

2.4. Measurement Uncertainty Under Controlled Conditions.

In order to determine the measurement uncertainty of the optical measurement systems presented in this study, a motion of known size is measured in various distances. To achieve this, a light emitter is mounted to a motorized vertical stage (Thorlabs Lab Jack, MLJ150/M) and the motion is measured simultaneously with the MP and TWA-system. The measurement systems are oriented in a way that the light emitter appears on the edge of the MP image, and in case of the TWA, not the real but a virtual FOV is used. This way for both measurement systems, the most challenging scenarios are chosen.

Since the vertical stage is not able to perform oscillations, a trajectory with two steps of size 1 and 2 mm with linear motion in between is chosen. In Figure 4, the measured displacements for MP and TWA are shown, respectively, for distances of 34 m (lower), 40 m (middle), and 50 m (upper diagram). To estimate the measurement uncertainty of both measurement systems, the measurement signals are evaluated in two time intervals T_1 and T_2 during which a linear motion by the linear stage took place. Start and end of the trajectories are excluded due to the nonlinearity of acceleration and deceleration. The conversion between image and object space is calculated using the object distance, the focal length f' , and the pixel pitch d_p . As the stage does not incorporate an integrated measurement system, which can be taken as reference, the displacement signals in T_1 and T_2 are evaluated by removing the linear slope and calculating the standard deviation of the detrended signal. This approach can be used, since the target step size values of 1 and 2 mm are reached very accurately.

The resulting standard deviations for the MP and TWA-systems with dependence on the distance between light emitter and measurement systems are shown in Table 1. The average standard deviation $\bar{\sigma}$ (averaged over both time intervals) of the MP-system ranges between 0.027 mm at 34 m and 0.034 mm at 50 m. For the TWA-system $\bar{\sigma}$, it is between 0.008 mm (34 m) and 0.02 mm (50 m). The results show that both measurement systems are capable to detect submillimeter displacements with high precision.

3. Overview of Field Study

This section addresses the introduction of a railway bridge, which is test object for a monitoring field study of the proposed optical measurement systems. In addition, other sensor systems like accelerometers, LVDT, and a video device are applied, in order to evaluate the capabilities of the optical measurement system and to investigate the dynamic behavior of the bridge.

3.1. Bridge Description. The measurement object of this field study is a double-track railway bar arch bridge near Hamburg, Germany. In Figure 5(b), a picture is shown. On the front track, where the measurement equipment is installed, trains with direction to Hamburg and on the rear track with direction to Berlin are crossing. This type of bridge is very common in Germany, and the presented one is used as high-speed rail bridge. It has a span width of 65.5 m, a system width of 10.2 m, and an arch rise of around 10 m. The maximum allowed train speed is 230 km/h. Figure 5(a) shows a cross section of the bridge with the positions of the installed sensors. Overall, seven light emitters, called E1 to E7, were installed on the bridge half. E1 is placed at the beginning and E7 in the middle of the bridge. Furthermore, nine acceleration sensors A1 to A9 and a LVDT were attached. As a symmetric deformation behavior to the center point of the bridge is expected, only half of the bridge is equipped with light emitters.

3.2. Measurement Sensors

3.2.1. Optical Measurement. As it is visible in Figure 5(b), the optical measurement system consisting of MP and TWA is located in a tent to protect it from weather effects. Not all emitters E1 to E7 can be measured with both measurement systems. Due to the previously defined FOVs of the TWA-system, it can only measure the displacement of emitters E1, E4, and E7. It is important to notice that E4 is considerably less bright than all other emitters, since it is covered by the

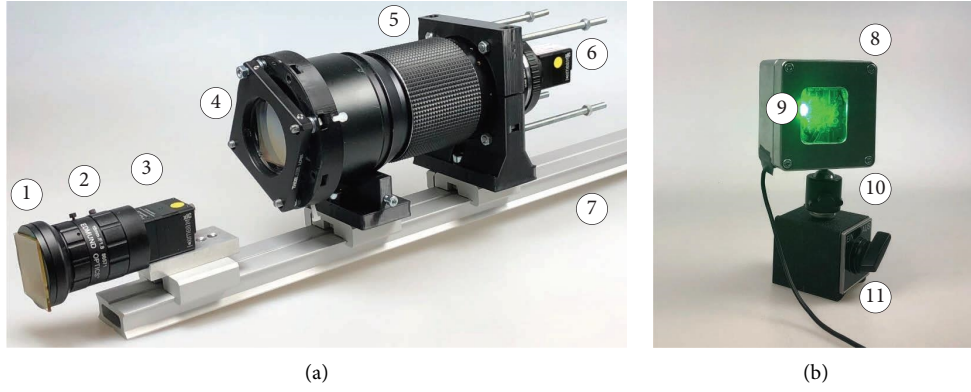


FIGURE 3: (a) Image of the proposed optical measurement setup consisting of the MP- (1–3) and the TWA-system (4–6). MP-system: 1—MP-hologram; 2—16 mm objective lens; 3—camera. TWA-system: 4—sinusoidal diffraction grating; 5—300 mm telephoto lens; 6—camera; 7—optical rail system. (b) Image of one light emitter used to attach to the bridge in the field study; 8—waterproof housing; 9—LED; 10—ball joint; 11—magnetic base.

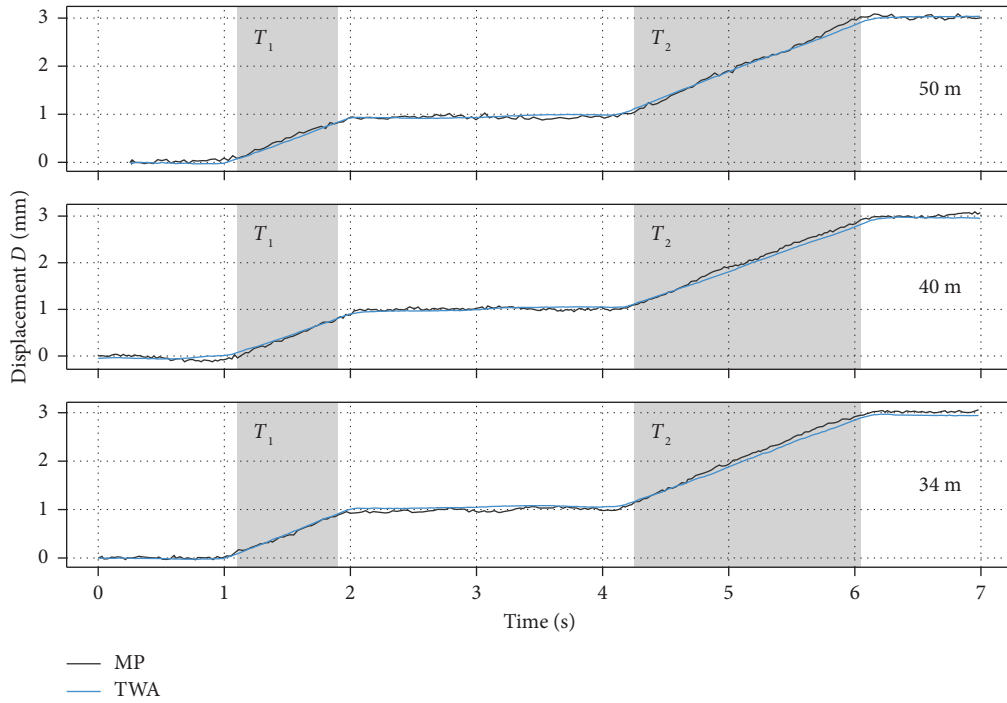


FIGURE 4: Measurement uncertainty estimation of the proposed optical measurement systems under controlled conditions. The trajectory of a light emitter attached to a linear stage is measured with the MP- and the TWA-system in a distance of 34 m (lower diagram), 40 m (middle diagram), and 50 m (upper diagram). The trajectory consists of a linear movement of 1 mm and 2 mm step height. The standard deviation is calculated in the time periods T_1 and T_2 for the detrended signals.

zeroth diffraction order of the TWA. Furthermore, the emitter position on the bridge of E4 cannot be chosen freely. It is defined by the fixed positions of E1 (start of the bridge) and E7 (bridge center). With the MP-system, all emitters except E4 can be measured because this emitter is not bright enough. The distances between the optical measurement system and emitters E1 to E7 are 26.5, 28.6, 30.6, 32.9, 35.7, 39.4, and 48.4 m. Those distances are measured using a laser rangefinder (Bosch GLM 150-27 C) and used to convert the measured spot shifts y_{sp} from image plane to displacement Z_w in world coordinates using

$$Z_{w,i} = \frac{d_{px} f'}{D_{em,i}} y_{sp,i}, \quad (3)$$

where $D_{em,i}$ is the distance to the emitter with index i and f' is the focal length of the objective lens.

A well-known challenge for camera measurement systems is changing lighting conditions. To reduce this influence, the following measures have been taken. First, the used LED light sources are very bright and the wavelength of the emitted light has a narrow bandwidth. This in combination with a narrow band-pass filter on camera side ensures that

TABLE 1: Standard deviations of the measurements shown in Figure 4 for the detrended signals in T_1 and T_2 depending on distance and measurement system.

Distance (m)	Meas. system	σ in mm		$\bar{\sigma}$ in mm
		T_1	T_2	
34	MP	0.016	0.038	0.027
34	TWA	0.005	0.011	0.008
40	MP	0.018	0.028	0.023
40	TWA	0.004	0.007	0.005
50	MP	0.030	0.038	0.034
50	TWA	0.016	0.024	0.020

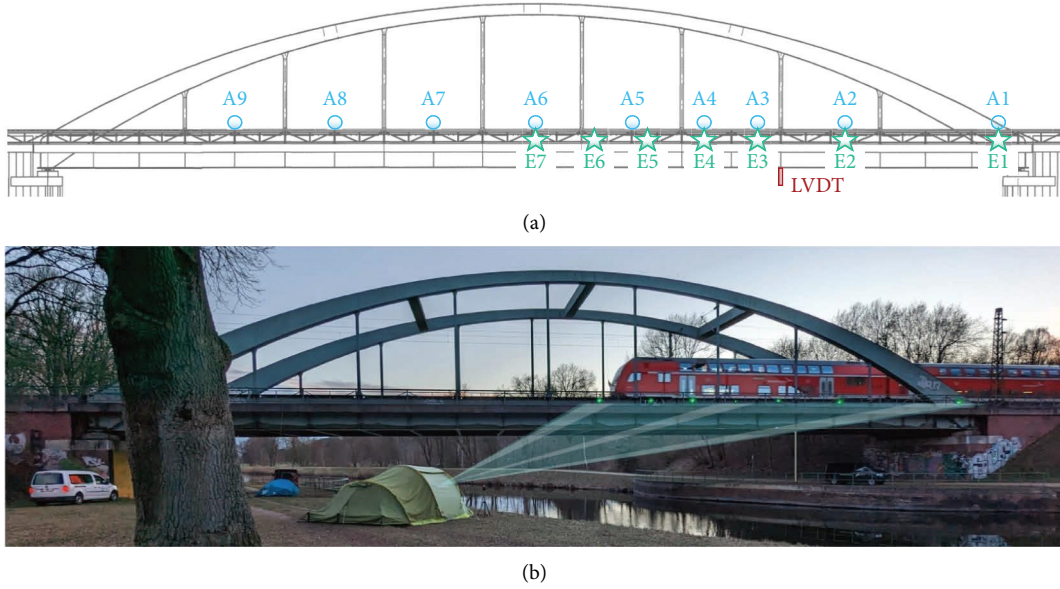


FIGURE 5: (a) Sensor arrangement of the studied bridge with emitter positions E1 to E7, accelerometer positions A1 to A9, and LVDT position. (b) Image of the studied bridge with the measurement tent and the FOV of the MP-system in light green and the segmented FOV of the TWA-system in light gray.

most ambient light is blocked. However, if the sun is shining directly into the measurement system, the influence on the spot position is very strong. Therefore, it was ensured to block sun rays from directly entering the aperture of the measurement systems.

3.2.2. Video Device. An additional video camera was installed in the tent, in order to estimate the type and speed of the trains passing by. Therefore, a short focal length lens ($f' = 8.5$ mm) and a monochromatic camera (Ximea XiC MC023CG-SY, pixel pitch $d_p = 5.86 \mu\text{m}$) are used. To reduce the data amount to be saved, only a ROI of $1936 \text{ pixels} \times 300 \text{ pixels}$ per image is stored, leading to a FOV of around 47×7.3 m. The acquisition frame rate is set to 5 Hz, so that at least 4 images of each train compartment of a passing train with a speed 230 km/h are acquired.

3.2.3. Accelerometer. In addition to the optical measurement system, nine acceleration measurement units A1 to A9 were installed on the same side of the bridge as the light emitters (see Figure 5(a)) to measure the dynamic acceleration of the

bridge. The accelerometers (GEMAC Motus XC6MZ360-O) can collect vibration data in the three spatial coordinates and measure the inclination with respect to those axes, leading to the detection of the 6-axis motion. The measurement range is ± 8 g and the resolution is 0.244 mg. The accelerometers are connected via the CAN interface and the data acquisition rate is 100 Hz.

3.2.4. Inductive Displacement Transducer. In order to validate the measurement results of the proposed optical measurement systems, a LVDT (HBM WA20, measurement range = 20 mm, linearity deviation < 0.1%) is installed to measure the bridge displacement at a certain bridge position. The bridge spans a river and there are small roads on either side of the bridge. One of these roads is used to install a tripod with a rod to mount the LVDT. Thus, this setup measures the displacement between the road below the bridge and the bridge. The LVDT is placed as close to the quarter point of the bridge as possible. The exact location is shown in Figure 5(a). Therefore, the LVDT measurement signal can be compared to the displacement of E3 (measured with the MP-system) and to E4 (measured with the TWA-system).

4. Measurement Results

The correctness of the measured signals is verified by comparing the displacements of the MP- and TWA-system to the LVDT signal. During the field test, three trains are measured: Train 1—freight train (speed $v = 83$ km/h); Train 2—high-speed train Intercity Express (ICE) (speed $v = 175$ km/h); and Train 3—high-speed train ICE (speed $v = 223$ km/h). For the first two trains, all sensor systems are working. In case of the last train, the battery for power supply of the accelerometers and LVDT was empty and, therefore, only the optical measurement systems recorded data.

In order to validate the capability of the optical measurement systems in a real-world application, the measured displacements of Train 1 and Train 2 are compared to the LVDT, as shown in Figures 6(a) and 6(b). The upper plots in Figure 6 show the displacements of E3 (measured by the MP-system), E4 (measured by the TWA-system), and of the LVDT. In (a), the signals are shown for a slow freight train and it can be seen that the displacements of all three sensors agree well. Small deviations may occur because their positions on the bridge are not exactly the same. The displacement of E4 might be slightly larger because its position is furthest to bridge center. For slow moving trains like Train 1, the middle of the bridge is expected to have the largest displacement. In (b), a high-speed train crosses the bridge. Again, the signals match well, and small deviations may occur due to excited vibration modes. The lower plots in (a) and (b) show the displacement of the E7 emitter mounted in the center of the bridge. In this case, both optical measurement systems measure the displacement of the same emitter. It can be seen that for both trains, the signals agree very well. The outlier in (b) at $T = 8.2$ s can be attributed to a bright light at the end of the high-speed train. This light is also visible in the image of the MP-system and, therefore, slightly alters the CoG of some spots when it passes. The TWA-system is not affected, as the narrow band-pass filter used blocks the light.

In Figure 7, the measured displacements over time and bridge position of Train 2 (a, c) and Train 3 (b, d) are presented. The upper diagrams (a, b) show the vertical displacement signals of the emitters measured with the MP-system. In diagrams (c) and (d), the bridge displacement over bridge position is presented at four points in time. Half the bridge is shown in the background of the diagrams to visualize the emitter positions on the bridge. The signals in (a) (Train 2) show that E5, E6, and E7 have an almost constant deflection of around 5 mm and E2 and E3 show an oscillation with an amplitude of around 1 mm. This oscillation is considerably more stimulated by the faster Train 3, as shown in (b). Here only E7 (bridge center) has an almost constant deflection. The emitters nearest to the quarter point of the bridge have the highest oscillation amplitude. However, the overall amplitude is smaller than that in (b). This is due to the fact that Train 3 crossed the bridge on the rear track (direction to Hamburg) and Train 2 on the front track (direction to Berlin), where the light emitters are installed. In (c), the deformation is shown for the time period

when the train starts to cross the bridge. At $T = 0.25$ s, the bridge is bent upwards and then starts to deflect. In (d), the sinusoidal standing wave is visualized, which has its node in center of the bridge, where emitter E7 is located. The deformation of each emitter over time is shown in Visualization 1 [44] (Train 1) and Visualization 2 [44] (Train 2).

In order to compare the dynamic response measured with the optical measurement systems to the accelerometers and the LVDT, in Figure 8(a), the spectra of all sensors placed near the quarter point of the bridge are shown. To be able to show all signals in one diagram, they are shifted by an offset of 0.02, respectively, to each other. Accelerometers A3 and A4 are located at the same positions as the emitters E3 and E4. For Train 2 in (a), the spectral peaks measured with the TWA- (E4) and the MP-system (E3) are 1.70 Hz and 2.68 Hz, respectively. The spectral peaks measured with the LVDT and the accelerometers A3 and A4 are 1.70 Hz and 2.60 Hz, respectively. In Figure 8(b), the spectral responses of emitters E1 to E7 are shown for Train 3. The spectral peak frequency is 2.1 Hz and its magnitude is biggest near the quarter point of the bridge (E3 and E4). E7 (center) only shows low frequency oscillations below 1 Hz, which can be attributed to the static deflection of the bridge during the train crossing.

5. Discussion

In order to quantify the accuracy of the proposed optical measurement systems, a laboratory test with a vertical linear stage placed in different distances is carried out. The linear stage vertically positions a light emitter with known trajectory and the signals of the vision systems are compared. The resulting standard deviations of the errors of TWA and MP are 0.02 and 0.034 mm, respectively, for a distance of 50 m, which is very promising. However, the accuracy of vision-based systems depends on various factors such as object distance, intrinsic camera parameters, and environmental conditions and might not be directly comparable to the achieved results in a field test. Therefore, in the presented study, a field test is carried out, where a LVDT and accelerometers are used to validate the measured displacements and dynamic responses. Furthermore, as the two presented optical measurement systems are independent of each other, their signals can be compared for validation as well (see Figure 6(b)). It turns out that also in the field test, the measured displacements and dynamic properties of the bridge correspond very well to the validation data acquired by the LVDT and accelerometers.

Similar to any other measurement system, the presented ones incorporate advantages and disadvantages. The precision of the proposed measurement techniques depends on the amount of light that can be captured of the observed object points. To achieve a high SNR, active light emitters have to be applied to the measured object, which can be difficult in terms of power supply and accessibility to the measured object. On the other hand, this circumstance also offers the possibility to have a continuous monitoring system also during night time, where classical passive vision systems might not work. Moreover, the active emitters might be

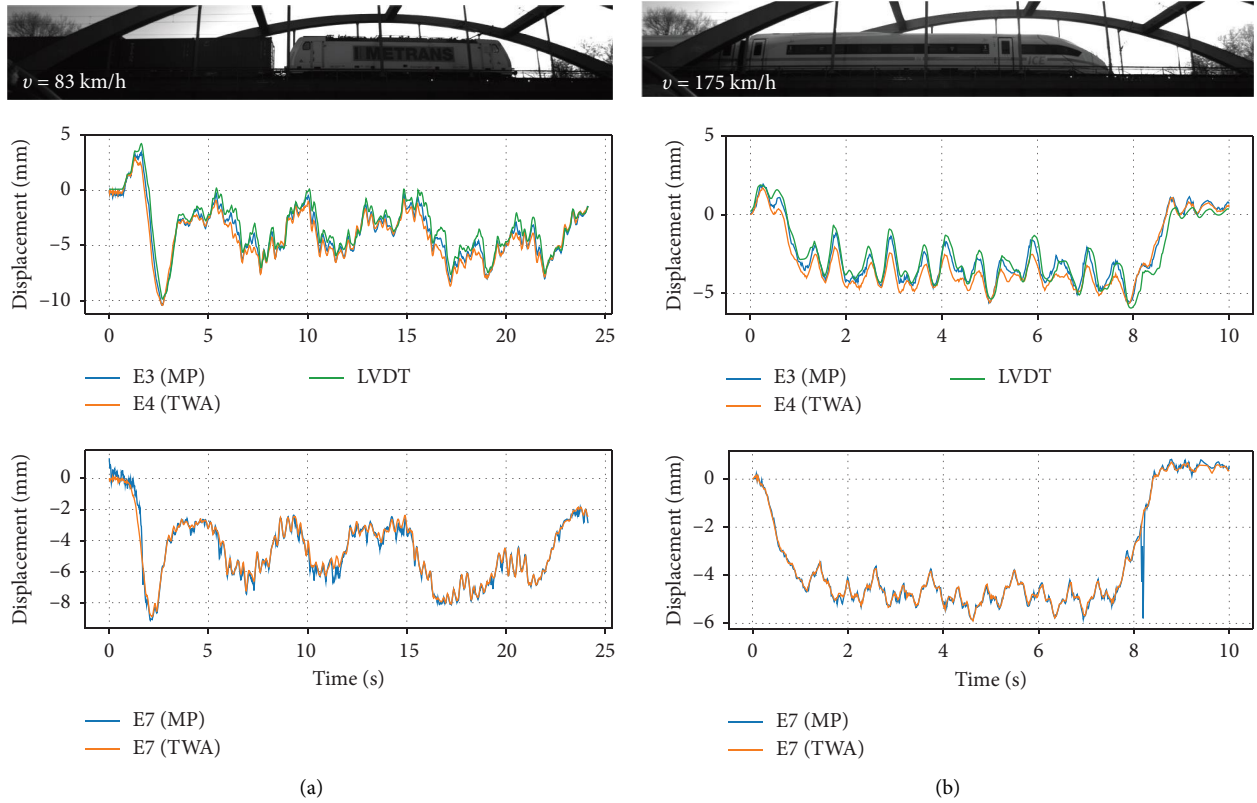


FIGURE 6: Validation of the optical measurement systems. Comparison of MP, TWA, and LVDT displacement measurement signals for two different trains. (a) Train 1—freight train, $v = 83$ km/h. (b) Train 2—high-speed train ICE, $v = 175$ km/h. In each upper diagram, the displacement signals of the two emitters E3 (measured by MP) and E4 (measured by TWA) are plotted together with the LVDT signal. Slight deviations between the signals might be ascribed to different positions of the emitters and the LVDT on the bridge. The lower diagrams show the displacement signal of emitter E7 measured with MP and TWA-system. The outlier in (b) at around $T = 8.2$ s of the MP-system occurs due to a bright light attached to the end of the train, which is affecting the CoG position of some spots.

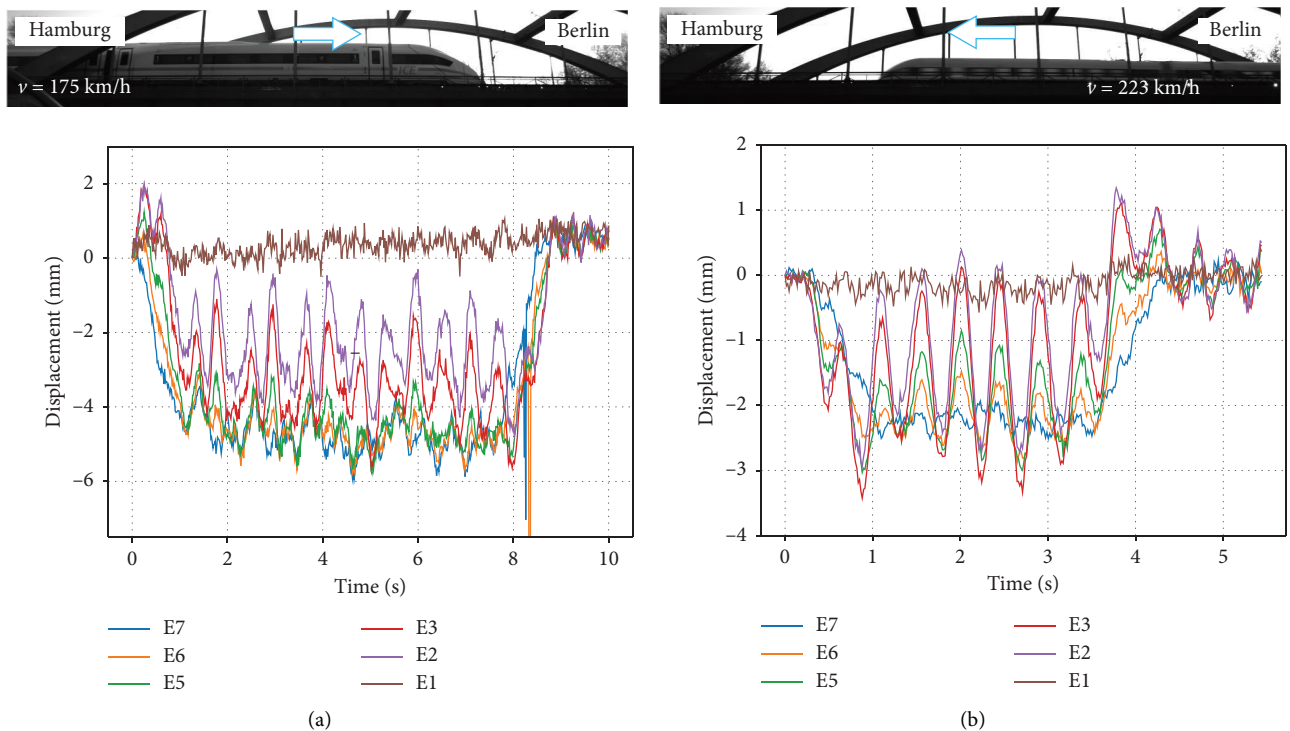


FIGURE 7: Continued.

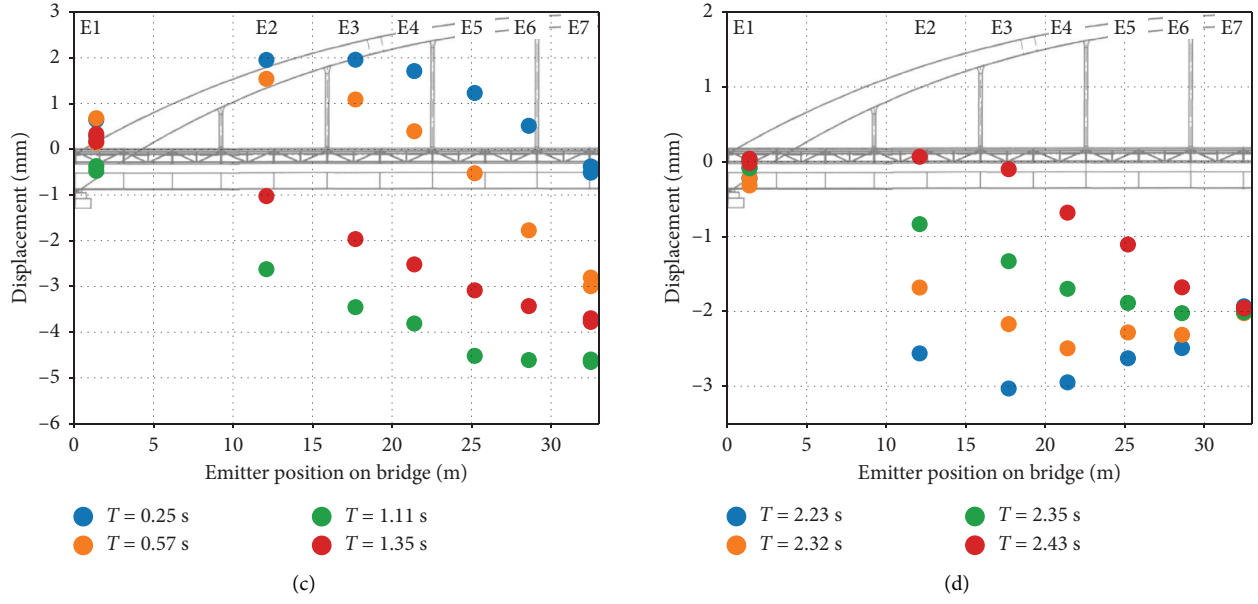


FIGURE 7: Displacements at different bridge positions for Train 2 (a, c) and Train 3 (b, d). The upper diagrams (a) and (b) show the displacement signals of the emitters over time. The lower diagrams (c) and (d) show the displacement over the emitter position on the bridge at 4 different points in time, in order to visualize the deformation states of the bridge. The displacement over time for Train 1 to Train 3 is shown in Visualization 1 [44], Visualization 2 [44], and Visualization 3 [44].

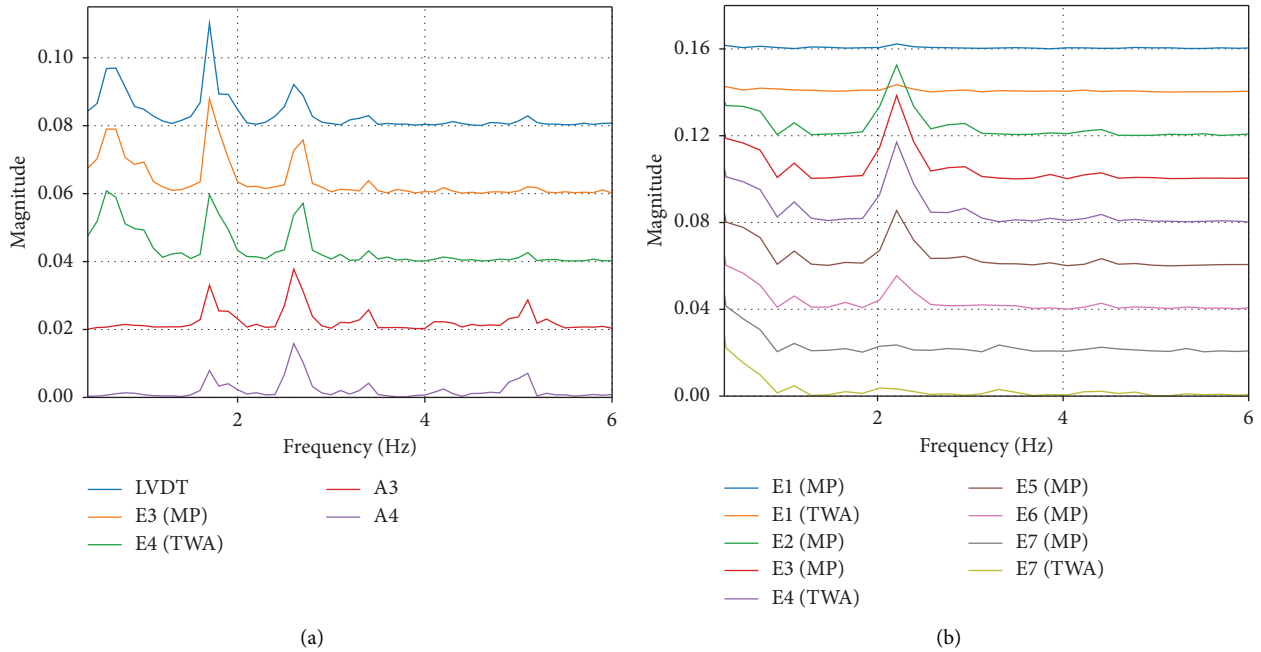


FIGURE 8: Frequency spectra of Train 2 and Train 3. (a) Frequency spectra of emitters E3 (MP) and E4 (TWA), accelerometers A3 and A4, and LVDT are shown in one diagram. (b) Frequency spectra of all emitters E1 to E7 are plotted. In order to visualize all signals in one diagram, in (a) and (b), the signals are shifted by an offset of 0.02, respectively, to each other.

replaced by small retro reflective targets which can be externally illuminated. It has to be investigated if the amount of light would be enough in this case.

The MP method uses the concept of averaging over a lateral domain to reduce the measurement uncertainty. This concept is also used in DIC, where the resolution as well as the precision of lateral position measurements depends on

the size of the correlation patch [12]. However, using large correlation patches decreases the lateral resolution and sampling of the object. Moreover, slight deformations of the target or illumination changes, for example, due to sunlight, can have a great influence on the correlation result. The MPM avoids those problems, as spatial averaging is realized in the image space instead of the object space. One challenge

regarding TWA is the predefined positions of the virtual FOVs, which are defined by the grating period. Therefore, the position of the measurement setup is given and can only be varied slightly. Here the use of a spatial light modulator instead of a lithographically fabricated diffraction grating could be useful, as the grating period can be set flexibly. Thus, the virtual FOV positions can be adjusted according to the scene. It has to be investigated if the loss of light due to worse diffraction efficiency of the SLM is acceptable in case of the TWA.

The produced CGHs can be easily etched into glass by a well-known reactive-ion etching process. This results in a very durable glass element. For long-term operation in the field, the element can be mounted such that the diffractive surface is directed toward the objective lens. This way, the outer surface is flat and, therefore, for cleaning, one uses the same procedures that are employed for flat glass plates or windows (e.g., isopropanol wiping). Thermal expansion of the glass (hologram) might be present but is typically less of a problem than the thermal expansion within the objective lens or the image sensor body. For very high demanding accuracy, the thermal behavior should be calibrated in order to be able to later correct for thermal expansion.

One advantage both presented methods offer is the fact that relative movements between all emitters can be calculated. Thereby, not only internal deformations of the object can be investigated but also environmental vibrations affecting the measurement system can be suppressed. This is achieved by calculating the relative movement between emitters mounted to the object and an emitter that is not connected to the moving structure, and, therefore is only exposed to environmental vibrations. For more details of this concept, see [40]. Furthermore, emitters could also be applied to other parts of the structure, for example, the bar arch of the studied bridge, in order to monitor its entire deformation. Another advantage of both presented systems is their simplicity in terms of technical components, processing, and cost. Both consist of a simple lens-camera setup, which is only upgraded by a CGH. If ordered in larger scale, CGHs can be manufactured rather easy by molding processes, which makes the overall cost of both setups very low. Especially the sinusoidal grating used in the TWA is a very common and easy-to-get part.

6. Conclusion

In this article, two independent and in the context of SHM novel imaging-based measurement systems are presented and compared to classical measurement approaches like LVDT and accelerometer. Both systems use CGH in order to improve accuracy and FOV compared to classical imaging systems. In the MP-system, a CGH is used to replicate the single spot of an object point to a predefined pattern in image space. By averaging the CoGs of all spot replications, the measurement uncertainty is improved compared to classical single spot evaluation. In the second measurement system (TWA), the advantage of a long focal length is combined with a large FOV by the use of a diffraction grating. Both the MP-system and the TWA-system are

analyzed regarding their measurement uncertainty under controlled conditions and in a field study. The mean measurement uncertainty under controlled conditions at a camera-to-target distance of 50 m is 0.034 mm for the MP and 0.020 mm for the TWA-system.

The field study is carried out at a double-track railway bar arch bridge with a span of 65 m. For the purpose of validation of the measured displacements and dynamics, a LVDT and accelerometers are installed. It is shown that the measurement signals of both presented measurement systems correspond very well to the applied validation sensors. The advantages of the proposed measurement systems are their ability to precisely measure both the simultaneous displacement of several object points and also their dynamic behavior. In addition, the simultaneous data acquisition also offers the means to compensate for environmental vibrations that affect the measuring system and to monitor internal deformations occurring within the structure.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*)

Three videos showing the displacement signals measured with the MP- and the TWA-system during the passing of the three trains studied are available at [44] as Visualization 1, Visualization 2, and Visualization 3. In the videos, the transient displacement of each emitter with respect to its local attachment position on the bridge is shown.

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