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Digital Image Correlation based on projected pattern for high frequency vibration measurements

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Abstract

The dynamic characterization of mechanical components is a crucial issue in industry, especially in the field of rotating machinery. High frequency loads are typical in this field and experimental tools need to fulfill severe specifications to be able to analyze these high-speed phenomena. In this work, an experimental setup, based on a Digital Image Correlation (DIC) technique with a projected speckle pattern, is presented. The proposed approach allows the measurement of vibrational response characterized by a single sinusoidal component having a frequency up to 500 Hz and an amplitude lower than 10 μm.

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Keywords: Optiocal touch probe; Geometrical inspection; Reverse Engineering

1. Introduction and background

The vibrational response of mechanical components is a crucial issue in several industrial fields. In particular, rotating machineries represent an application subjected to high vibrational solicitations, and generally, the bladed wheels are the critical part of the machine (compressors and turbines). Cyclic loads lead to fatigue damage, fretting, efficiency loss and noise. These issues must be taken into account when new products are developed in order to

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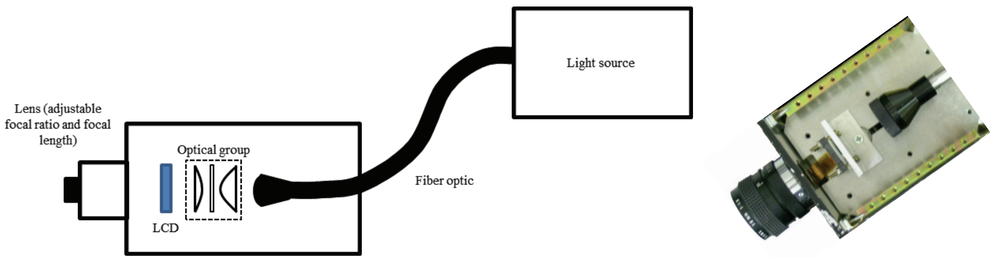
enhance the in-service performances. Worldwide leading companies in the field of energy production facilities spend a great effort to solve these issues, from the design stage to the validation stage. Theoretical and numerical models can surely give guidelines for the dynamic characterization of the components. However, they cannot replace the experimental validation, which is essential for safety issues. Experimental Modal Analysis (EMA) and experimental Harmonic Response Analysis (HRA) are then valuable tools for machine validation [1-3]. Several contact techniques have been developed to measure the dynamic response of the components such as extensimeters or accelerometers. Anyway, these contact sensors may influence the response of the component and have severe limitations in the data transmission when the component is rotating. For this reason, in the last few years, non-contact techniques have been developed [4]. Among these techniques, the most common approach uses the Laser Doppler Vibrometer (LDV) sensor, which guarantees high sensitivity measurements in a wide frequency range. Traditional LDV sensors allow measuring the vibration of a single point at a time, thus imposing severe limitations in terms of testing time. A great number of measurement points could enhance the mode shapes reconstruction. For this reason, some approaches considered the placement of the LDV tool on an anthropomorphic robotic arm in order to achieve a great positioning accuracy and facilitate the acquisition of multiple point measurements [5]. This set-up allows the measurement of several points on the bladed wheel during the vibration excitation, with an overall testing time of about one minute for each single measured point. However, the full-field reconstruction of the deformed shape still requires a long testing time even with the proposed automatic procedure. Scanning LDV (SLDV) sensors were then developed in order to speed up the whole process: moving mirrors deviate the laser beam in order to measure multiple points in a relatively short time [6, 7]. This approach, however, still provides 1D vibrational measurements. Complex arrangements, based on three separate SLDV sensors, were proposed to overcome this limitation and measure the same physical target point to gain 3D velocity information [8]. Anyway, these setups are expensive, and the acquisition of the various points is not exactly synchronous, hence an external reference signal is still needed. Moreover, the accurate positioning and orientation of the measuring laser beam represents a critical issue when dealing with complex geometries.

This paper is aimed at describing an approach that lays the foundations for the development of a full-field optical scanner to acquire machinery components vibrating in the range 1-10 kHz. High-speed cameras, however, are characterized by remarkable costs and limited resolution, which is not suitable for the acquisition of small amplitude vibrations. The proposed approach is instead based on the use of low frame rate cameras, a custom-made monochromatic LCD projector and the Non-Harmonic Fourier Analysis (NHFA). The available frame rate, indeed, would not allow to measure high-speed vibrations due to the Nyquist-Shannon theorem. However, if only one (known) frequency is present in the measurement, the actual amplitude and the signal phase can be reconstructed [9]. An accurate evaluation of the signal properties can be achieved by using a down-sampling approach and the NHFA least square fit procedure [10, 11]. Having a single sinusoidal component is the typical case of HRA, so that the technique is well suited to perform this kind of test in a full filed fashion. On the other hand, since the method does not allow to perform classical Fourier analysis, it is not suited for conventional EMA testing. Anyway, it could be used to improve EMA results obtained with other (punctual) setups: once natural frequencies and eigenmodes of the components are obtained exploiting conventional techniques, a full-field description of the mode shapes can be obtained by exciting each single mode separately and measuring the response with the proposed approach.

In the present activity, a single sinusoidal excitation, imparted by an electrodynamic shaker at a given frequency, has been applied to a metallic specimen. A Digital Image Correlation (DIC) algorithm has been used on a speckle pattern in order to determine 2D surface displacements. The proposed down-sampling approach has been adopted to reconstruct high-frequency phenomena with low frame rate acquisitions by properly triggering the camera. The more severe limitation of the approach is then represented by the exposure time, which must be much lower than the vibration period, so that the measurement target appears still during the single frame acquisition. Preliminary tests have been carried out by both using a speckle pattern prepared on the specimens' surface and a speckle pattern projected by using the custom-made projector. The obtained results demonstrate the feasibility of the proposed approach to determine high frequency amplitudes even with low frame rate cameras. These findings enable 3D shape measurements of vibrating components by adopting, for example, a calibrated stereo camera pair.

2. Experimental setup

The proposed methodology is based on the industrial camera Velociraptor HS (Optomotive), having a relatively low frame rate (300 Hz), short exposure time (20 µs) and a resolution of 2000 × 1000 pixels. In this work, a ratio of 100 between the exposure time and the vibration period has been chosen in order to obtain a maximum measurable frequency of 500 Hz. Commercial multimedia projectors present severe limitations when the projection needs to be acquired by a digital camera due to light intensity fluctuations and screen update frequency. Laser projectors were considered to overcome these issues. Anyway, each different projection pattern must be printed with a specific process, thus lowering the method flexibility and increasing the costs (since the patterns must be separately provided). Hence, a custom-made projector has been developed by assembling a transmissive TFT LCD display, a fiber optic illuminator, an optical group collimating and focusing the light beam and a zoom lens. The twisted nematic LCD panel (CRL-OPTO, Model XGA3-SLM), controlled through an electronic board connected to the VGA port, displays binary and continuous greyscale monochrome patterns with a spatial resolution of 1024 × 768 pixels. This allow to rapidly adjust the projected pattern to each specific measurement in terms of speckle sizing and density. The adopted light source for the fiber optic was a 150-watt, tungsten halogen bulb. A scheme of the described projector is reported in Fig. 1, along with a picture of the assembled prototype.



(a) (b)

Fig. 1. (a) Layout of the developed LCD projector and (b) assembled prototype.

A flat cantilever beam (70 × 230 mm) has been used as test specimen. The excitation has been imposed by an electrodynamic shaker driven with a sinusoidal signal having a frequency ranging from 100 Hz to 500 Hz. The different frequency values have been used to verify the feasibility of high-frequency measurements and the validity of the selected exposure-to-period ratio. The LCD projector has been used to project a speckle pattern on the cantilever beam (Fig. 2). The proposed layout provided a steady image, since the projection is constant during the whole acquisition and no LCD updates are required. Moreover, the light intensity appears to be stable during time. The main drawbacks of this solution are represented by a low maximum light intensity value and a distribution of the light intensity that is not uniform across the projection field. Additionally, the projector needs to be placed close to the target surface due to focusing issues and light intensity limitations. Hence, both the projector and the camera are not orthogonal to the specimen surface, thus enhancing focus problems and the non-uniformity of light intensity in the final acquired image (some examples are shown in the next section). For this reason, in this work a second approach has been followed. The same speckle pattern has been also printed and glued on the surface's specimen in order to exclude the projector influence on the measurement of high-frequency phenomena.

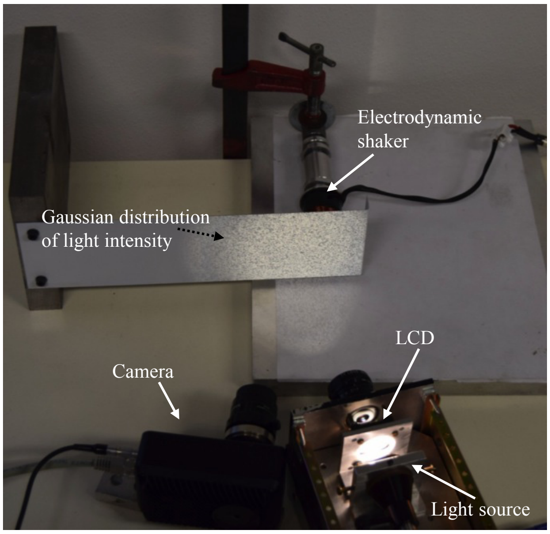
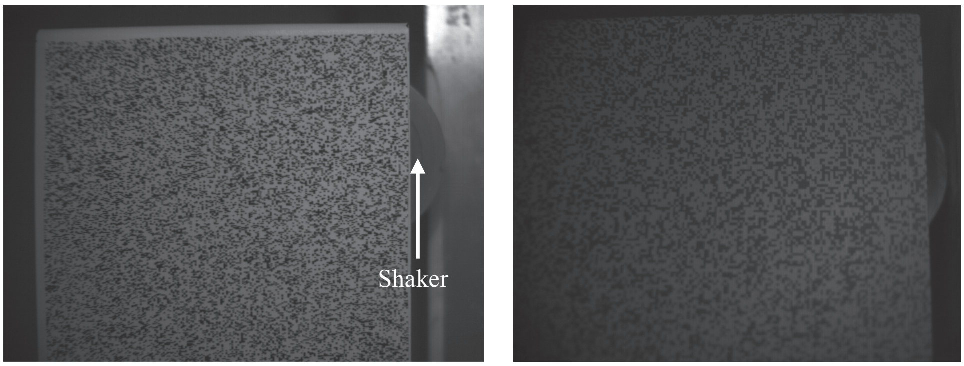


Fig. 2. Experimental setup with the projected speckle pattern.

The full-field displacement map has been obtained by applying a 2D-DIC algorithm to find the corresponding image points exploiting the speckle pattern. The average size of the projected speckles is adjusted by changing the distance between lens and LCD panel (in the direction of the optical axis), while the image brightness is corrected by regulating the projector light intensity and the exposure time of the camera. The DIC algorithm proposed by Christoph Eberl, et. al. [12] was used. The 2D full-field displacement map is then determined over time with respect to the first acquired image, which is used as reference for the evaluation of the displacement values. The acquisition procedure with the proposed experimental setup is straightforward: the speckle pattern is glued or projected on the specimen, the exciter is driven at the selected frequency and the camera acquires several frames during the vibration. Acquisitions were performed at 10 Hz, which is a low frame rate with respect to the vibration frequency. This choice was made in order to demonstrate that the displacement reconstruction is still possible even if the signal is strongly down-sampled, provided that it is composed by a single frequency contribution. Some punctual displacement signals over time were analyzed by means of NHFA in order to investigate this aspect. This procedure allowed to verify if the acquired frequency was coherent with the known imposed excitation frequency, and to evaluate the actual vibration amplitude for each point of the specimen.

3. Results

The first measurements have been carried out by using the speckle pattern painted on the specimen. These measurements are simpler than those carried out by using the projected speckle pattern since no projection issues are introduced. Moreover, the 2D-DIC algorithm can be used to identify the local in-plane (x and y) displacements from the measured images since the pattern is physically fixed to the specimen. On the other hand, the displacement field obtained with the projected pattern does not directly represent the deformed shape but requires further elaboration and the results interpretation is not a trivial task [13]. Figures 3a and 3b show the speckle pattern glued and projected on the specimen surface, respectively. The experimental setup with the glued pattern allows the camera to be frontally placed with respect to the specimen, thus providing the whole measured region to be properly focused during the acquisition. The shaker is placed in an asymmetric location on the specimen causing a mixture of bending and torsional deformation, depending on the natural modes of the structure. The tests were repeated with the frequency values ranging from 100 to 500 Hz. Each acquired frame corresponds to a displacement field of the specimen. An example of the displacement map along the x-direction, obtained with a 500 Hz excitation, is reported in Fig. 4a. The results obtained for a point near the maximum displacement value (white cross reported in Fig. 4a), are reported in Fig. 4b. The blue circles in Fig. 4b represent the displacement values actually measured during the test. These data have been further elaborated through NHFA to obtain an accurate estimation of amplitude, phase and frequency of the actual signal, which was down-sampled during the measurements obtaining the reported blue circles. This approach has allowed the reconstruction of a theoretical sinusoidal signal having the determined amplitude, phase and frequency, which was then analytically down-sampled to reproduce a simulated acquired signal (black line in Fig. 4b) for comparison purposes. The results show that the actual measured signal and the reconstructed one are comparable, thus confirming that the measured signal represents a down sampled sinusoidal vibration having a 0.14 pixels amplitude (corresponding to 8.4 μm with the adopted acquisition setup) and a frequency of 503 Hz. Both camera specifications and test procedure were assumed suitable for the application since good results were obtained in the reconstruction of a 500 Hz vibrational frequency, which was considered an upper limit of this work. However, the glued pattern presents some limitations in real cases since it is not always possible to glue or to paint a pattern on the measured surface. Furthermore, this approach is time consuming and requires a try and error phase to select the best pattern in terms of dots size and density. For these reasons, a projected pattern would be preferable for industrial applications. A projected speckle pattern could indeed be adjusted in order to fit specific needs, without physically modifying the measured surface. The main drawback of this approach is that the obtained displacement maps do not directly represent the displacement field of the surface, but they represent the displacement field of the projected dots on the deformed target. Indeed, the projected dots are not physically attached to the target, so that the actual deformed shape of the object cannot be directly obtained through DIC algorithm. However, it is still possible to estimate the actual displacement field, under certain hypotheses, since the displacement of the dots depends on the deformed shape of the measured object. Results obtained with the projected pattern cannot be directly compared with the results of the glued pattern, since the computed displacements represent two different physical quantities. However, the aim of the present research is to evaluate the feasibility of the technique and to verify hardware specifications. Thus, measurements can be considered successful if the projected pattern can be properly acquired by the camera and if the displacement field can be computed through the DIC algorithm. The projected pattern shows a low and not uniform light intensity, which could be improved by changing the light source of the projector. Nevertheless, DIC analysis showed adequate results and further projector improvements were planned for future system enhancements. The results obtained with the projected pattern and an excitation frequency of 500 Hz are reported in Fig. 5. The reconstructed sinusoidal signal reproduces the measured signal, showing that the vibration could be described by a sinusoidal wave having a frequency of 500 Hz and a 0.13 pixels amplitude (corresponding to 9.2 μm with the adopted acquisition setup). Results obtained with the projected pattern are really close to those obtained by using the glued pattern even if the signal appears to be slightly affected by higher noise.



(a) (b)

Fig. 3. Beam edge with the pattern: (a) glued and (b) projected.

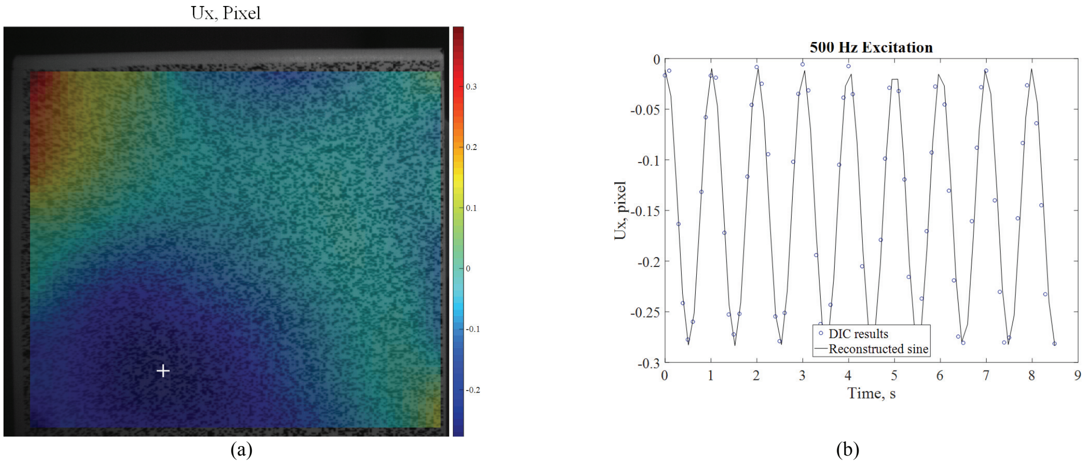


Fig. 4. Displacement values along the x-direction, for a single frame, obtained with a 500 Hz excitation by exploiting the glued pattern: (a) full-field map and (b) results obtained by analysing multiple frames for the point highlighted with a white cross.

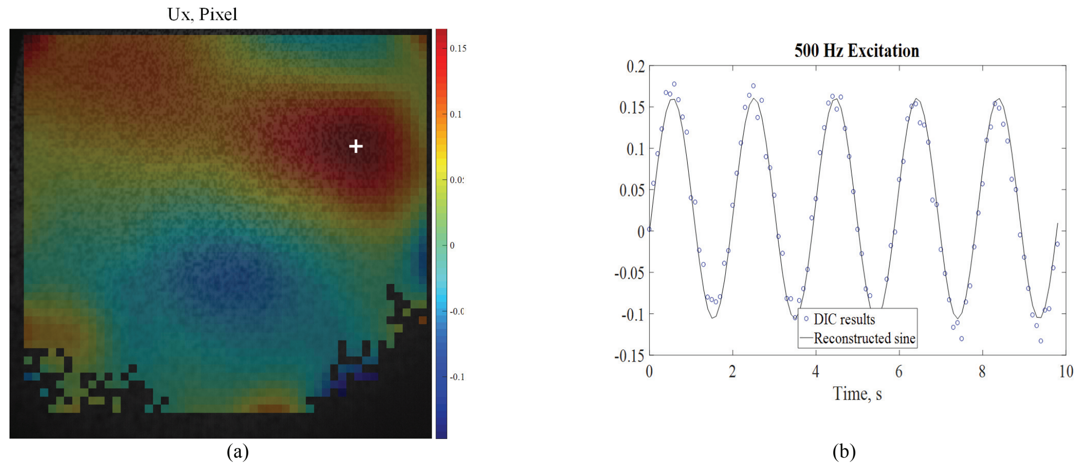


Fig. 5. Displacement values along the x-direction, for a single frame, obtained with a 500 Hz excitation by exploiting the projected pattern: (a) full-field map and (b) results obtained by analysing multiple frames for the point highlighted with a white cross.

4. Discussion and conclusions

The aim of the present research activity is the measurement of vibrational response of mechanical components by developing a 3D optical scanner. This issue requires a challenging setup. High-resolution cameras should be used to detected small amplitude vibrations. Additionally, a high frame rate would be essential to properly measure high frequency phenomena (Nyquist-Shannon theorem). These camera-side limitations are summed to the projector-side limitations. Firstly, since the exposure time of the cameras need to be much lower than the vibration period, in order to avoid blurred images, a high light intensity of the projection is required. Moreover, the use of multimedia projectors is characterized by many problems as limited depth of focus, light intensity variations, color wheel noise and screen update frequencies. Due to all these hardware limitations, at the present research stage a simplified setup was tested to verify the hardware specification needed for the application, and also to validate the proposed methodology through preliminary steps. Reliable methods for the optical acquisition of 3D points, as fringe projection techniques [14, 15] or 3D laser scanning [16], are sensible to object movements since they require the recording of a sequence of images. In this work, the projection of a speckle pattern has been considered since it reduces the measurement time to a single frame (single exposure time). A custom-made projection system has been assembled in order to enhance the depth of focus and provide a more stable image. Moreover, an industrial camera having a relatively low frame rate has been used. The down-sampling issue was solved by using NHFA algorithm to reconstruct the signal amplitude by means of a least square fit of the acquired sinusoidal signal. The obtained results demonstrate that the adopted experimental layout is able to reconstruct the vibrational response of a cantilever beam up to 500 Hz frequencies, provided that a single sinusoidal component is contained in the measured signal. The camera specifications were validated since the results shown that a ratio of 100 between exposure time and vibration period is adequate to produce high quality images either with the glued and projected speckle patterns. Images acquired from the projected pattern are characterized by higher noise, which is probably due to the low and non-uniform projector light intensity: this issue could be addressed by considering an optimized projection solution.

These achievements pave the way for the development of a 3D surface scanner based on stereo camera pair and a custom-made projection system (Fig. 6). The stereo camera setup, hardware-triggered to guarantee an optimal synchronization, is preferable with respect to the single camera-projector setup in order to improve the measurement accuracy, allowing the evaluation of small amplitude vibrations, which are typical of high frequency responses. The speckle pattern can be designed for the specific application by controlling the LCD panel with a PC. The 3D reconstruction can then be obtained by solving the stereo-matching problem between the calibrated cameras.

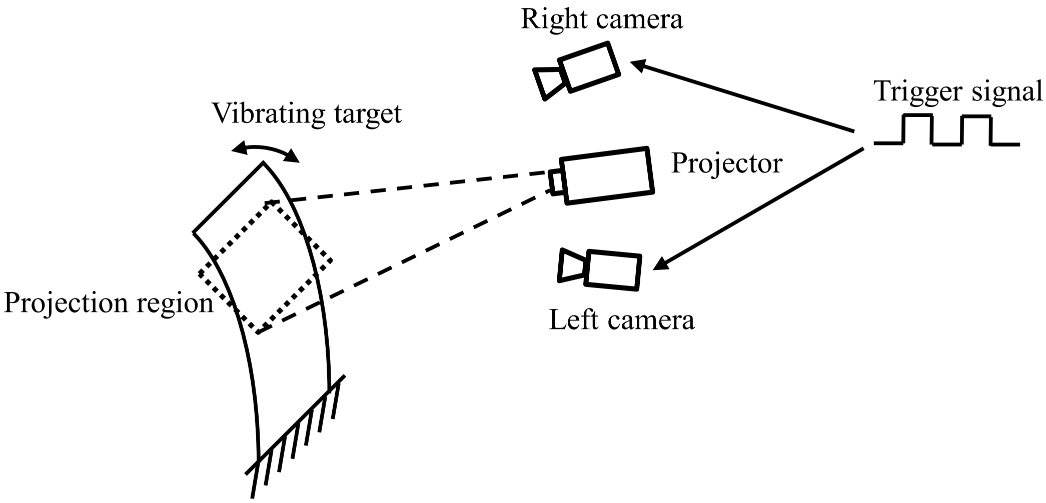


Fig. 6. 3D measurement acquisition setup.

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