

Assessing the Viability of Visual Vibrometry for Use in Structural Engineering



V. Slinger, D. Lao, V. T. Nguyen, S. Singh, and J. Gattas

Abstract Visual vibrometry is a computer vision methodology that allows a user to perform modal analysis on an object using typical video cameras, for example a standard smartphone. There is significant potential in using visual vibrometry for structural monitoring and building modal analysis; it significantly reduces cost and set-up time as compared to traditional contact and non-contact based modal analysis techniques, and allows for the measurement of non-conventional structures which might be difficult to otherwise instrument. This paper describes an initial benchmarking of the effectiveness of the visual vibrometry technique in structural modal analysis, with testing conducted on a simply supported beam and a complex semi-rigid frame structure using both visual vibrometry and classical contact-based methods. Results indicated that visual vibrometry was effectively able to detect natural frequencies under 20 Hz for both structures, with reasonable correlation seen between visual and contact-based measurements, as well as analytical and numerical solutions. The poor detection of higher frequency modes was attributed to the receptance frequency response, generated when the collected visual displacement data is transformed to the frequency domain. Doing so highlights low frequency responses but suppresses intermediate and high frequency responses. Use of high-speed cameras may improve high-frequency detection, but further work is needed to determine practical limitations.

Keywords Visual vibrometry · Structural dynamics · Structural health monitoring · Modal analysis

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1 Introduction

Modal analysis has been widely used for many decades within various fields of engineering, to detect the natural frequencies of objects and structures (Fu and He [6]). In the field of structural engineering, modal analysis has proven to be effective for ascertaining the dynamic properties of a huge range of engineered structures and is a key technique for applications in structural dynamics, structural health monitoring, and quality control for manufactured building products [3].

Modal testing is typically undertaken using an impact hammer or shaker for excitation of the test specimen, with structural response then measured using contact or non-contact based methods [6]. Contact-based methods typically involve attaching accelerometers directly to the structure. Collected data is highly precise, but set-up can be time and labour intensive, so it is impractical for many applications outside of geometrically simple specimens in laboratory environments [2]. Non-contact methods were developed to reduce these limitations and commonly involve the use of Laser Doppler Vibrometers for remote measurement of structural displacement [5]. Laser vibrometers can typically only measure a single location on a given surface and have a relatively high price point, again limiting their use for continuous displacement field measurement or measurement of structures in situ.

Camera-based computer vision technologies have recently seen much interest as a non-contact method that can aid or replace conventional modal analysis methods. Computer vision processing of video from a basic camera has been shown to allow for quasi-real time bolt tightness monitoring, overcoming many of the shortcomings associated with conventional human inspection-based structural health monitoring techniques [1]. A methodology referred to as *visual vibrometry* has been found capable of extracting the frequencies of vibration modes and subsequently deducing material properties of a vibrating object, using both high speed and regular video cameras [5]. Visual vibrometry approaches are highly appealing as they avoid many of the impracticalities associated with laser vibrometry and it are likely to be significantly cheaper than a scanning or multi-beam laser vibrometer, even with use of a high-speed camera. Video cameras are also easier to operate and likely to be more adaptable and compatible with varying test circumstances. These benefits give visual vibrometry great potential for improving the efficiency of structural health monitoring and quality control.

This paper describes an initial benchmarking of the effectiveness of the visual vibrometry technique in structural modal analysis. Testing is first conducted on a simply supported beam, using both visual vibrometry and classical contact-based methods, verified by analytical and numerical methods. A complex semi-rigid frame structure is then also tested, again with both measurement methods and with results verified against a calibrated numerical model.

2 Simply Supported Beam

As an initial benchmark, a modal analysis was conducted on a simply-supported timber beam using visual vibrometry and classical contact-based assessment techniques.

2.1 Specimen

The tested beam was a non-structural grade timber stud, with cross sectional dimension of 90 mm by 45 mm and a length of 2400 mm, as shown in Fig. 1. It had a mass of 2.26 kg/m and was oriented about its weak axis for all tests conducted. Timber is not naturally a homogeneous material; thus, the Young's modulus of any given stud varies with length, however for the purposes of this comparative study, overall average Young's modulus was considered. The tested stud had an average Young's modulus of 4757.4 MPa, provided by the manufacturer Hyne Timber from their in-house mechanical grading process.

2.2 Experimental Test

2.2.1 Visual Vibrometry Method

Visual vibrometry modal testing was conducted by exciting the beam at mid-span using a hammer, with the subsequent vibrations recorded by standard smartphone at 30 Hz and 120 Hz. To minimise noise, the camera was mounted firmly at a distance and the footage was taken outside in bright natural light and with a still background. This minimised potential flickering from artificial light.



Fig. 1 Tested specimens: simply-supported beam (left) and semi-rigid timber frame (right)

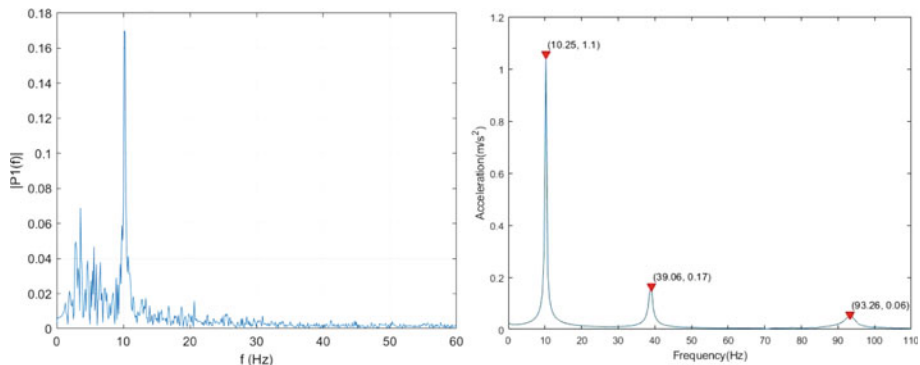


Fig. 2 Measured beam frequents. On left, normalized movement with visual vibrometry frequency sampling at 120 Hz. On right, contact-based test 1, Accelerometer 1, acceleration with frequency

Figure 2. Measured beam frequents. On left, normalized movement with visual vibrometry frequency sampling at 120 Hz. On right, contact-based test 1, Accelerometer 1, acceleration with frequency.

2.2.2 Contact-Based Method

The modal test was conducted using impact hammer excitation and contact-based accelerometer response measurement. The beam was positioned to vibrate about its minor axis, with an effective length of 2360 mm caused by 20 mm overhang at each support. Seven accelerometers were positioned symmetrically about mid-span, at 1/6, 1/4, 1/3 and 1/2 span length as measured from beam ends. These positions were selected such that the first three natural frequency modes and their corresponding mode shapes could be detected. The beam was excited via single impulse at the mid span and data acquisition collected at a sampling rate of 2000 Hz. This was repeated a total of 13 times, with separate data sets collected each time for post-processing.

2.2.3 Results

The data obtained from the visual vibrometry (VV) test was post-processed in MATLAB based on modified code from Davis et al. [4] and transformed to the frequency domain by Fast Fourier Transformation (FFT). At 30 Hz, no discernible trends were evident in the frequency domain data, however at 120 Hz a peak in the normalised movement data is evident at 10.14 Hz. This can be observed in Fig. 2.

From the contact-based (CB) test, analysis was performed on data from accelerometer 1 (at 1/6 span length) as it was able to detect vibration from all of the

Table 1 Measured and predicted frequencies for simply-supported beam test

Mode	VV Freq. (Hz)	CB Freq. (Hz)	Analytical (Hz)	Numerical (Hz)
1	10.14	10.63	10.26	10.27
2	N/A	39.33	41.05	41.07
3	N/A	93.71	92.35	92.41

first three natural vibration modes. The data from accelerometer 1 was transformed to the frequency domain using MATLAB's in-built FFT function. In order to improve the accuracy of frequency estimates and avoid inferences based on single data sets, the frequency values determined from the 13 separate tests were examined and averaged together. Results are shown in Fig. 2. The first three natural frequencies of the beam are easily discernible as 10.629 Hz, 39.325 Hz and 93.710 Hz, with VV and CB results summarised in Table 1.

2.3 Analytical and Numerical Solution

2.3.1 Analytical Solution

For a freely vibrating simply supported homogeneous beam with constant cross-section, Eq. 1 can be used to determine the natural frequency of any given mode (Nilsson and Liu [7]).

$$f_n = n^2 \left(\frac{\pi}{2L^2} \right) \sqrt{\frac{D'}{m'}} \quad (1)$$

Given that n represents the vibration mode, the frequency of the 2nd mode is 4 times that of the 1st mode, the frequency of the 3rd mode is 9 times that of the 1st mode, et cetera. For a rectangular cross section:

$$D' = \frac{bd^3}{12} E \quad (2)$$

which becomes $D' = 6.75 \times 10^{-7} E$ from substitution of specimen geometric dimensions. Substitution of the specimen's average modulus then gives D' and Eq. 1 gives the first three natural vibration frequencies of the beam, as summarised in Table 1.

2.3.2 Numerical Solution

Using the beam properties described in Sect. 2.1, a numerical model of the beam was developed in structural analysis software SPACEGASS to provide a numerical prediction for the frequencies of the first three vibration modes, also summarised in Table 1.

2.4 Discussion

The first natural frequency observed in the vibrometry test correlates well with the experimental contact-based modal analysis prediction as well as the analytical and numerical solutions, implying that the technique employed has effectively detected this natural frequency. Variation between the specific natural frequency values predicted could be attributed to a variety of errors, including inaccuracies in data collection and imperfect simply supported test conditions.

Since the Nyquist frequency of the 30 Hz test is 15 Hz, theoretically the first mode should have been detected in this vibrometry test, however it was not. Equally, the Nyquist frequency of the 120 Hz test is 60 Hz, implying that it should have also detected the 2nd mode but it did not. This could be attributed to the vibrometry methodology utilizing displacement data. Transforming this into the frequency domain generates a frequency receptance response, which is known to exaggerate low frequency responses and suppress intermediate or high frequency responses.

Even just with detection of the first mode, the visual vibrometry technique is sufficiently accurate for prediction of the specimen material properties. Substituting Eq. 2 into Eq. 1 and re-arranging for E gives a predicted Young's modulus a value of 4639.6 MPa, which is within a few percent of the actual average specimen value of 4757.5 MPa.

3 Complex Semi-rigid Frame Structure

Visual vibrometry and contact-based modal analysis were conducted on a complex semi-rigid frame structure to further test and contrast the capabilities of the technology.

3.1 Specimen

The test structure, shown in Fig. 1, is a complex semi-rigid arch frame composed of MGP10 timber elements held together via tension straps. The x and y dimensions were defined for in plane horizontal and vertical movement, and the z direction was defined for out of plane movement.

3.2 Experimental Test

3.2.1 Visual Vibrometry

The visual vibrometry test was conducted by exciting the frame in the x direction, with the subsequent vibrations recorded by standard smartphone at 30 Hz and 120 Hz. Video was captured from a front and side view. Data collection and processing was otherwise as described for the simply-supported beam. As was the case with the simply supported beam visual vibrometry test, no discernible trends were evident in the frequency domain data transformed from the 30 Hz video, however at 120 Hz peaks within normalised movement data are evident. This can be seen in Fig. 3.

3.2.2 Contact-Based Method

The modal analysis was conducted using an impact hammer for excitation and contact accelerometers for response measurement. The frame was free to move in any direction and thus a total of 6 accelerometers were used, 3 for each of the x and y spatial dimensions. Data was logged and processed using a Dewesoft SIRIUS HD ACC DAQ (data acquisition) system and the Dewesoft X3 DAQ software package.

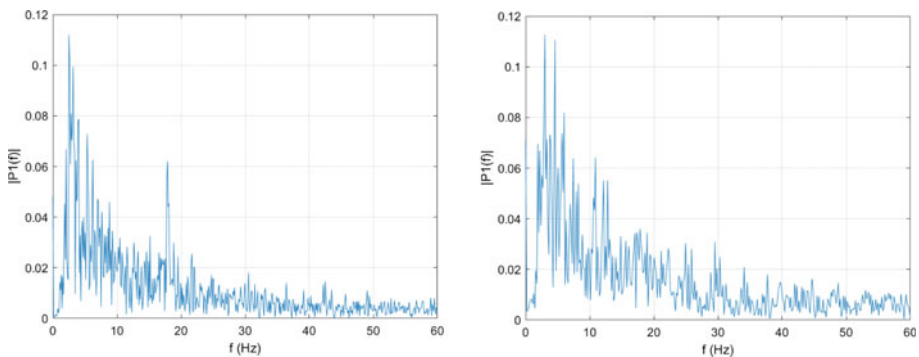


Fig. 3 (a) Front and (b) side view normalized movement with frequency sampling at 120 Hz

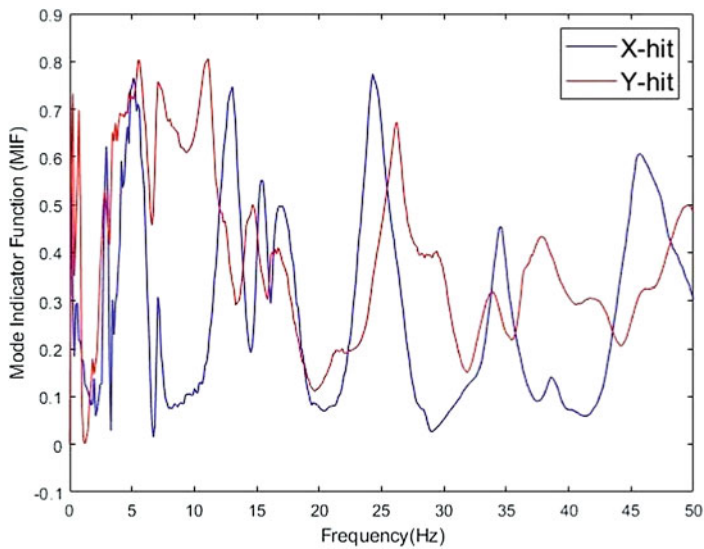


Fig. 4 X and Y direction strike modal indicator function with frequency

Two tests were conducted, once with the frame excited in the x direction and once excited in the y direction. For each contact-based test conducted, 5 separate hammer strikes were performed, and these results were averaged within the Dewesoft X3 software. The results are shown in Fig. 4, displayed as mode indicator function values to more clearly highlight frequency spikes.

3.3 Numerical Model

3.3.1 Model Parameters

Given that the structure is complex, it is significantly more difficult to validate the obtained experimental modal frequencies. There are no analytical solutions available for this structure, so instead a numerical model of the frame was constructed in structural analysis software SPACEGASS. Members were designated as MGP10 from the SPACEGASS AusfTimb library, which assigns them a Young's modulus value of 10000 MPa. Connections between frame members were simulated as semi-rigid by inserting very short intermediate members of significantly reduced cross-section. By adjusting the dimensions of these intermediate members, the stiffness of the joints in the frame model can be adjusted.

3.3.2 Semi-rigid Joint Calibration

Calibrating the numerical model requires calibrating the rotational stiffness of the frame joints until the first numerical modal frequencies align with experimental results. Since the frame was free to move in all directions, in plane and out of plane (transverse) vibration modes influenced the experimental results obtained. The stiffness of joints was iteratively calibrated by restraining the frame model such that the in plane and out of plane modal frequencies could be isolated. These were then matched as closely as possible with the experimental results obtained from the vibrometry test.

The first two clear data peaks come from the front view test (Fig. 3a) which are at frequencies of approximately 2 and 2.8 Hz. This closely aligns with the first out of plane and in plane modal frequencies predicted by the SPACEGASS model for intermediate member sizes of 20 by 30 mm and 17 by 20 mm, respectively. The validity of these initial frequencies is supported by the modal analysis results, which also shows MIF peaks at approximately 2 and 2.8 Hz.

3.4 Discussion

Tables 2 and 3 summarise the numerical and experimental frequency findings for both in plane (XY) and out of plane (Z) vibration modes. As was observed from the results of the simply supported beam vibrometry test, the receptance frequency

Table 2 XY natural frequencies of semi-rigid frame

Mode	Numerical	CB Freq.	VV Freq.	Notes
1	2.85	2.93	2.51–3.16	There are two major peaks close together in visual vibrometry data, the 1st mode frequency could be interpreted as being anywhere between these two
2	9.42	9.28	8.83–9.42	The CB frequency observed is represented by a very wide peak and the corresponding value is taken as the mid-point. This mode is only visible from the Y direction CB hit test
3	19.73	N/A	N/A	This frequency is present within the numerical model but is not observed from any of the test data. This could potentially be attributed to the mode not being initiated by the excitation points tested
4	32.8	30.0	N/A	No frequency spikes in this range are evident within the visual vibrometry test data
5	45.7	45.5	N/A	No frequency spikes in this range are evident within the visual vibrometry test data

Table 3 Z natural frequencies of semi-rigid frame

Mode	Numerical	CB Freq.	VV Freq.	Notes
1	1.83	1.83	1.85–2.07	There are two major peaks close together in visual vibrometry data, the 1 st mode frequency could be interpreted as being anywhere between these two
2	5.03	5.13	5.05–5.34	Results corroborate each other, all else unremarkable
3	10.20	10.99	10.89	Visual vibrometry peak at this mode only discernible from side view data
4	17.97	16.99	17.87	Visual vibrometry peak observable from front view data
5	28.91	26–29	N/A	No frequency spikes in this range are evident within the visual vibrometry test data. There is a CB peak over this range which corroborates numerical results

response highlighted low frequencies but did not detect any frequencies higher than about 20 Hz, with the highest frequency peak detected being 17.87 Hz.

After adjusting the numerical model to fit the first two modal frequencies, the subsequent modal frequencies below the 20 Hz limit could be correlated with the vibrometry results and these with the modal analysis results. Some of these correlations were not as clear as the correlation between the first two frequencies across the test types and varied by up to 1 Hz in some instances. Despite this, an overall correlation between the numerical results and vibrometry results exists and this reinforces the method's validity for structural characterisation.

4 Conclusion

The results of the study suggest that visual vibrometry can be used to detect the natural frequencies of structures both simple and complex in nature. When combined with numerical or analytical models, this could be an effective means of obtaining properties of numerous types of structure, from simple to very complex.

Given the quick set-up, low-cost equipment, and fast post-processing time, visual vibrometry can be concluded to be significantly easier to implement than contact based modal testing. The viability of this technology suggests that it could hold great potential for use in improving the efficiency of a variety of industries such as structural verification and health monitoring, and could also create new opportunities in digital building certification.

The results suggest that there are practical limitations associated with receptance frequency response functions, which are an integral component of visual vibrometry. Since the low frequency region of a sample is highlighted when transformed,

structures with very high modal frequencies would likely require high speed cameras in order to effectively detect them. Further research should be conducted to ascertain the limitations of high-speed cameras used for visual vibrometry of building structures.

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