# MEASUREMENT OF 2D VIBRATION MODES USING AMPLIFICATION OF HIGH SPEED VIDEO IN THE PRESENCE OF NOISE

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## ABSTRACT

The amplification of video allows sub-pixel movement to be revealed. This has been applied to measure structural vibration using high speed video. A perspective correction has been defined to allow 2D modal analysis to be conducted on a flat plate showing that accurate displacement measurements across the surface can be made. Furthermore, the effect of using various excitation signals including white noise and swept sine has demonstrated that it is possible to extract several mode shapes in a single measurement. Finally, measurements have been conducted on a Dyson Airblade V hand-drier in operation showing that high speed video measurement of vibration can be applied to industrial noise control problems. The main advantage of this method is ease of testing compared to traditional single point accelerometers and measurement of time variant signals compared to a scanning laser vibrometer.

***Index Terms—*** Vibration, measurement, image processing, high speed video, modal analysis

## 1. INTRODUCTION

Eulerian video magnification is a technique for amplifying small motion captured in video [1]. Among several possible applications is the measurement of structural vibration. As a video inherently captures the entire scene simultaneously, it is naturally suited for analysis of modal vibration where the phase relationship between different spatial locations is crucial.

Previous work by Chen et al. [2] used amplification of video to measure 1D mode shapes on a cantilever beam and on the cross section of a circular pipe. We have sought to apply and extend this technique to allow vibration analysis to be performed in industrial noise control engineering, specifically for goods made by Dyson: vacuum cleaners, hand driers, cooling fans, etc. To apply video magnificaition to vibration measurement in this case it is necessary to analyse complex geometries, to have quantitative as well as qualitative output and to be robust to noise.

This work was completed by Daniel Zheng during a 3 month internship at Dyson in collaboration with the remaining authors.

## 2. BACKGROUND

Video magnification is a technique which works by amplifying color and brightness variations in individual pixels. It is therefore ideal for tracking changes in color, but with more care over processing of different spatial-wavelength variations, it can also be used to reveal subtle sub-pixel movement.

The image is first decomposed into its spatial frequency components, i.e. into different components based on the strength and sharpness of any edges or other image features [3]. The second step applies the pixel-wise temporal magnification to each component, and finally the components are recombined with a weighting according to a specified amplification factor to increase the motion. Using video magnification causes the tiny, sub-pixel displacements associated with vibration to be made visible.

Once the motion is visible in the video, fixed points can then be tracked and hence the vibration magnitude can be derived. Note that as with any discrete time system, the sample frequency must be sufficiently high to capture the desired signal according to the Nyquist criterion. Hence in this work we have made use of a high speed camera in order to track vibrations occurring in the audible frequency range. Although Davis et al. [4] have exploited the rolling shutter of a standard consumer camera to extract audible sound from video this has not been considered here.

## 3. MEASURING 2D VIBRATION USING PERSPECTIVE CORRECTION

As the video magnification works parallel to the image plane, 1D modes, such as those of a beam, can be easily visualised by aligning the image parallel to the motion. For 2D modes, such as those of a simple plate, if the motion is parallel to the image then points in the depth of the image will be obscured. If the image is facing the plate directly, the motion is into the plane and will not be picked up even with motion magnification. Therefore the plate must be viewed at an angle (fig. 1).

To extract the motion perpendicular to the plate we must correct for any perspective distortion. In the case of a flat plate, the vibration amplitude can be found using some

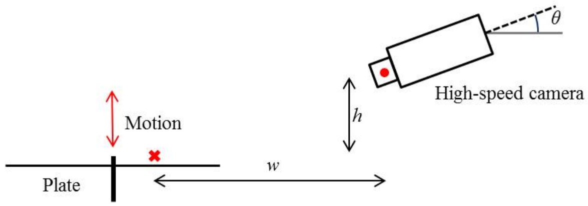



**Fig. 1**. The normal vibration of a plate was measured using a high speed camera viewing the plate at an angle.

trigonometry

$$\frac{1}{x} \propto \cos(\theta) + \frac{w}{h}\sin(\theta) \tag{1}$$

where $x$ is the displacement of the plate, $\theta$ is the angle of the camera, $w$ is the horizontal distance from the camera to the point on the plate which is being analyses and $h$ is the vertical distance from the plate to the camera (fig. 1).

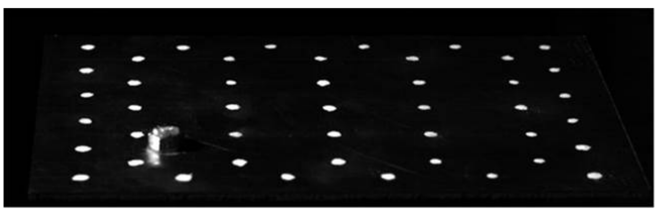


**Fig. 2**. The plate was marked with a grid of points that enabled the vibration to be tracked.

To convert this amplitude data into standard units, there also needs to be a reference distance in the video frame, from which the number of pixels per mm can be calculated, taking into account the correction factor above. For a general reference height, let

$$K = D_{ref}/P_{ref} \tag{2}$$

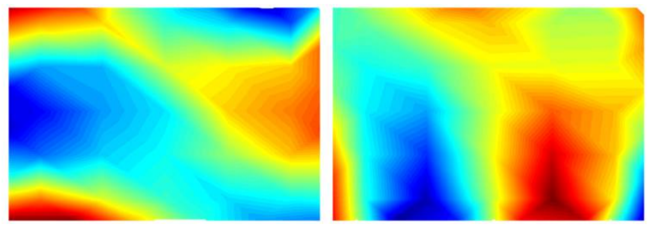
be the conversion factor for pixels to mm, where $D_{ref}$ is the reference distance in mm, and $P_{ref}$ is the same distance measured on frame in pixels. Let $h_0$ and $w_0$ be the vertical and horizontal distances of the point of reference to the focal point of the camera lens. Then the the displacement (ignoring for the moment any amplification of the motion) is given as:

$$x = x_p K \frac{\cos(\theta) + \frac{w}{h}\sin(\theta)}{\cos(\theta) + \frac{w_0}{h_0}\sin(\theta)} \tag{3}$$

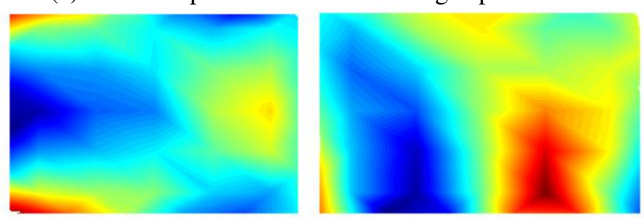
where $x_p$ is the displacement in pixels taken from the video tracking. Therefore the perspective distortion can be corrected for as long as the distances of each point from the camera are known.

For this particular experiment, the plate was mounted on a shaker table using a stinger to approximate a point force. A National Instruments card controlled with Matlab was used to acquire data which also controlled the shaker table. Using Matlab allowed arbitrary excitation signals to be generated. The nut which attached the plate to the stinger (fig. 2) was used as a reference for the pixel to mm conversion factor.

For the first test, the plate was excited with a sinusoidal input at known resonances of the plate. The amplitude was set such that the motion was just barely visible in the videos before the amplification routine, so it would not have been easy to track reliably. The amplification routine allowed for excellent tracking of the mode shapes of the plate with a very close match to the mode shapes derived using traditional modal analysis with a fixed position accelerometer and roving impact hammer [5].



(a) Mode shapes derived from the high speed video



(b) Mode shapes derived from impact hammer tests

**Fig. 3**. There is excellent, quantified agreement between the mode shapes derived from the high speed video and the impact hammer tests at $1337\,\mathrm{Hz}$ (left) and $1762\,\mathrm{Hz}$ (right). The color axes for all plots are identical.

## 4. ACCURACY OF VIBRATION AMPLITUDE

Extracting the vibration amplitude at a single point on the plate allows direct comparison of the measured displacement with that derived from an accelerometer. In this case the accelerometer is used to measure a single point while the plate is excited with a sinusoidal force from the shaker and the displacement of that point is measured from the high speed video.

In this case the accuracy of the displacement amplitude is found to be very good with an error of around $0.2\,\mu\mathrm{m}$ (table 1). As the displacement at the higher frequencies is lower, this error becomes significant, around $20\,\%$ of the value with an excitation at $1780\,\mathrm{Hz}$. However, it should be noted that the displacement error is less than a thousandth of a pixel.

Additionally, the linearity of the amplification factor has been measured by successively reprocessing the video with higher amplification and measuring the raw pixel displace-

**Table 1**. Displacements obtained using amplified video are in close agreement with those measured with an accelerometer.

| f/Hz | x/μm (accel) | x/μm (video) | Error/μm |
|---|---|---|---|
| 402 | 15.8 | 15.9 | 0.10 |
| 1355 | 3.60 | 3.80 | 0.20 |
| 1780 | 0.95 | 0.74 | 0.21 |

ment. For values of amplification between 5 and 25, the increase in pixel displacement was found to be perfectly linear (fig. 4). This result gives confidence that the routine is doing what it is supposed to and that even reasonably high values of amplification can be used.

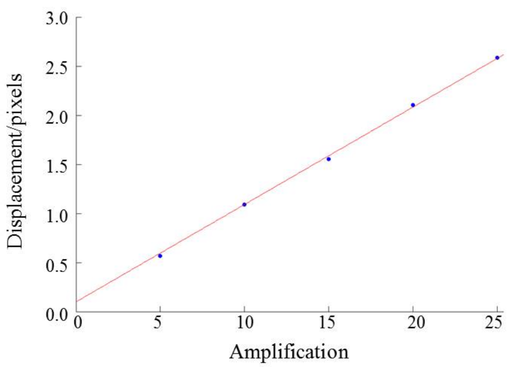


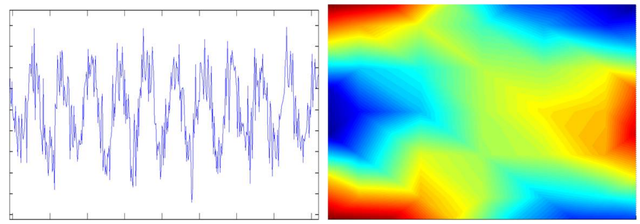

**Fig. 4**. The displacement extracted from the amplified video is linear with the amplification factor.

## 5. ROBUSTNESS TO NOISE

When the routine is to be applied to products in operation, it would be useful to be able to separate motion in specific frequencies or frequency bands from complex vibrations spanning a range of frequencies. To this end, tests were carried out to determine the effectiveness of this temporal filtering.

Initially, the plate was excited with a sinusoidal signal at the known 1355 Hz mode with white noise added. Filtering as described in [6] was applied to amplify the signal at the frequency of the sinusoid which gave excellent results (fig. 5). The close similarity to the modes measured with a pure sine (fig. 3) suggests that the noise did not have much of an adverse impact on the analysis.

To further test the robustness to noise we attempted to extract individual mode shapes from a video of the plate which had been excited with pure white noise the advantages of this, if it worked, being that the resonant frequencies would not need to be known to perform the experiment, and that only one video recording would be needed to capture data about



(a) Excitation (b) Mode shape

**Fig. 5**. Filtering the video signal when the excitation is a noisy sine allows the mode shape to be recovered with very similar results to fig. 3 which had no noise.

all of the modes. Additionally, it is more representative of the product in operation.

Unfortunately tests with a white noise excitation found that the higher frequency modes (1350 Hz and 1780 Hz) were not picked up by the video amplification method. Further investigation with an accelerometer revealed that this was due to an insufficient amplitude of vibration in these modes. However, it was possible to extract the mode shape of a lower frequency mode (400 Hz) from the video which demonstrated that the filtering method with a broadband signal was possible (fig. 6).

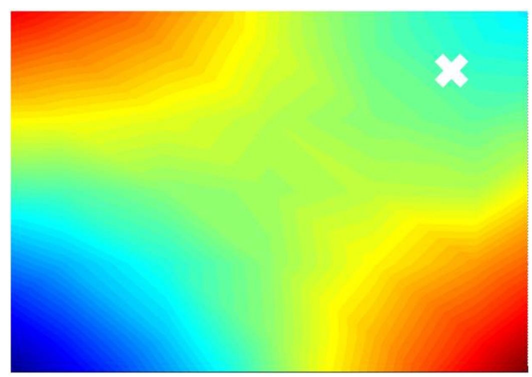
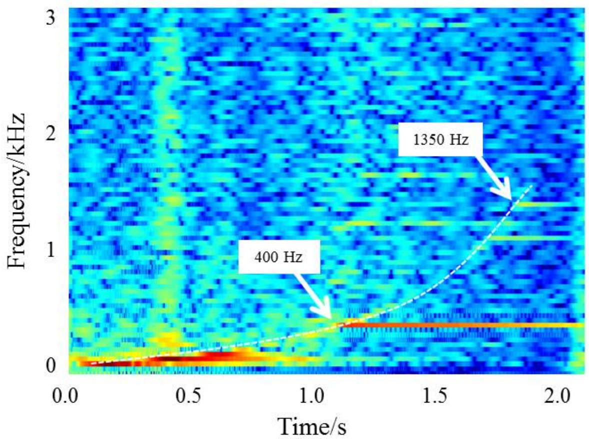


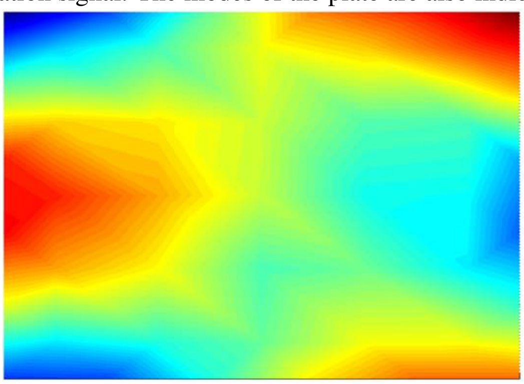
**Fig. 6**. The 400 Hz mode was extracted by filtering the video while the plate was excited with white noise. Note that the forcing is applied at the position of the white cross, which causes the asymmetry in this mode.

To investigate this further a swept sine signal was used to excite the plate. In order to keep processing requirements on the video magnification reasonable, it was only possible to use a 1.5 s sweep from 100 Hz to 1500 Hz. A spectrogram created from a single point on the plate shows bright horizontal lines which correspond to the decaying modes (fig. 7a). The mode shape of the resonance at 1350 Hz was extracted (fig. 7b).

The use of a swept sine excitation in this way allows an immediate measurement of all the resonances of the system including a full characterisation of the mode shapes in a single pass. This measurement method could also be used with an




(a) The dotted line approximatively shows the swept sine excitation signal. The modes of the plate are also indicated.



(b) Mode shape at 1350 Hz.

**Fig. 7**. Using a swept sine excitation identified the resonances and the video can be filtered to extract particular mode shapes.

operational measurement with a motor ramp-up/ramp-down allowing this characterisation to be performed in-situ without modification to the system. In this case there is an advantage using high-speed video over a scanning laser vibrometer as only a single pass is required.

## 6. APPLICATION TO OPERATIONAL MEASUREMENTS OF PRODUCT

The Dyson Airblade V hand-drier has been used to assess the measurement of vibration using video magnification on a "real life" application. In this case, the product has several flat surfaces so the simple perspective correction described in section 3 can be applied directly. The excitation signal is the motor of the product in operation.

The vibration has been measured by filtering the raw video at a range of frequencies as described in the previous section and then tracking a grid of marked points. From this analysis the modes of the front of the fascia at 100 Hz and the side panel at 100 Hz and 200 Hz are observed (fig. 8). Note that the displacement amplitudes have been obscured for commercial purposes but have been validated against accelerometer data.

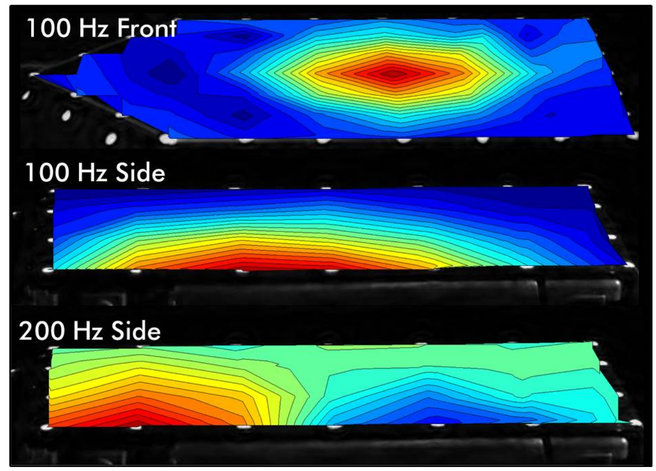



**Fig. 8**. The modes of the fascia of the Airblade V hand-drier have been extracted during operation of the product.

## 7. CONCLUSIONS AND FUTURE WORK

The application of amplification of high speed video to vibration measurement has been demonstrated. The technique of video magnification [1] and the application to modal analysis [2] have been described previously in the literature. Furthermore, there is more recent work on processing of high speed video to measure vibration [7].

In relation to this past work the novelty in this paper is, firstly, we have defined a perspective correction which allows the quantitative measurement of 2D modeshapes, an extension on the measurement of 1D mode shapes and the more qualitative analysis reported in other works. Secondly, the analysis of a video using filtering when the structure is excited using noise and swept sine signals has been shown to extract mode shapes accurately, again to our knowledge this has not been reported previously. Finally, we have shown a definite application to engineering vibration analysis using an operational product.

The next step for this work is to extend the perspective correction to complex surfaces as currently we have limited our analysis to flat plates. Measuring the 3D vibration of complex shapes may require the correlation between multiple camera locations. Another area of investigation would be to use the vibration data to calculate the radiated acoustic pressure or based on the radiation impedance or to use an input force transducer to calculate the structure mobility.

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