Video-based Methods for Measurement of Vibration Mode Shapes

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***Abstract*— Non-contact measurement methods for vibrations and displacements of aerospace structures are convenient because of their ease of setup and ability to measure hard-to-access regions. They typically only require line of sight such as when a video camera or laser instrument is aimed at the desired locations of measurement. Standard methods for testing of aerospace structures which involve the use of strain gauges or accelerometers need to be physically attached when access may present issues in large structures, dense instrumentation can be costly, and the logistics of running wiring can be complicated. By contrast, the resolution and processing of measurements from standard sensors is simpler, while non-contact methods may have more complicated data processing or resolution limitations.**

This paper will provide a general overview of the current state of the art of computer vision and photogrammetry methods for measuring operational resonant frequencies and vibration mode shapes of aerospace structures. We will do a deep dive into video-based methods that use optical flow and related algorithms collectively called Motion Magnification, that provide visualizations of vibrations and displacements. We will describe the theory behind these computer vision algorithms, review recent work by researchers and companies in the field, and discuss capabilities and limitations of these methods, specifically the impacts of camera quality, noise, and video compression algorithms on measurements. We will give examples of measurements made in both laboratory settings and real-world vibration testing scenarios with a wide variety of camera hardware ranging from expensive high-speed cameras to consumer action cameras. Examples include an airplane wing recorded by a cell phone camera, the Space Shuttle, and the Space Launch System modal testing campaign. We will finally discuss potential future developments in the field. We hope to convey a thorough understanding of the theory and capabilities of these techniques, to guide experimentalists and testing engineers in using these methods accurately and effectively.

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1. INTRODUCTION

Modal analysis and vibration testing are important during the development of aerospace structures and components to ensure that they survive unique load environments during operation, as well as ensuring that the as produced final product matches the design (model validation). Measurement of articles under test for both purposes is typically carried out with contact sensors, accelerometers or strain gauges, which can provide high resolution data, but only at the locations at which they are placed. Placement of these sensors can be time consuming, add mass loading, or be inconvenient depending on the type of structure or component and the measurements needed for the test.

The ideal sensing system would be able to obtain 3D displacements, velocities, and accelerations in all 3 axes at all locations on an article under test without any contact, mass loading, or surface preparation. Absent that pipe dream, researchers and practitioners have been trying out non-contact methods of measuring structural motion, with a popular method being computer vision or photogrammetry. Video cameras come in all shapes and sizes, both as scientific instruments and consumer electronics, and are generally convenient to set up and use, with interpretation and processing of the video data being more complicated than time series signals from traditional accelerometers.

Recently, there has been great interest in video-based methods that use optical flow and related algorithms colloquially called "motion magnification" that provide visualizations of structural vibrations and operational mode shapes. This allows for more intuitive interpretation of video data as well as providing a processing technique for obtaining displacements from video data. This paper will describe the theory behind these algorithms, review recent work by researchers in the field, and discuss the capabilities and limitations of these methods. We will also give examples of measurements made in laboratory and real-world scenarios and how they differ.

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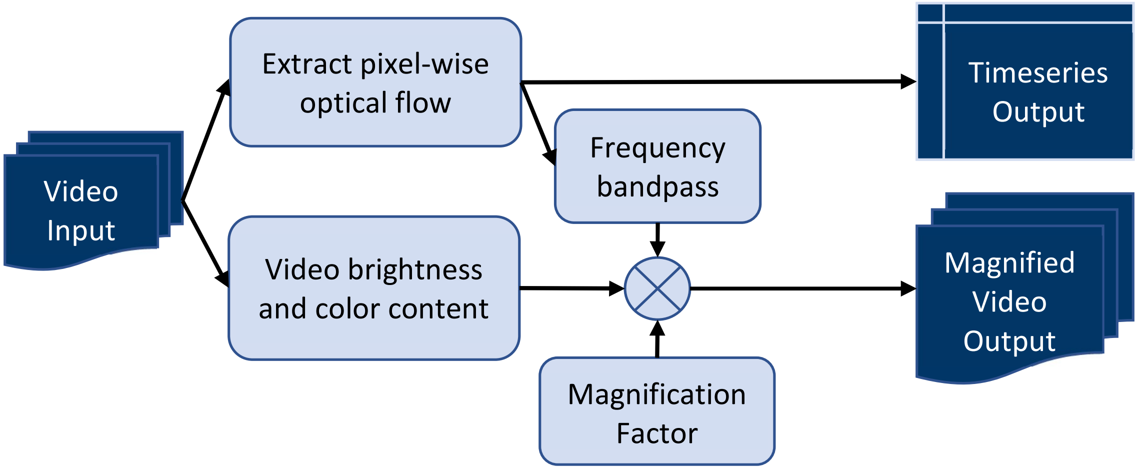


Figure 1. Simplified video processing pipeline for video motion magnification and displacement extraction

2. VIDEO-BASED METHODS AND APPLICATIONS REVIEW

This section presents a review of video-based methods and those related to motion magnification. It is not meant to be an all inclusive detailed review, but more of a whirlwind tour of the work that has been happening in the field to the best of the author's knowledge.

Computer Vision Beginnings

The concept of optical flow is central to understanding how video cameras can be used as displacement or vibration sensors [1]. In simple terms, optical flow is the apparent motion of objects, or more generally textures, from frame to frame in a video or series of images. An ideal optical flow method would be able to determine the interframe displacement of objects (projected onto the 2D image plane of a camera) everywhere in the frame. Methods of determining optical flow from video are many, but one method common is to use local phase which is the phase of a local wavelet function representative of an edge or texture [2]. Another common method of determining optical flow is digital image correlation (DIC) which correlates textures or patterns in the amplitude (pixel brightness) domain [3]. This paper will generally focus on methods derived from phase-based optical flow methods, however DIC based methods are also valid. Both methods are generally able to extract sub-pixel motions from video or a series of images, and that is what forms the basis for motion magnification. As a note, a video is merely a series of images, so for simplicity video will be used throughout the paper to describe both.

Video Amplification/Motion Magnification

One of the first papers that introduced the concept colloquially called motion magnification, used amplitude (brightness or color) based optical flow determination in addition to temporal filtering (frequency bandpass filtering) to magnify small, subtle motions in videos [4]. This was expanded shortly after by using a phase-based method to determine optical flow and to apply the video magnification [5]. Figure 1 shows a very simplified video processing pipeline for how the motion magnification effect is achieved.

A key feature of both these methods is that they operate on motions in an Eulerian way, where motion vectors are fixed in the frame of the video, rather than tracking or following the objects (which would be Lagrangian). For a video with only small, subpixel motions, an Eulerian description of motion is sufficient, but more on this topic later.

A modified way for calculating optical flow and performing the temporal band-pass filter allowed for improved speed of the processing enabling real-time video magnification [6]. This allowed for a slick demonstration that used a camera with very short exposure time to achieve a stroboscopic effect to alias down higher frequency motions to typical video rate (30fps) which could be processed in real-time, to show amplified motions on a laptop screen of the object vibrating in the real world.

These two papers [7,8] are good references for a summary of the algorithm development work and initial set of applications done at the time in a wide variety of fields.

Proliferation and Expansion of Video-based Methods

The ability to extract subtle motions from videos as well as a frequency bandpass filter on those motions lends itself to being used for vibration and operational mode shape measurement of objects and structures [9,10,11]. These methods can then be extended to use the identified operational mode shapes and displacements as measured from video, for damage detection algorithms [12,13,14]. Around the same time, at least two companies have commercialized similar technology that measures and exaggerates subtle motions in videos (unrelated algorithm development paths a.k.a. multiple discovery) RDI Technologies [15] and MEScope from Vibrant Technology Inc. [16].

Other applications include quantifying aeroelastic modes [17], measuring vibrational modes of an airplane wing from

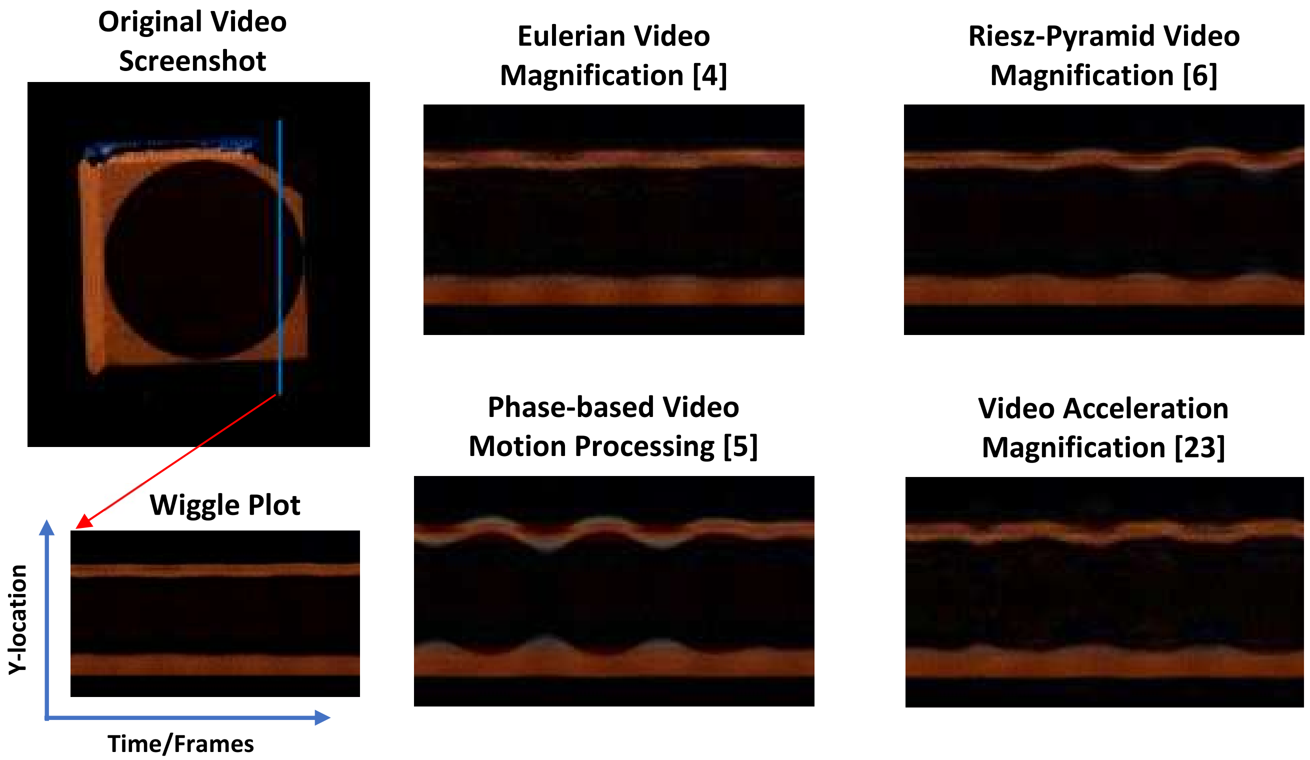


Figure 2. Comparison of different video magnification algorithms performed on the same video of an object measured under laboratory conditions with a high speed camera. The wiggle plots act like a finish line camera and show the time evolution of one line of pixels over time, plotted spatially. Note that the Riesz-pyramid technique ramp up in motion amplitude is due to the IIR filter used.

the passenger seat [18], solar coronal imaging [19], and visualization of shell buckling [20] among many others.

Small and Large Motions

The pixel-wise extraction in displacements in an Eulerian manner, precludes simple handling of large motions, because those motions, if not explicitly tracked, will span many pixels. Visualization and measurement of small motions on top of large motions is thus difficult.

A first try at handling this combination of large and small deflections in a video used image segmentation and masking to achieve an effect where the foreground objects of interest are tracked and magnified while the gaps due to large motion are infilled [21], similar to how the original motion magnification paper worked [22].

A clever technique that instead operated on the acceleration term of motion rather than the velocity term (interframe displacements) was able to achieve magnification of small motions on top of large linear motions [23] with another research team expanding the technique to be jerk-aware [24]. A qualitative comparison of the video results of different motion magnification algorithms [4,5,6,23] is shown in Figure 2, while a quantitative comparison of the runtimes is given in Table 1.

Table 1. Comparison of Motion Magnification Method Runtimes for 200 frames of a 142x152 pixel video

Methodology	Wall Time (seconds)
Eulerian Video Mag. [4]	2
Phase-based Video Motion Proc. [5]	12
Riesz-pyramid Video Mag. [6]	2
Video Acceleration Mag. [23]	137

Fun Applications

This section contains work that isn't necessarily directly related to motion magnification, however it contains some notable work that does use video clips of subtle motions for interesting applications and cool effects.

The visual microphone [25] uses displacement information from objects vibrating due to acoustic excitation to extract sound from silent video. Visual vibrometry uses frequency spectra from objects vibrating to estimate material properties of those objects [26].

A related application in static images magnified small deviations from lines and other geometric primitives to reveal hidden deformations that exist in the world [27].

An assumption of a constant background texture can allow any detected optical flow to be attributed to changes in refractive index in the air between the camera and the background, and thus can be used to measure fluid depth and velocity in video [28].

In most structural applications of phase-based optical flow and motion magnification, the goal is to quantify the operational mode shapes of a structure or object. Without any forcing input information, this provides 2D projected modal basis functions for the object that can be used to synthesize plausible object motions under an imaginary input force that stimulates the appropriate modes based on an applied modal participation factor [29]. With some image warping and a graphical user interface, this results in an "interactive dynamic video" where a user can apply imaginary forces to a real object and see how it moves and vibrates.

Applications in the "Real World"

Video measurements made out in the field or in operational conditions are more representative of the methodology's performance in typical use as compared to measurements made in near ideal conditions in a laboratory. A measurement was made of an antenna tower and the measured frequency was validated by a near field laser vibrometer measurement [30]. Measurements of bridges were done in [31,32] from distances of 80m and 447m respectively that demonstrate that the methodology holds even for long range measurements as long as proper mitigating steps are taken (to be discussed later). For aerospace structures, measurements were made during the Space Launch System (SLS) integrated modal test (IMT) as well as during the dynamic rollout/rollback test (DRRT) rocket stack rollout and rollback from the pad [33]. This measurement campaign will form the basis for many examples in Section 5.

Applications Beyond 2D Video

The previously discussed work primarily involves what one normally thinks of as a standard camera or video camera. Motion magnification has been adapted to a variety of different kinds of sensors or sensing modalities including neuromorphic sensors [34], radiographic images [35], and 3D volumetric data [36]. The benefit of neuromorphic sensors is that they are event-driven and have much lower data rates with much higher dynamic range since they only sense changes in a scene. Radiographic images and 3D volumetric data would allow for visualizing internal and full 3D motions of objects as long as the data can be collected.

Machine Learning Based Implementation and Methods

Over the last decade computer vision has experienced a resurgence of interest in neural network-based methods for doing basically everything; motion magnification is not immune. For background, optical flow is well estimated by convolutional neural networks [37,38]. A machine learning implementation of motion magnification [39] achieves qualitatively similar results on a wide variety of different videos with a clever training scheme using synthetic videos. Much newer neural network based methods using neural radiance fields (NeRF) [40] is able to achieve a holy grail of 3D motion magnification [41] or modal analysis of dynamic 3D scenes [42].

3. CAPABILITIES AND BENEFITS

This section will discuss capabilities and limitations of video-based methods which may also apply more generically to non-contact methods of measurement.

Convenience of Experimental Setup

Using video-based methods is quite convenient as digital cameras have greatly improved due to the proliferation of cameras in smartphones and digital photography equipment. Those sensors have also enabled a niche market of inexpensive machine vision cameras that are very capable of low noise measurements. On top of that online video sharing platforms (e.g. YouTube) have also made it relatively easy to find source videos to analyze.

Necessary Equipment—For making your own video measurement, the necessary equipment is as simple as a cell phone camera, and a solid mounting surface, typically a tripod. Then, if you want to collect a video anywhere, you just need to move the camera around. This allows for flexibility during large testing campaigns not typically available with traditional contact sensors.

Target Preparation—The article under test may or may not need surface preparation to present a good visual target for measurement. Often, visual texture or contrast on an article under test is sufficient in limited locations, or foreground background edge contrast can be used to extract displacements. However, if the target is somewhat uniform and/or full field measurements are desired, some sort of visual texture will likely need to be applied to the article under test. Speckle patterns popular for DIC are a good option as well as QR-like codes or ArUco markers which both allow for specific marker identification as well as a high contrast pattern.

Full field measurements—If there is sufficient visual texture over the whole image, optical flow measurements can be made over the full field. In this case, every pixel or group of pixels can end up representing a virtual sensor that is placed on the object of interest or on objects in the background. This is valuable for mitigating the effects of platform motion (discussed later).

4. LIMITATIONS

This section will discuss capabilities and limitations of video-based methods which may also apply more generically to non-contact methods of measurement.

Measurement Noise

Measurement noise is an inherent limitation of all sensor measurements. This has been well quantified by [43,44] and effectively comes down to a couple of factors: the amount of light, visual contrast, camera bit depth, and intrinsic camera noise.

Cameras are 2D Measuring 3D Objects

Except for the neural radiance field methods [41,42] mentioned previously, most all methods are operating on the image in the sensor plane of the camera which is a 2D projection of 3D objects in the real world. This means that unless the motion of an object of interest is purely orthogonal to the sensor plane of the camera, the motion will be a projection of the 3D motion. In some cases, this merely results in a cosine term which can be accounted for and corrected if the viewing geometry is known. In other cases, this can be taken advantage of to place a video camera off axis of the motion to be able to project the depth motion of an object onto the 2D image plane of the camera.

Rolling shutter effect

The rolling shutter effect is due to the readout of most camera sensors, where horizontal lines of pixels of the sensor are read out at a time, rather than all pixels being read out at the same time (global shutter). This can potentially introduce a "jello effect" on images, especially of rotating objects like helicopter rotors and airplane propellers. Objects exhibiting large motions can also become skewed due to this effect. Machine vision cameras with global shutters are not subject to this effect.

On occasion, this effect can be used to your advantage to sample an object's motion at a much higher rate than the frame rate of the video by taking advantage of the separate line readout as separate time samples, as demonstrated in [25].

Platform Motion

A general limitation of non-contact methods, is that it can be difficult to distinguish platform or sensor self motion (aka. egomotion) from the actual motion of the article under test. Motion of the measurement camera itself, can either be due to its mounting (e.g. tripod) or the if the structure it is mounted on has its own vibration modes. There are three potential mitigation techniques: mount/platform stiffening or stabilization, egomotion measurement from background video, and external sensor motion measurement.

The simplest way to mitigate platform motion is to stiffen the camera mount or platform such that the dominant resonant frequencies are higher or out of band than that of the article of interest. Good experimental practice will generally take care of this to minimize motion of the camera on its own mount to remove the effects of wind or local vibrations on the camera.

The best option is probably egomotion measurement from the background of the video where there are objects that can also be used to measure motion that can be assumed to be stationary in the world frame. This technique is used in [30,31,32] to recover the true motion of the object of interest and mitigate the effects of the camera's self motion.

Variable and/or Insufficient Lighting

For most optical flow methods, lighting is assumed to be temporally consistent. Time-varying lighting can be misinterpreted as motion, and this can be an issue for lighting that varies at frequencies that are in band with the motions being measured. Strong flicker in lighting due to AC mains voltage frequency can also result in spurious frequency peaks or apparent motion.

Video Compression

Video compression artifacts can show up in either the spatial domain (blocking artifacts) or in the temporal domain (keyframes and inter frame compression). Generally, modern forms of compression retain high quality at reasonable file sizes don't impact the video results too much. However, videos that have been recompressed and reencoded multiple times or those that have been encoded for heavy data saving, will potentially be impacted.

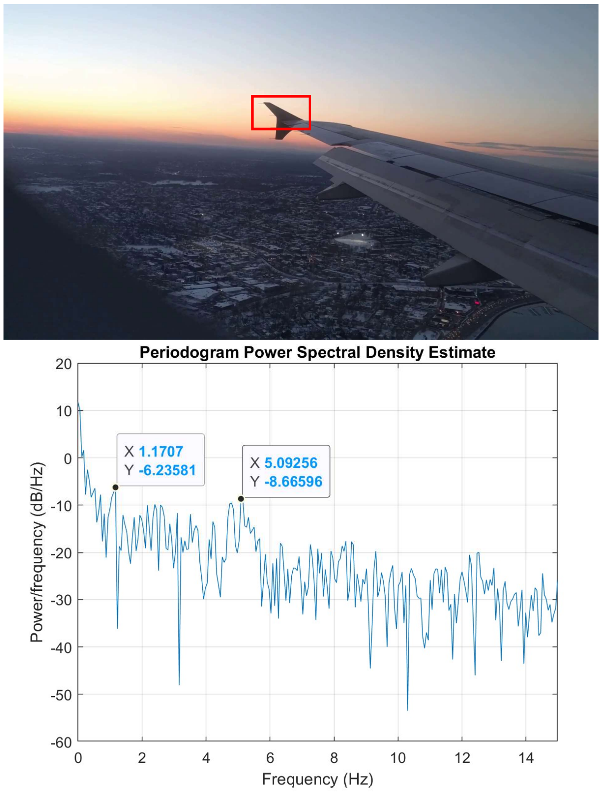


Figure 3. Power spectral density of motion from the region of interest in red from the winglet. The frequency peak at 1.17 Hz represents vibration of the wing while the peak at 5.1 Hz is likely egomotion of the cell phone camera.

5. EXAMPLES

This section presents example measurements taken with a wide variety of cameras (cell phone, consumer, professional), from a selection of aerospace applications.

Airplane Wing from Cell Phone Camera

A measurement was made of an airplane wing from a window seat in an Airbus A320, taking inspiration from [18]. A cellphone camera was used to record video at 30fps during the approach phase of flight. From a crop of the winglets, we are able to extract the likely resonant frequency from one of the wings at 1.17 Hz as shown in Figure 3. At a higher frequency of 5.1 Hz, we see the egomotion of the camera, which is confirmed by visual examination of the motion magnified video (done with video acceleration magnification [23] to handle the large background motion).

Space Shuttle Twang

The rocking motion of the space shuttle known as the "twang" was visualized from a NASA video found on YouTube [45]. This is shown in Figure 4 along with a plot of the horizontal motion of the top of the shuttle stack. Even though the motion can be visually seen upon close examination in the original video, the magnified version makes the "twang" far more obvious.

SLS Testing, IMT and DRT

Some limited results showing spectrograms of displacements from the SLS testing are shown here. Some of these results were previously presented in [33].

IMT—During the integrated modal test (IMT), shakers were attached to the integrated rocket stack to excite it through with both sine wave and random noise. Figure 5 shows the measurement setup we used a consumer Sony camera as well as a screenshot from the measured video. Figure 6 shows spectrograms of the motion while undergoing a sine sweep excitation. Hotspots in the mode shapes of the rocket that can be visualized from the recorded video using motion magnification methods.

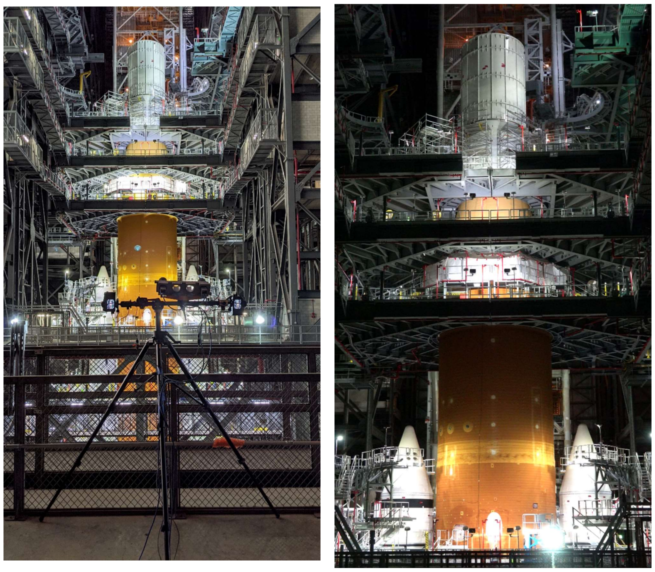
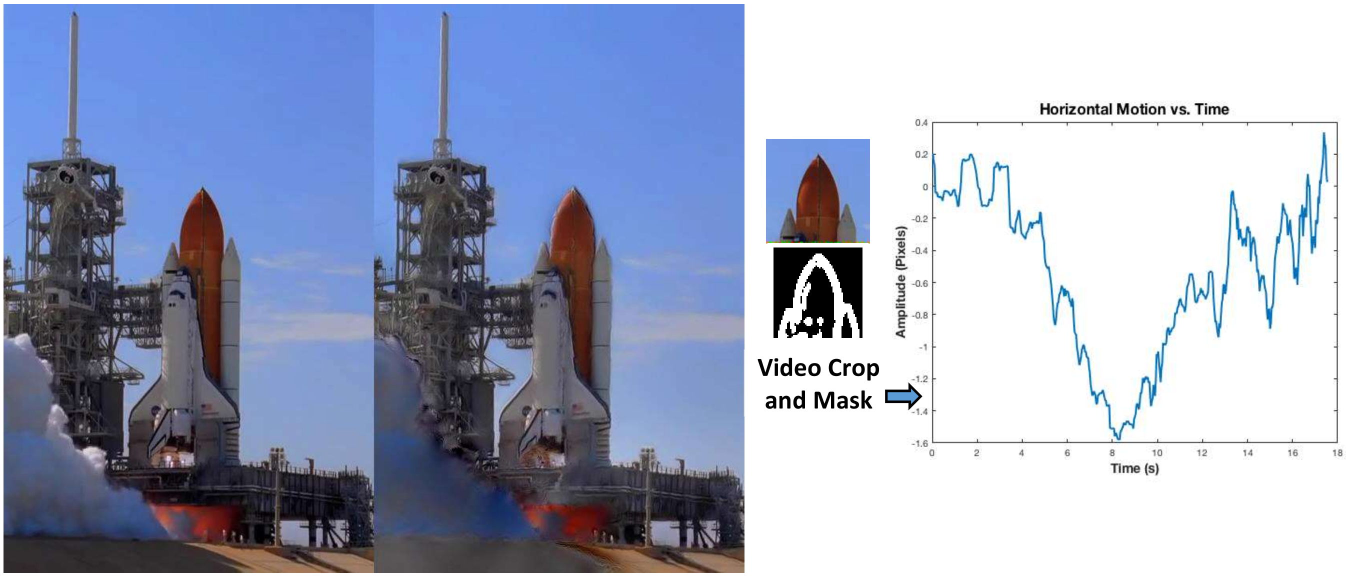


Figure 5. Experimental setup during IMT on the left with a screenshot from an example video as measured by the camera on the right.



Original Video **Magnified Video x20**

Figure 4. Space shuttle "twang" due to the main engines starting before the solid rocket boosters fire. Original and magnified video screenshot shown on the left with displacements extracted on the right. Video footage originally from YouTube courtesy of NASA [45].

DRRT—The dynamic rollout/rollback test (DRRT) was an opportunity to make another set of measurements while the fully stacked rocket was being rolled out to the launch pad for testing while on the mobile launcher (ML). Several different speeds and motions were tested to excite the structure in different ways. Figure 7 shows the experimental setup with a GoPro on the ML deck and a screenshot from the recorded video showing the bottoms of half the core stage and solid rocket booster. Figure 8 shows a spectrogram collected from that video with motion from the core stage showing a couple different speeds of motion as well as a braking test.

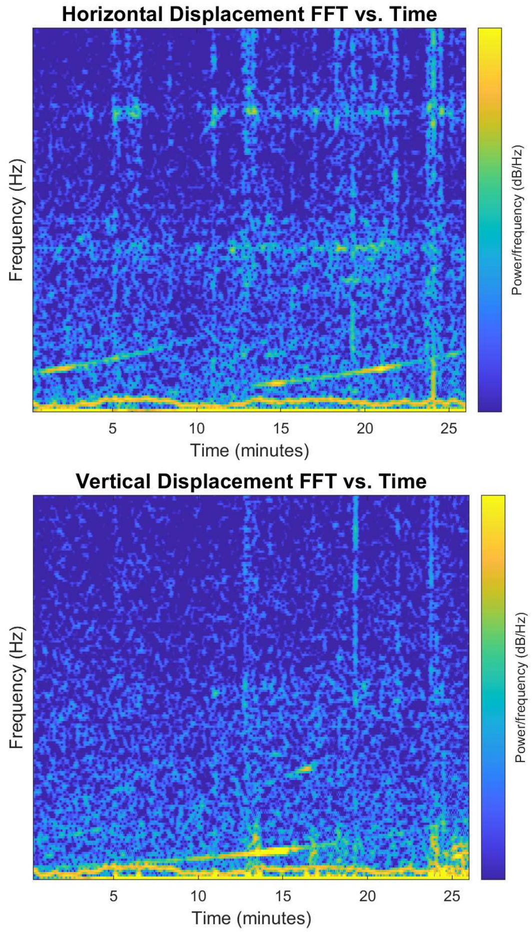


Figure 6. Spectrogram of SLS motion undergoing sine sweep excitation during IMT. Bright spots show where operational mode shapes are likely to be found and visualized with motion magnification.

Figure 7. Experimental setup with a GoPro camera during SLS DRRT on the bottom with a screenshot from the GoPro video on the top.

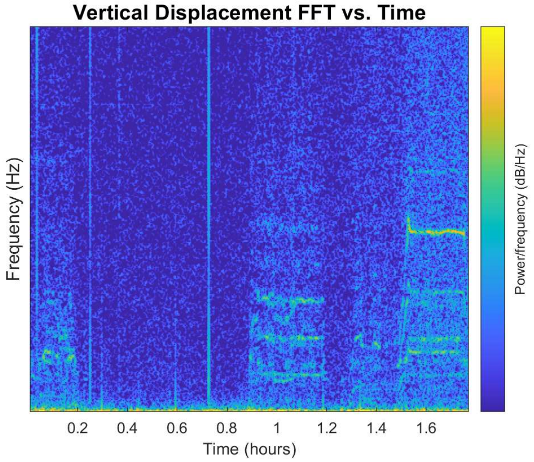


Figure 8. Spectrogram of SLS Core motion during Rollout.

SLS Launch

Many videos were collected by NASA's professional photography team to provide engineering data for post-launch analysis. At least one video showed some motion of the launch abort system (LAS) at the top of the rocket stack, which was a good opportunity to magnify and visualize its motion. The video tracking of the vehicle is extremely good, however there is still some residual motion as well as the bulk motion of the ML being left behind as well as the exhaust

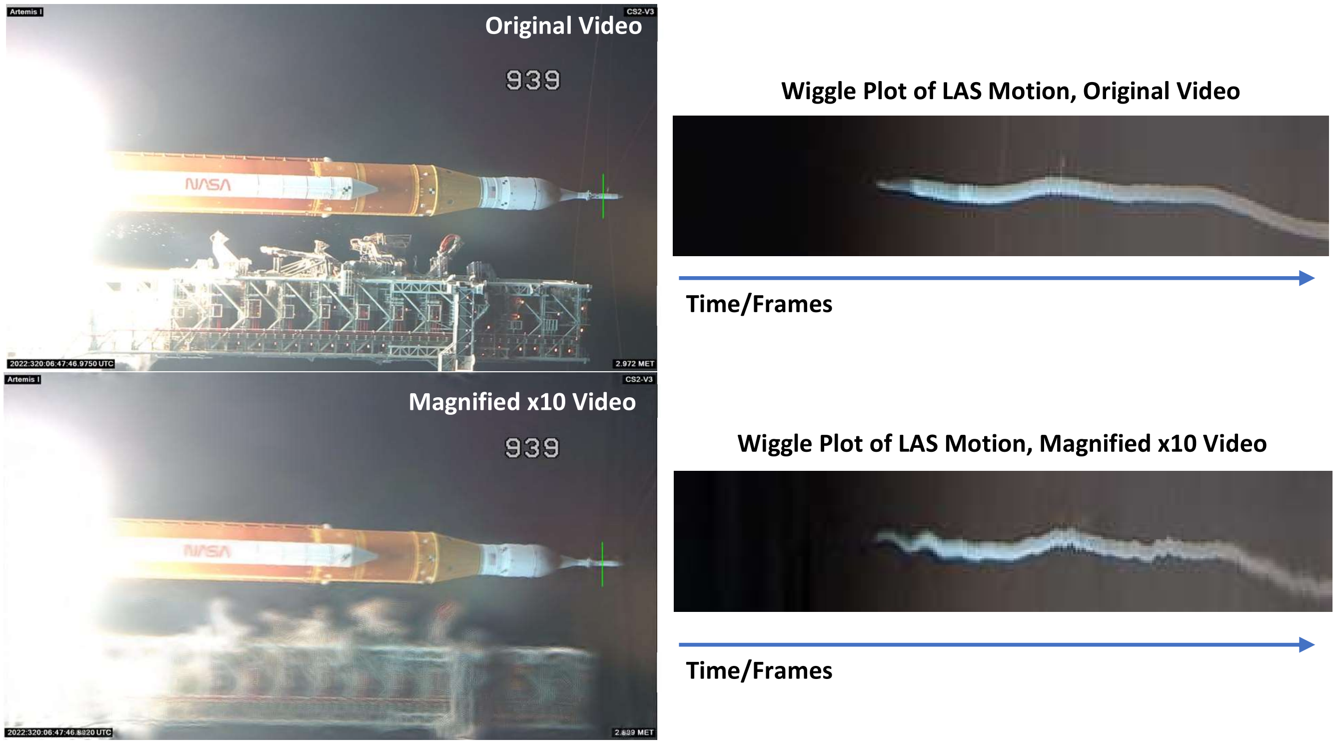


Figure 9. Tracking video of Artemis I Launch from Pad 39B perimeter [46]. The vibration of the LAS can be seen in the magnified wiggle plots, taken from the green slice on the screenshots of the videos on the left. The wiggle plots represent 310 frames or ~5 seconds worth of data.

plume, necessitated the use of video acceleration magnification [23]. Results of the magnified video are shown in Figure 9. Further analysis of these videos and others from IMT and DRRT is ongoing in preparation for future Artemis flights.

6. SUMMARY

Video-based methods for measuring operational resonant frequencies and mode shapes of structures are a very useful tool for practitioners and researchers looking to instrument and characterize structures and test articles outside of typical laboratory conditions.

Future Needs

Currently, video-based methods perform well in controlled experimental conditions as well as "real world" field conditions when displacements are sufficiently large and the camera setup is high quality. In the future, especially for capturing the 3D motion of larger structures, we need methods that can make use of ad-hoc collections of dissimilar cameras that are not being held stationarily. NeRF based methods [41,42] show promise for this capability. This can greatly expand the collection capability of video-based methods to capture operational mode shapes of structures.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

Many thanks are due to our collaborators over the years including everyone from MIT CSAIL and MIT CEE, as well as some outside collaborators from UNH, colleagues from UMass Lowell, Sandia, and anyone else who has adopted and contributed to motion magnification research. We also thank Raul Rios, Katrina Magno at MIT as well as Kevin Franks, Kelsey Buckles, Dan Lazor, JR Booker at NASA MSFC for their support of and contributions to this work.

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