MOTION AMPLIFIED VIDEO APPLICATION TO MACHINERY DIAGNOSIS

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Abstract: Vibration detection can be performed by a meter, or a single channel spectrum analyzer. The former has quantified vibration amplitude levels since the 1950's, while the latter was able to implement the Fast Fourier Transform (FFT) since the 1960's to break vibration down into its frequency components. Multiple channel FFT analyzers enabled the process of Operating Deflection Shape (ODS) determination, which has been an important tool in visualizing the vibration of the machine and its system, including the foundation and piping networks. The input for ODS is the phase-linked signal set from a group of accelerometers, moved over often hundreds of test points. The data is superimposed onto a CAD model, and then scaled-up vibrations are animated at frequencies of interest. This process provides valuable insights, but is time-consuming and therefore expensive each time it is applied by experts, and it is error-prone. An alternative method has been developed that is based on evaluation of high resolution/ high speed videos. The method provides information equivalent to a high-sensor-count ODS, by treating each pixel as an accelerometer, using the pixel's light intensity modulation to translate information embedded in the video into vibration motion able to be observed and interpreted by human investigators. This method is known by some as Motion-Amplified Video (MAV).

Key words: Motion Amplification; video; Operating Deflection Shape; Turbomachinery; diagnostics; health management

1. INTRODUCTION

Turbomachinery, pump, and motor vibration is often useful in determining whether or not a machine is operating properly, and for diagnosis of problems if the operation appears improper, or if reliability issues have been experienced (e.g. fatigue cracking, or premature failure of bearings and seals). For several decades, a visual method called Operating Deflection Shapes (ODS) has been an important tool in getting a complete and simultaneous view of the vibration of the machine and its system (e.g. piping, foundation, and driver or driven machine). The input for ODS is the phase-linked signal spectra from a group of accelerometers, moved over often hundreds of test points while one phase-reference accelerometer is kept at a consistent location and direction. The data is superimposed onto a simplified CAD model of the machine and system, and then the exaggerated (but to-scale) vibrations are animated at frequencies where the response is sufficient to be of interest to the researcher or troubleshooter. This process takes several days for complex machinery and systems, operated at a variety of process points.

An innovative method has been developed that is based on evaluation of high resolution/ high speed video taken of the operating machinery. The method provides information equivalent to a high-sensor-count ODS, by treating each pixel as an accelerometer, using the pixel's light intensity modulation to determine local vibration displacement frequency spectrum. From this information, realistic magnification of slow-motion video footage permits microscopic vibration to be amplified and thereby observed and interpreted by the human investigator. This method may be called Motion-Amplified Video (MAV). This method is much faster than ODS, yet provides similar information at many more locations (at least in directions in the 2-D field of view), with less opportunity for error.

2. BACKGROUND

ODS Methods:

About 1980, some researchers developed the concept of "seeing" vibration. Their approach was to acquire data at many locations and directions on a vibrating structure, and then allocating those motions to a stick-figure CAD model. This model was then animated on a computer video screen, or the extremes of the vibration in the model were plotted by a computer printer or plotter. This technique became known as Operating Deflection Shapes (ODS). The following outline summarizes the technique:

- It is based on the "natural excitation" frequency spectra of the rotating equipment
- The User acquires vibration data from various locations and directions on the machine (hundreds of vibration measurements)
- One sensor is always kept at the same location and direction, to provide a reference signal as other probes are "roved"
- A large database is built up of amplitude vs. frequency and phase angle
- A 3-D CAD model is constructed, and assigned motion from each individual vibration data point
- Some dedicated software is used to amplify the results filtered at specific frequencies of interest, creating animations of the CAD model of the equipment and related piping and foundation.

ODS is a powerful method for perceiving the source and relative importance of vibrations in machines and their foundations and systems. It also often provides visual "hints" concerning options to reduce any excessive vibration. However, in general ODS has its drawbacks as well. The pros and cons of ODS are summarized in the list below:

- ✓ Powerful and intuitive diagnostic tool
  - Can clearly demonstrate modes and frequencies of vibration
- ✓ Proven over decades of application
- ✗ Time consuming
  - Data acquisition – hundreds of data points
  - Post processing – compiling database to match model points
- ✗ Potential for bookkeeping error
  - Match all gathered data points to appropriate place and direction on the model
- ✗ Requires proximity – not appropriate for restricted access
  - Heat, radiation, shock, accessibility/scaffolding requirements

Motion-Amplified Video (MAV) Methods:

This led researchers to wonder whether the troubleshooter could truly see vibration. Academic researchers, some of whom are listed in the References (Ref. 1-3) had this thought about 25 years ago, and have been gradually perfecting techniques. Basically, these techniques fall into two categories: 1) tracking of specific points, edges, or (as machine-vision scientists call them) "blobs", and 2) performing statistics, including signal vs. time as well as signal FFT frequency spectra, on the individual independent pixels. The former are called "Lagrangian Methods" by many researchers, and the latter are called "Eulerian Methods". A rich literature basis exists for these methods. This paper's references emphasize the Eulerian technique.

The motion-amplified video method may be summarized as follows:

- Uses high speed, high resolution video
  - Eulerian method is equivalent of millions of accelerometers, 1 per pixel
- Analyzes/quantifies motion
  - Frequencies
  - Displacement (2-dimensional)
- Algorithms amplify motion to human visual threshold
  - Filterable by desired frequencies, high resolution up to 3.4 kHz in the system developed by the authors
  - Amplifies up to 1000+ times the actual motion, using a statistical algorithm that can perceive and magnify motions down to less than 1% of pixel. At a 10 foot field of view, motions of 50 millionths of an inch, peak-to-peak, can be reliably detected and quantified, based on both controlled laboratory as well as practical field tests.

History:

Figure 1 shows a picture of a galloping horse, taken in 1878. The story behind the photo is that it was one of twelve photos taken by cameras staged along the track, such that a side-shot photo was taken about every quarter of a second. These photos were then imprinted onto paper, and the photos were stacked together in series into a “flip deck” of cards. By flipping the cards, once each quarter second, a nineteenth century “video” was made of the horse running. This video settled a bet between the founder of Stanford University and his friend about whether or not all of a horse’s hooves are off the ground at the same time when it is at full gallop. The answer is “yes”, as is clear from the video of this incident, shown during the MFPT2019 presentation of the present paper. The dynamic situation of the horse’s motion was made fully evident, and looking at it today, it is also clear from the video that if there was a problem with the horse’s gait, that could have been easily diagnosed as well.

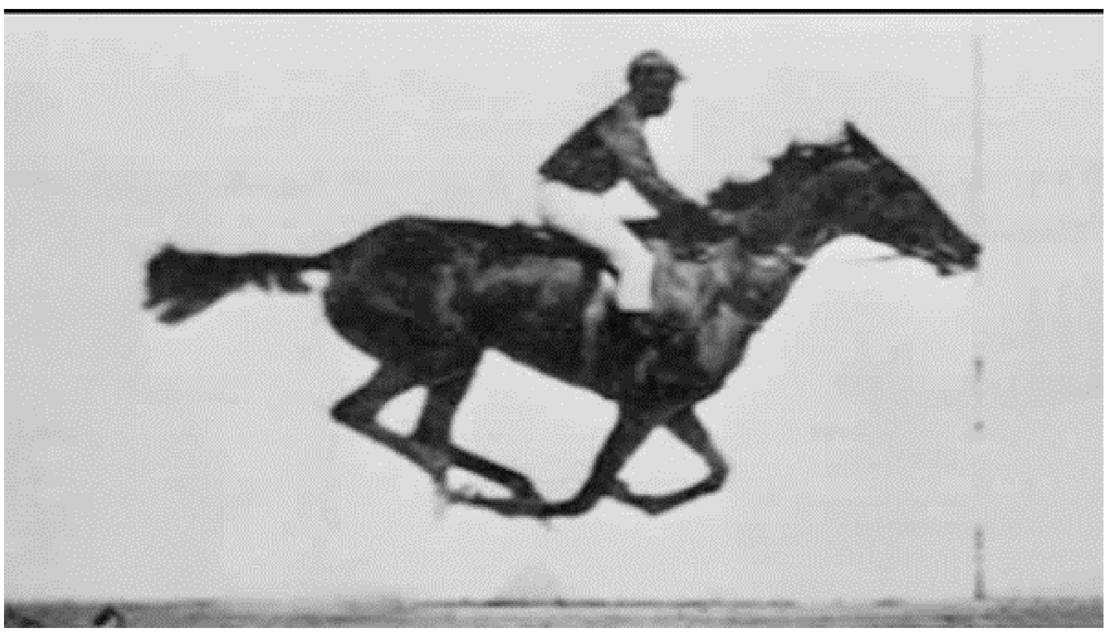

Figure 1: Galloping horse video from 1878

This has led to various researchers, in the US as well as Europe, to attempt to develop such video acquisition and evaluation processes to study other dynamic phenomena.

In fluid dynamics, laser-doppler velocimetry (LDV) has been able to track streamlines, and similar processes have been applied to mechanical vibration. In a lower-tech method, strobe lights have been used on machinery for many decades to “freeze” motion. These method have been useful in interpreting dynamic behavior if relatively large motions are involved. However, displacement magnification was not achieved.

In the 1920's, advanced research organizations used relatively high speed cinematography to guide development and to evaluate the validity of new vibration analysis procedures. A good example is the work of Wilfred Campbell at GE. At the time, steam turbines driving generators were growing larger, and as they did they encountered unexplained fatigue failures. Campbell's work, as exemplified by the photo in Figure 2 (a single frame of a "movie" or video taken by his cameras), determined that bladed disks had much more complicated natural frequencies than had been predicted up to that time, including zero-vibration nodal lines in their mode shapes, now known as nodal diameters and nodal circles. When the associated natural frequencies matched a strong excitation frequency (such as the number of stator nozzles times running speed), and when simultaneously the mode shape of the natural frequency matches the lobes of a circumferential static pressure pattern (such as associated with the number of blades versus number of stator nozzles), a strong resonant response was seen to occur.

Based on this insight, GE and eventually others were able to avoid damaging resonances by either adjusting natural frequencies, or by adjusting problematic lobe patterns of the nozzle pass frequency. The Campbell Diagram, well known to turbomachinery engineers, became a graphical method of codifying this procedure.

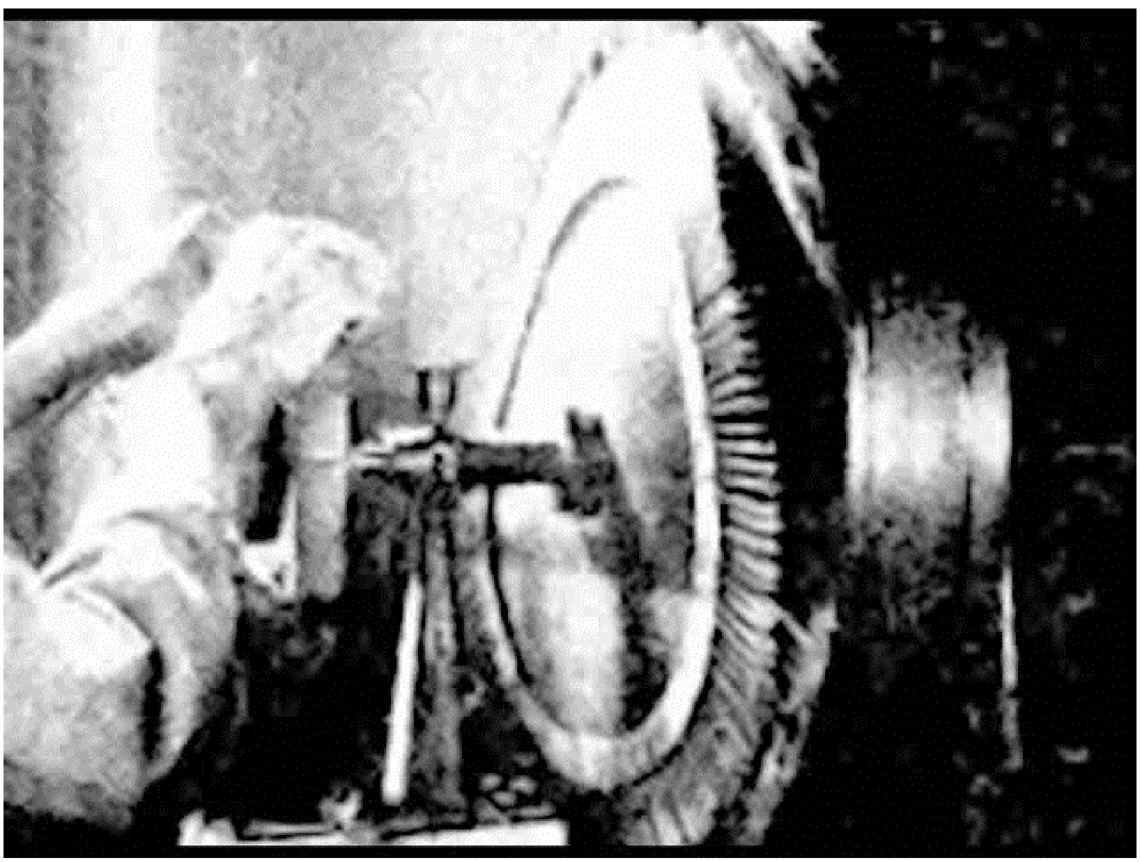

Figure 2: Campbell's bladed disk video from 1926

This range of efforts, and others, led scientists and engineers to an appreciation for the power of video to uncover useful information in dynamic scenes, assuming that appropriate algorithms, implemented by software, were able to be used to evaluate the video footage.

In the US, several universities, including MIT [1], [2], have been actively pursuing MAV. At MIT, the particular technology which became the core of their research was an Eulerian approach [3], which essentially tracks the variation of individual pixels over time, and then exaggerates those differences. To the human eye, no matter how long and hard you stare at a machine with vibration at, say, several times the ISO limits, you would struggle to detect any motion. For a computer, however, the tiniest per-pixel fluctuations (between white and slightly-off-white, say) are easy to detect. MIT originally developed their software to measure the vital signs of neonatal babies without physical contact, but they realized that there are other, far-ranging applications. For biological applications, Eulerian MAV detects changes in skin color, as well as exaggerates movements. The steps and hardware associated with Eulerian MAV are illustrated in Figure 3.

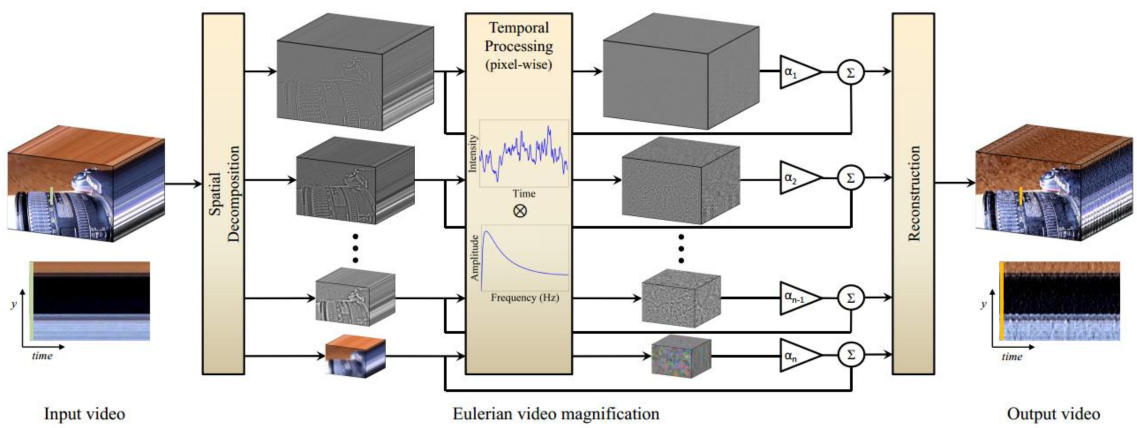

Figure 3: Illustration of the MAV process, as implemented by MIT [3]

Research by the authors:

The authors' organization initiated its detailed research into engineering uses for high speed video in 2003. The US Department of Defense contracted the authors' group to study how to make non-lethal projectiles operate reliably, ensuring that they functioned without harming humans or animals. Applications included various forms of "soft bullets". High speed video, up to 20,000 frames per second, documented their transient behavior during flight and impact.

A later application (2005) involved an inexpensive video sensor to use pattern recognition software to rapidly identify rocket-propelled grenades (RPGs) fired by a belligerent, so that defensive steps could be taken. Following this was use (2011 to present) of high speed video to determine the moment-to-moment effectiveness of passive counter-measures to fool MANPADS missiles fired by “bad guys” to bring down (for example) an airliner, providing feedback facilitating improved countermeasure design. More recently (2015 to present), the authors’ group was contracted to use high speed video and pattern recognition to rapidly characterize lethal ranges of various munition types, so friendly military forces are better able to ensure sufficient buffer zones for civilians, schools, and hospitals.

During this process, the authors began applying Eulerian algorithms to measure and amplify motions of individual pixels [4]. Different procedures were tried during both government and IRAD-funded testing, and after several years a successful method was achieved. Transient motions and vibration levels as low as tenths of a mil (i.e. several microns) of machinery surfaces were demonstrated first in the laboratory, and soon after in on-site machinery troubleshooting.

The authors’ methods are based on the Eulerian approach, which observes the intensity variation of individual pixels, combining their effects statistically into a full scene. Alternative methods typically keep track of motion pixel-to-pixel, the so-called Lagrangian techniques. Variations include feature tracking, and an approach called “optical flow”. These Lagrangian methods are good for amplifying motions that occur over multiple pixels, e.g. motions of more than 2mm (0.080 inches) for a 3 m (10 foot) field-of-view. However, these approaches are limited in how small a displacement they can detect for a given field of view and a given camera resolution, in that interesting vibration levels can be well below such limits, particularly at higher frequencies of vibration. If higher camera resolutions are used to overcome this limitation, the computational overhead becomes excessive. Eulerian methods have been shown to work best for detection of small displacements, since motions as low as 1/1000 of a pixel have been demonstrated. Typically, as shown in Fig. 3, Eulerian methods build a time history for each pixel, and then apply signal processing techniques common to more conventional vibration detection methods, such as digital filters, time and frequency domain digitization (Laplacian and Fourier), and amplification of the subsequent amplitudes by simple multiplication. In some implementations, an FFT is useful to separate motion from individual frequencies and/ or vibration modes, to make vibration sources and/ or mode shapes more evident. Multiple frequency animations can be made from the same ten second video strip.

The benefits of MAV performed in this manner are that it becomes a powerful and intuitive diagnostic tool. It realistically demonstrates modes of vibration, and is easy for non-experts to understand. Importantly for certain applications, the technique does not require contact, so that surfaces at 1000 F, or that are radioactive, or that are 50 feet vertically above near a ceiling, can be observed without difficulty. Furthermore, items such as instrumentation wires or lubrication lines, which would change their behavior if mass-loaded with even a small accelerometer, can be evaluated in realistic manner. The results are obtained quickly, and at modest cost and effort.

Applications and Case Histories:

Several examples will be presented as videos during MFPT2019, and are available embedded in PowerPoint presentation slides from MFPT to those who were in attendance.

Gas turbine in a combined cycle plant:

The photo in Figure 4 is one frame of a 1300 frame per second video taken of a newly installed aeroderivative gas turbine in a co-gen portion of a wastewater facility. The plant was not sure how to measure vibration on such a machine, which had some sections too hot for classical measurement (e.g. accelerometers), and many instrumentation wires, thin tubes, and guide vane linkages that were difficult to instrument, and might have their natural frequencies or spectral response altered by accelerometer attachment. The MAV video quickly determined that, in this complex system, all subcomponents were vibrating in a manner that would be considered normal, and no problematic resonances were evident. Zones near bearings were quickly proved (in ten seconds of video and minutes of post-test processing and evaluation) that the turbine and generator met all ISO 10816 vibration criteria.

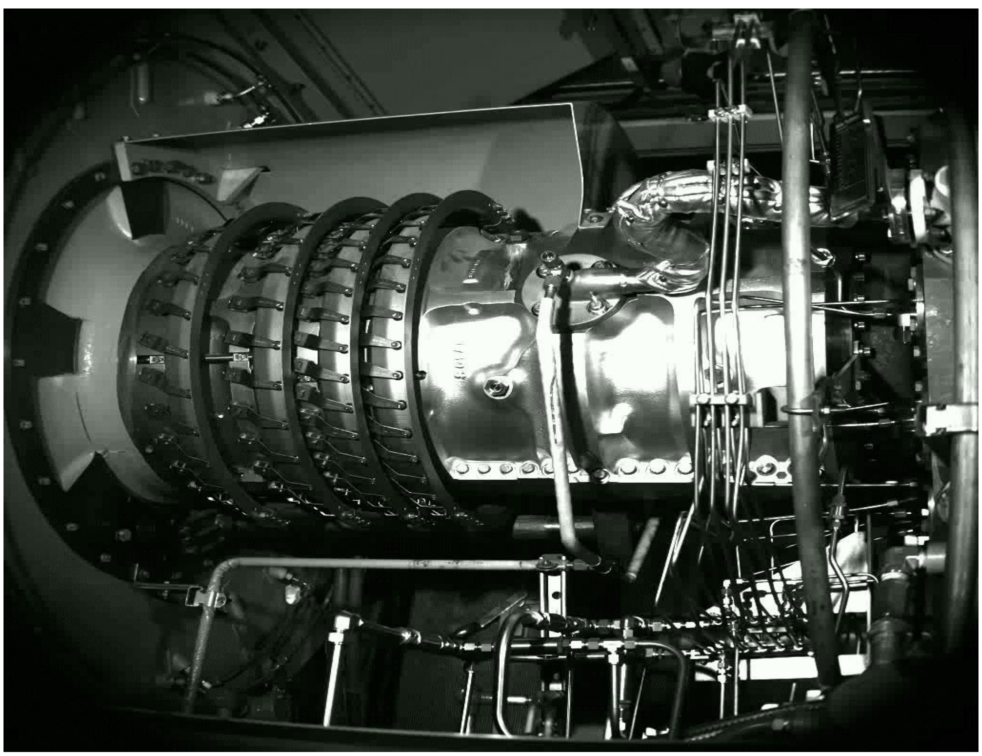

Figure 4: Frame of the MAV process applied to a gas turbine generator

Fatiguing thermowell sensor in a gas pipeline at a refinery:

In many applications involving pipelines and their rotating prime movers, instrumentation is attached in a manner that leads to natural frequencies excitable by higher frequency excitations (such as vane or blade passing frequency) within the variable speed operating range. Although the higher frequency excitations such as vane pass are usually relatively weak compared to running speed excitations, small bore appurtenance pipe connection natural frequencies typically have very high amplification factors (order of 100). When the weak excitation is multiplied by the high amplification factor, high enough amplitudes can occur to cause fatigue. However, fatigue can occur due to other reasons as well, such as residual stresses from rough installation, corrosion fatigue, or (low) stress corrosion cracking. Furthermore, measuring for high vibration and/ or resonance is complicated by accelerometer mass-loading that can dramatically change the vibration, or the possibility that the peak vibration is occurring someplace other than the measurement location.

The latter was true in the thermowell case provided as an example in Figure 5. There was a natural frequency resonance leading to fatigue cracking at the base of the small bore pipe attachment to the pipeline pipe subject to temperature measurement. The plant tried measuring this at the cantilever (where the large mass is) end of the device, and from this measurement had ruled out excessive vibration by relatively strong (in this case) vane pass pressure pulsations. However, strong resonance was actually present, causing vibration high enough to result in steps toward high cycle fatigue whenever the vane pass "tuned in" to a precise resonance. The MAV was able to show the problem was a second cantilever (coat-hook-shaped) mode, where the cantilever end top did not move side-to-side as much as it twisted, causing the "head" to "nod" up-and-down. One view that helped make this point was the end-on view, as shown in Figure 5, in combination with a side view. The primary reason for bore fatigue became immediately evident.

Figure 5: Frame of the MAV process applied to a gas pipeline small bore thermowell

High noise in an industrial fan:

An industrial fan was producing extremely high noise (120 dB) due to blade passing frequency (8 blades, with a frequency of about 480 Hz). Everyone including the OEM was baffled because accelerometer measurements on the fan casing, motor, and piping indicated surface velocities were too low to result in such high acoustic response. The MAV video, taken at a frame rate to permit full-screen video up to 640 Hz, clearly showed that the problem was a strong "pulsing" in-and-out of the upper sidewall, where the pulse direction was opposite on the left side versus the right side. This led to almost no motion along the vertical centerline, hence the source of the OEM's confusion. A frame from the video is shown in Figure 6.

Figure 6: Frame of the MAV process applied to an industrial fan

Vibration of a coil of copper tubing in a gas turbine application:

Strong vibration was observed in a copper coil which was part of the instrumentation system for a gas turbine. Any attachment of an accelerometer to this coil would have dramatically disturbed its vibration. MAV, as shown by the frame in Figure 7, was able to perform a dynamic study of the motion, and based on simple stress-deflection calculations performed from the video evidence, proved that the vibration was harmless.

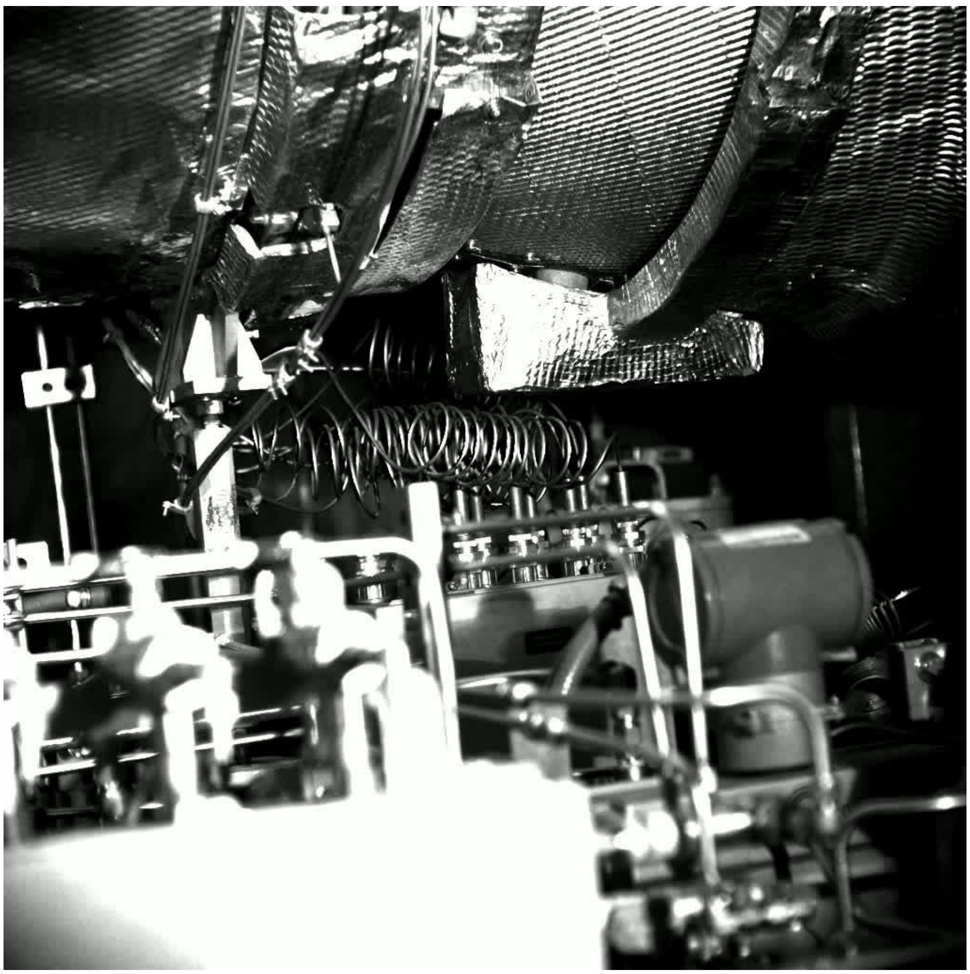

Figure 7: Frame of the MAV process applied to an instrumentation coil of a gas turbine

Vertical turbine pump/ motor coupling imbalance:

MAV based on the Eulerian approach can also successfully document lateral vibration of rotating shafts. The frame from an MAV video shown in Figure 8 shows a vertically oriented coupling, as seen through the discharge head/ motor stand coupling access "window". The video clearly shows that the coupling is whirling, and moving more than the shafting above or below it. The displacement was found to indicate excessive coupling imbalance.

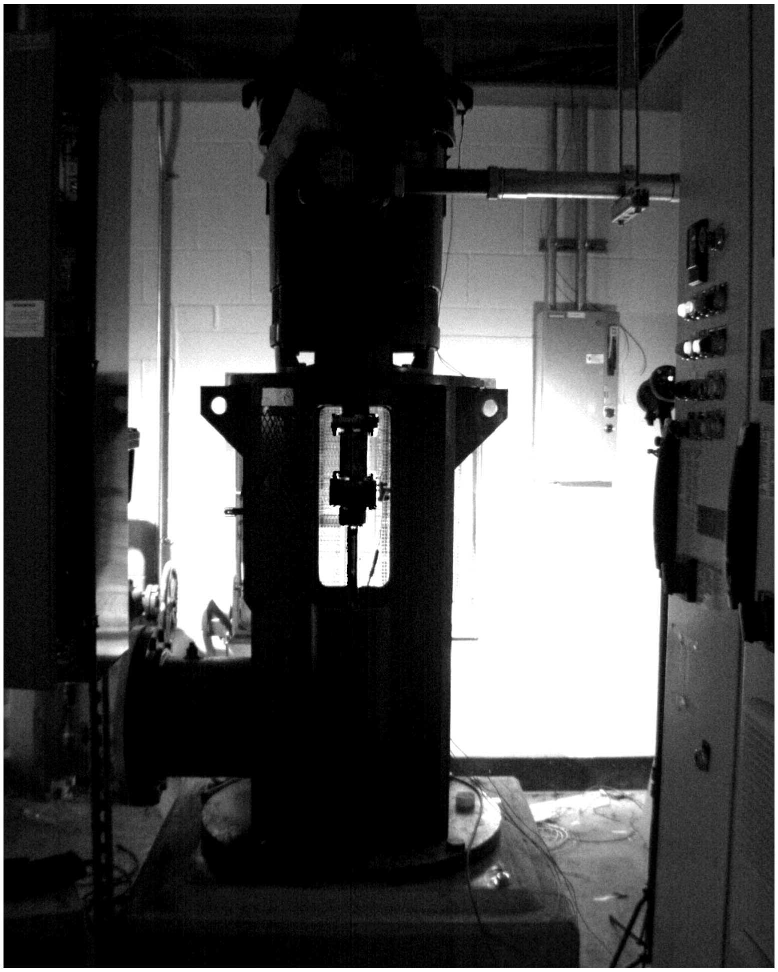

Figure 8: Frame of the MAV process applied to a vertical turbine pump/ motor coupling

MAV of a complex piping network:

The complicated piping network shown in MAV frame of Figure 9 would take days to quantify its motion, and to determine natural frequency mode shapes near important excitation frequencies. Through use of Eulerian-based MAV, both low frequency (e.g. order of several Hz) and high frequency (e.g. hundreds of Hz) character were able to be detected for all pipes, hangers, and attachments in the field of view of the camera. This data was acquired in about 10 seconds, followed by a couple hours of careful video inspection and filtering by frequency. The 1000x motion amplification made it very easy to determine which pipes were not sufficiently supported, and which pipes or hangers might be in jeopardy of eventual failure.

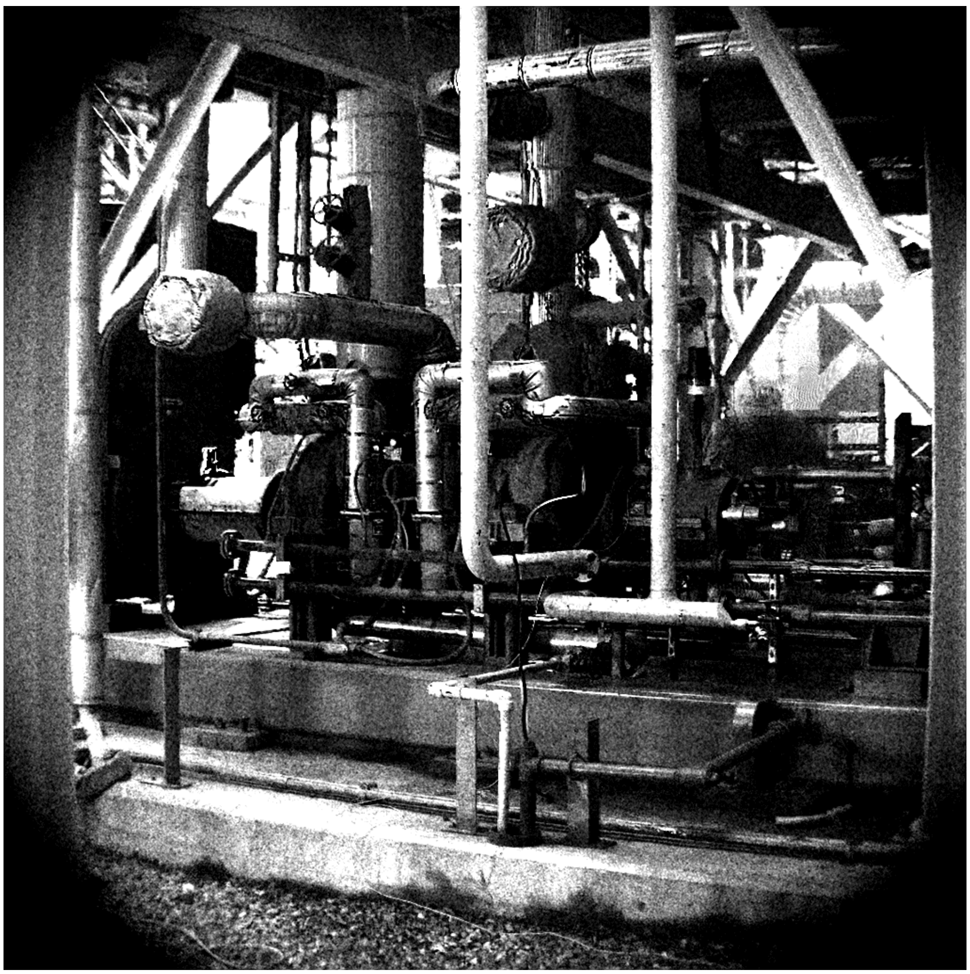

Figure 9: Frame of the MAV process applied to a complex piping network

Steam turbine driver with axial rotor motion at coupling:

A steam turbine driving a feed pump had been experiencing chronic fretting of the teeth of its gear coupling. As clearly shown in the MAV video, a frame from which is shown in Figure 10, the steam turbine rotor was undergoing something called "axial shuttling", with strong axial motion at an acoustic frequency. Once this motion was detected on a "full system" basis, the reason for the coupling problems became clear. Having this knowledge did not by itself solve the problem, but it presented the nature of the problem in a manner that focused further tests on acoustic issues, which in turn allowed identification and removal of the root cause.

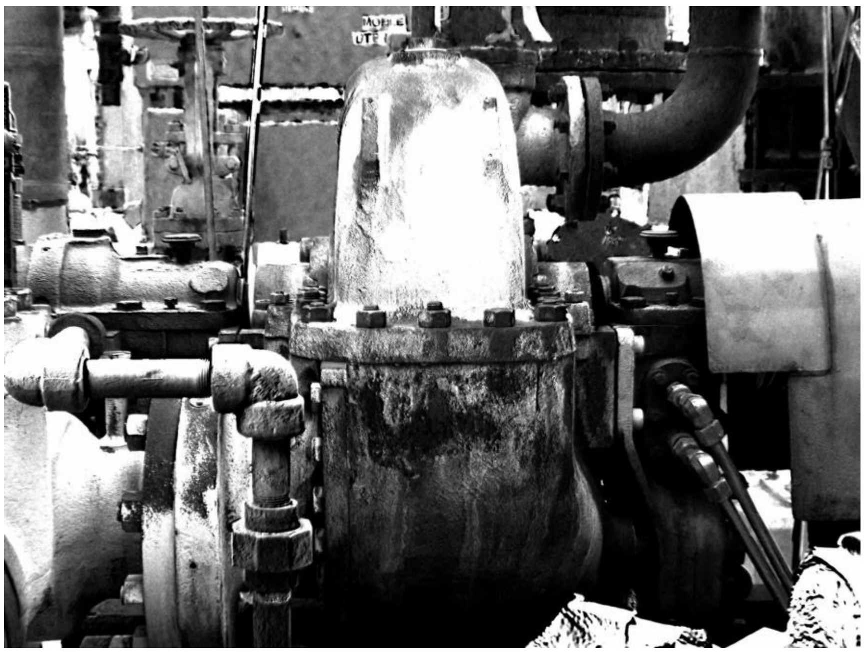

Figure 10: Frame of the MAV process applied to steam turbine "axial shuttling"

Pump/motor offset misalignment:

Figure 11 shows a frame from an MAV video that clearly shows the out-of-phase "bounce" motion of a pump versus its motor, making the offset misalignment present evident. The Eulerian method can be "queried" to determine the frequency spectrum of this out-of-phase motion, which would show in this case a strong 2x component, along with significant axial motion, and the displacement involved. This displacement can be quantified by analyzing the degree of light modulation in high contrast pixel zones, providing the ability to quickly determine machinery that is not aligned in a chemical plants with hundreds, or in some large plants thousands, of installations.

Another issue obvious in the MAV is soft foot under the pump. Eulerian-based MAV typically does an excellent job locating soft foot, since it can measure to 0.050 mils p-p.

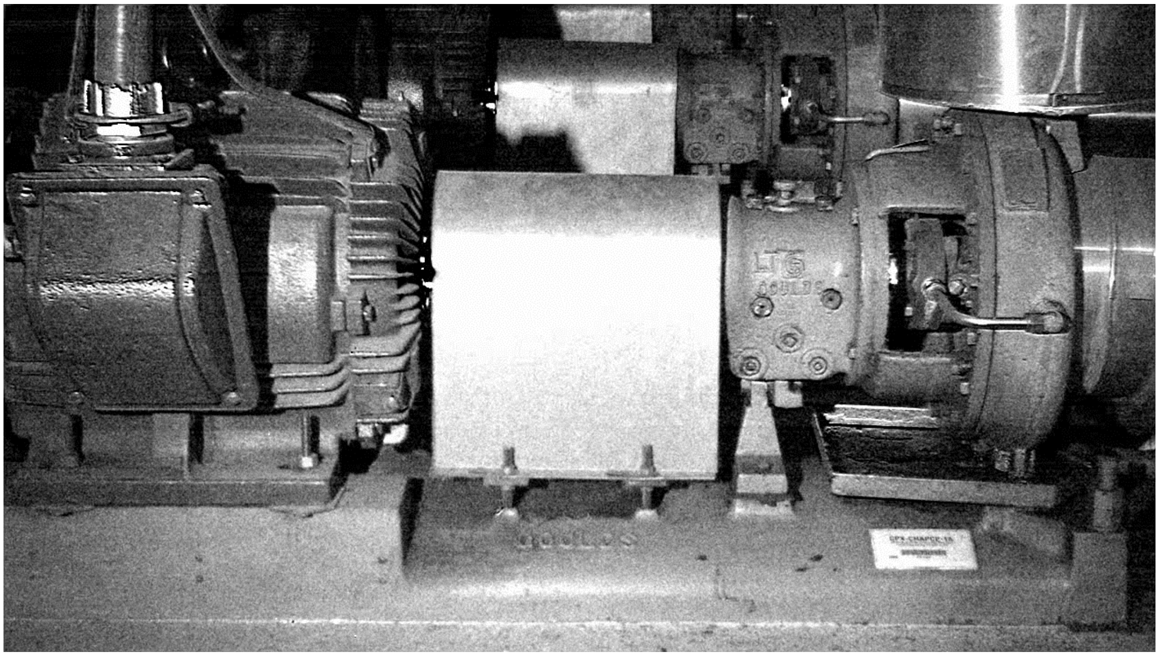

Figure 11: Frame of the MAV process applied to offset misalignment of a pump/ motor

3. Future Research

The following summarizes the research currently underway at the authors' organization:

1. Real-time processing and display
2. Handheld walkabout troubleshooting system
3. Specialty cameras, such as borescope attachment, underwater, and drone-carried
4. Rotating field-of-view
5. Synchronized arrays of cameras

4. Conclusions

As presented, the new video-based motion amplification procedures and equipment now on the market can be very useful for vibration-based diagnosis of machinery. It has advantages over the classic ODS method in many instances, and at least can help limit the amount of ODS required by demonstrating what is moving, and what is not. MAV also typically takes much less time and "logistics" than ODS to implement.

MAV benefits are:

- ✓ It is a powerful and intuitive diagnostic tool

- Realistically demonstrates modes and frequencies of vibration
- Easy for non-experts to understand (management, etc.)
- Comprehensive set of data points

✓ It does not requires "contact" – perfect for restricted areas
- Heat, radiation, accessibility/scaffolding requirements

✓ It is fast
- Millions of data points ready to evaluate in minutes, not days

✓ It is cost-effective
- Helps focus effort for accelerometer-based ODS or strain gages.

Motion-amplified video represents an important addition to a vibration diagnostic tool kit.

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