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A comparison of Operating Deflection Shape and Motion Amplification Video Techniques for Vibration Analysis

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As a Senior Staff Engineer for Engineering Dynamics Incorporated, Mr. Price is responsible for performing analytical and field services in the areas of vibration, pulsations, stress analysis, fluid flow and acoustics. Mr. Price's master's degree research at Purdue University involved identification and removal of noise transmission paths in small reciprocating compressors. During the research, unique signal processing techniques involving multi-dimensional coherence measurements were developed. He has also written or helped to write computer codes for solution of acoustic problems in two and three dimensional cavities using the finite element method, and for other problems associated with dynamic energy propagation in systems.

At EDI, Mr. Price has been the principal investigator for many field studies diagnosing problems in the petrochemical, utility, paper, and other industries. He has also been the major contributor in the design and development of complex data acquisition and long-term monitoring systems that have proven useful at quantifying and identifying intermittent vibration problems.

ABSTRACT

The Operating Deflection Shape (ODS) technique that was derived from Experimental Modal Analysis has served well to assist users in quantifying vibration amplitudes, determining vibration mode shapes, looseness between components, the most effective location and direction to add stiffness, and identifying cracks in beams and foundations. A new technique involving amplified video has now become accepted that promises to do much the same with considerably less effort. However, each technique has its own range of applicability.

Examples from the field using both techniques are provided to help users evaluate the relative strengths and weaknesses of the techniques.

INTRODUCTION

The last decade has seen development of Motion Amplification Video (MAV) as a technique for visualizing and measuring vibration of structures and machinery. An MAV processes a 3-5 second video clip of an object, extracts features that are moving from frame to frame, then amplifies and replaces the motion in each frame. The result is like a microscope for vibration. Deflection that is on a scale of a dozen microns (0.5 mil) can be rendered visible. With care, vibration amplitudes and mode shapes can be determined [1].

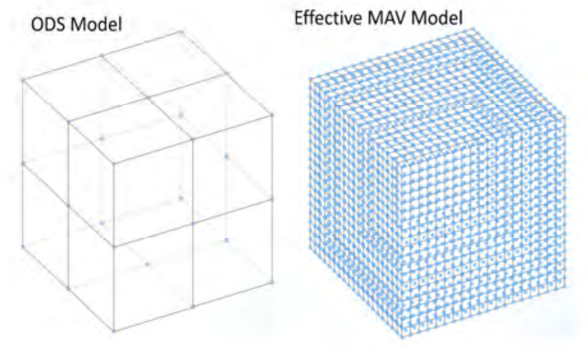

Figure 1: ODS vs MAV Effective Point Density

Similar information can be obtained in a graphic form using Operating Deflection Shape (ODS) techniques. In an ODS, data are obtained point by point with a single accelerometer and phase reference, or all at once with a large set of accelerometers. In either case, the point density is necessarily small – for typical test objects, on the order of 1 location per foot or less. An MAV, however, effectively acquires data for every pixel in the video frame at one go.

In the text that follows, data are acquired from several machines using ODS and MAV for each. The results are presented side by side where possible for comparison.

Operating Deflection Shape

An ODS analysis produces an animated representation of the forced response of a machine and/or structure. Such analyses have been used routinely since the mid-1980s to assist the vibration analyst in identifying problems and developing solutions.

The ODS technique is a subset of Experimental Modal Analysis (EMA) techniques that were developed by Ewins [2] and Brown [3], et.al, from the late 1960's. An EMA uses experimentally derived frequency response functions (FRF) to generate mass, stiffness, and damping properties, from which animations of the natural frequency mode shape can be produced. The modal parameters can also be used to normalize Finite Element Analysis models so that structural modifications can be designed.

While easily implemented for small test objects, it is often impractical to perform an EMA of large machinery and structures. Providing random or swept frequency excitation at levels high enough to overcome background noise becomes prohibitive. In such cases, forced response measurements can be used to generate an ODS. Measured amplitude and phase data are animated directly, without regard to the system modal parameters.

Since ODS techniques have been documented extensively in the literature, its treatment here will be only to present the procedures used by the author to obtain a useful analysis. The ODS procedure involves generation of a geometric representation of the machine or structure, selection of test point locations, acquisition of data, and animation of results.

Model Generation

Typically, an ODS model begins as simple geometric shapes or lines that represent the test object. The extent and complexity of the model is initially chosen based on what the analyst wishes to understand. As data are acquired, the model can become quite complex, depending on the results. Model generation should produce a recognizable geometry but does not need to be photo-realistic. In fact, more understandable results are often obtained by leaving out extraneous details of a model. Several examples of ODS models are included later in this tutorial.

A typical method for model generation is to start with parts of the machine that are known to be vibrating and continue adding components until a boundary is defined or the model represents the entire machine. For example, a reciprocating compressor would include the frame, cross-head guides, distance piece(s), cylinders, and pulsation bottles. It may be useful to include the foundation and grout cap, and perhaps a section of the floor. Piping can be added where it attaches to the pulsation bottles or cylinders when desired. The amount of piping to include depends on what is vibrating. A vertical pump might include just the motor, pump head, mounting plates and the foundation, but it could also warrant measurements of the pump column and bowl.

Model segments should be separated and independent at bolted joints and other attachments so that improperly bolted joints or slippage between components can be readily observed. In the example of the vertical pump, the motor could be a cylinder, the pump head could be another cylinder with discharge piping attached, then separate shapes added for mounting plates and the foundation.

For aesthetic reasons, the model can contain many more node points than would be practical to measure. The desired test point locations are identified on the model geometry based on accessibility and the density of information required. Depending on the software chosen, body rotation or simple interpolation can be defined to animate the unmeasured nodes.

Data Acquisition

For each test point location, a tri-axial accelerometer should be used to obtain vibration data in three dimensional space. Care should be taken to ensure the coordinate axes of the accelerometer referenced to the model geometry. For a phase reference, a once-per-revolution pulse is preferred. A reference accelerometer or pulsation transducer can also be used as long as the data contains energy at the frequencies of interest.

Vibration spectra are then obtained. An FRF measurement is commonly used, but the author prefers a composite spectrum of a Power Spectral Density (amplitude only) and Transfer Function phase. This provides a real amplitude value with the phase reference. Windowing of the data prior to the FFT should be a Flat-Top [4] or similar. This smears amplitude and phase into adjacent frequency bins, which improves amplitude and phase accuracy. To compensate for the bin smearing, a high resolution should be selected. Since the animation represents motion, scaling for the vibration data should almost always be in displacement, not velocity or acceleration.

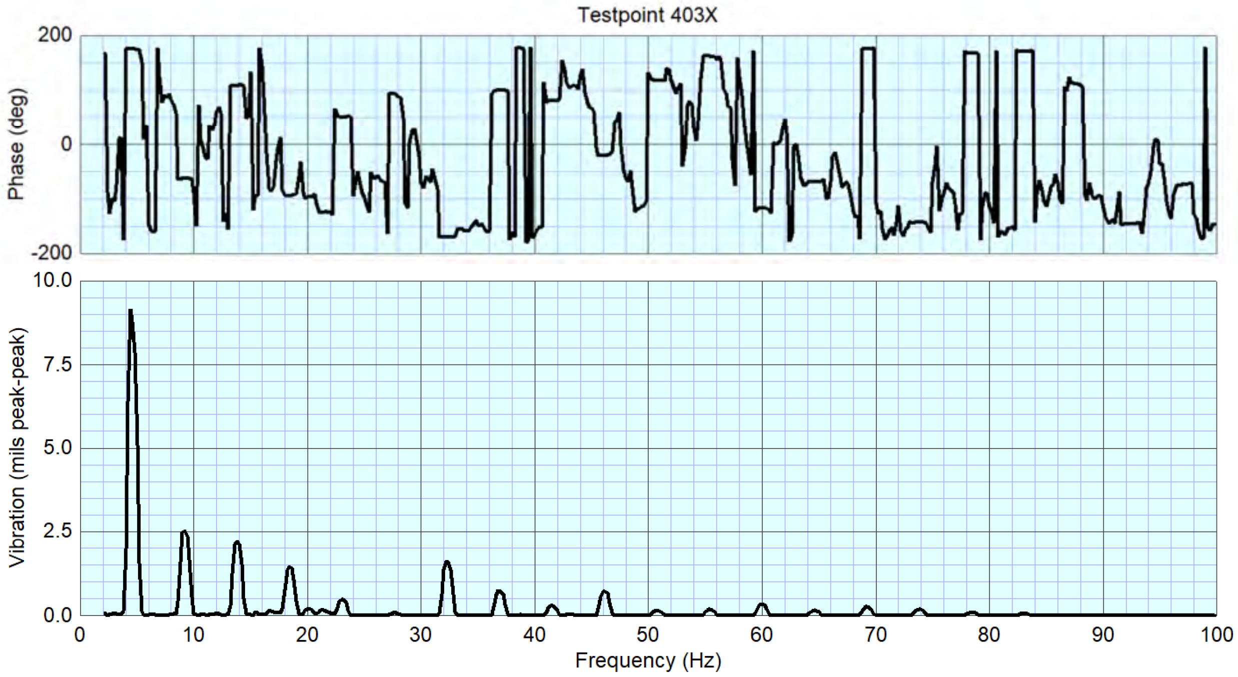

Figure 2: Example of Composite Spectrum for ODS

An example composite spectrum is shown in Figure 2. The real portion of the data from the PSD is shown in the lower plot, while the phase from a transfer function measurement between the moving accelerometer and the reference is above. Note that the phase data are valid (flat regions) only when aligned with a harmonic or other significant amplitude. The relatively wide region over which the phase is flat is a consequence of the use of a flat-top window.

Animation

Animating the data is specific to the particular software chosen for the ODS. Some packages require selection of nodes to interpolate non-measured model nodes, while other software can compute rotation and rigid body behaviors independently. In some cases, it will be necessary to temporarily remove objects from the model when one part obstructs the view to another part. Use of color gradients instead of or in addition to exaggerated motion can also be instructive.

Post-Process

If the data acquisition or ODS software can extract tables of amplitude and phase for different frequencies, it is beneficial to take advantage of that capability. The tables can be stored along with animations for future evaluation and trending.

Motion Amplification (Magnification) – Background

Early investigations providing the underpinnings of Motion Amplification include motion tracking and image generation used in astronomy and computer generated imagery (CGI) for movies and gaming. Extending these methods to the video domain, Motion Magnification technologies were developed at the MIT Computer Science and Artificial Intelligence Lab [5] around 2005. The so-called "Langrangian" approach identifies features that are moving and their trajectories using multiple video frames. Essentially a time-domain approach, the trajectories are extracted from each video frame, scaled up, and added back to the frame sequence. Techniques to manipulate pixels surrounding the trajectories are used to form the complete motion magnification.

Later, "Eulerian" frequency domain methods [6] were developed that involved decomposition of a video sequence into spatial frequency bands (changes over the space in one frame), then applying temporal processing (frame to frame). This technique could be applied either to amplification of motion or exaggeration in the color space. Further enhancement with ever more exotic transforms and/or processing (phase differences of Riesz Pyramids [7] and DVMAG [8]) have been developed. Commercial entities have also developed their own versions of the techniques with good success.

Each method can produce amplified motion video that is useful for understanding structural vibration characteristics. But artifacts such as excessive video pixel noise, edge boundary corruption, and blurring can be present to one degree or another. When motion amplification is applied to complex machinery and piping with diverse lighting, background confusion, camera motion and optical distortions, the resulting artifacts can sometimes be difficult to separate from actual motion.

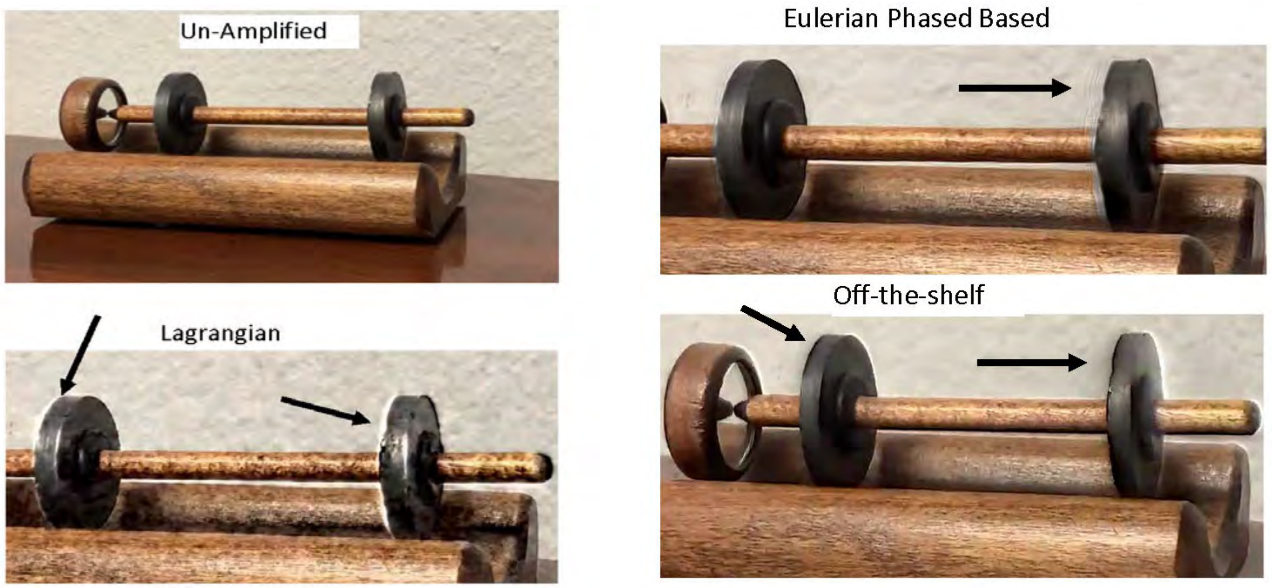

Figure 3: MAV Artifacts

MAV Procedure and Practice

With an ODS, selection of an appropriate accelerometer and data acquisition parameters determines the quality of the analysis. Similarly, an effective MAV depends on obtaining a high-quality video of the test object. Understanding and practicing good photography techniques is of primary importance.

Imaging Basics

A camera records an image by focusing incident light onto an imaging surface. One or more lenses bend the light so that all light rays from objects at “infinity” entering the aperture of the lens converge at the imaging surface. The degree to which the lens can bend light is called the focal length. Longer focal lengths provide a smaller field of view, which results in apparent magnification of the image.

For objects not at infinity, the lens must be moved so that the light rays from that object are focused at the imager. However, not all objects in the field of view are likely to be at the same distance. The range of distance that will be in focus depends on the degree to which incoming light is collimated. This property is known as “Depth of Field”. Using a small aperture will result in a large depth of field. The F Ratio (or *f*-stop) is a measure of the depth of field (Figure 4). Note that while a small aperture (high *f*-stop) will result in a large depth of field, the amount of light entering the lens will be reduced.

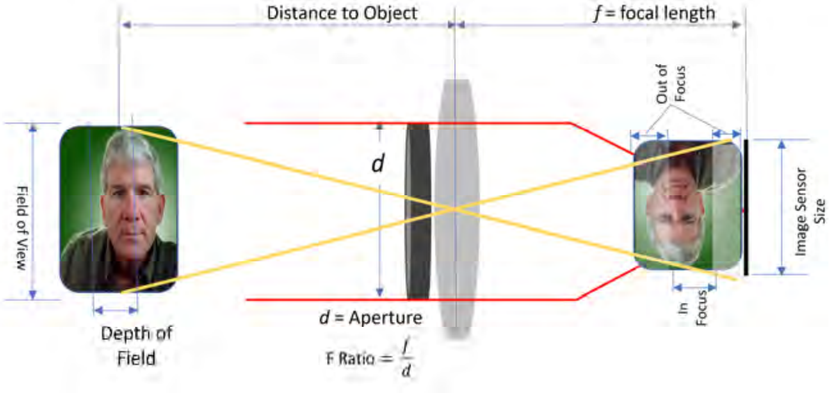

Figure 4: Focal Length, Aperture, Depth of Field, Field of View

Digital Imaging

A digital image is made up of an array of pixels representing an intensity and wavelength of light. Each pixel is measured using a CMOS or CCD sensor to convert photons to voltage. The quantum efficiency (QE) of the sensor and size of the pixel determines number of electrons that are captured to provide a voltage. Gain and offset are applied before passing the signal to an analog-to-digital converter (ADC). The bit depth of the ADC determines the range of values available to represent the actual intensity of the pixel. For example, a 1-bit ADC would provide only 2 possible values – black or white. A 14-bit ADC would allow 16384 possibilities. Higher bit depths result in more dynamic range, which can also be described as increased contrast resolution. Pixels that are at their minimum value are under-saturated (black) and can be said to have lost information since there may be even darker regions that are not represented. Similarly, pixels at their maximum value (over-saturated) might also have lost information available in brighter regions. Under- and over-saturation is analogous to clipping an accelerometer output when vibration is higher than it can represent, or noisy data when vibration is too low to detect with the chosen instrument.

The image resolution depends on the number of pixels in the sensor array. More pixels provide finer detail, which is beneficial for MAV. However, higher resolution often results in smaller pixel size, which reduces the sensitivity and the signal-to-noise of the sensor. Therefore, higher resolution video cameras will sometimes require more light to achieve an acceptable noise-free image.

Getting the Shot

The elements of digital video imaging are combined to obtain a video source from which the MAV is produced. The following aspects are important.

Composition

Standard rules of artistic composition do not apply. In many cases, the composition is completely dictated by limitations of the location. Sight-lines and obstructions can severely limit the available shot. Camera lens selection and the distance to the camera control how closely the field of view matches the object size. Objects in the background should be controlled or placed out-of-frame to avoid extraneous distractions. Since homogeneous regions with little or no texture produce locally ambiguous motion data, it might be necessary to add grid markings to such regions to help distinguish motion.

To maximize displacement resolution of the MAV, the test object should fill the entire frame. The minimum resolution of detectable motion can be computed from the focal length of the lens, the image sensor size and resolution, and the distance to the test object. For example, the FLIR grasshopper camera will allow a MAV displacement resolution of 10 microns (0.4 mils) using a 25 mm lens at 2 meters from the test object. Changing to a 50 mm lens or shortening the distance to 1 meter will improve the minimum resolution to 5 microns (0.2 mils). If the object needs to be far away to capture everything of interest, resolution decreases. For the FLIR example, at 10 meters, the minimum displacement resolution with a 50mm lens is 25 microns (1 mil).

Since an MAV is inherently a 2-dimensional representation of 3-dimensional objects, the motion data is only extracted in the direction perpendicular to the edges. Therefore, the *angle* of the camera to the test object affects the indicated vibration amplitudes. When the camera is at an oblique angle to the object, MAV derived motion amplitudes will be reduced by the sine of the angle to the object. Additionally, the depth of field must be increased to maintain good focus over the entire surface when at an oblique angle.

Focus

When the object of interest is at a far distance from the camera, the focus can be at “infinity”. All portions of the test object can be in focus at the same time. In many cases, however, a long shot will not have sufficient displacement resolution to present relevant information. For tighter shots (closer distance) it becomes more difficult to achieve focus over the entire area of interest.

In that case, the depth of field must be increased by using a higher *f*-stop. The camera focus is first adjusted for the primary or central area of interest, then the aperture is “stopped-down” to achieve focus over the area of interest. Of course, increasing the f-stop reduces the intensity of the light at the imager.

Exposure

Achieving proper lighting is often difficult in industrial situations. In general, lighting should be bright, but “flat” (consistent over the frame). An example of such lighting would be an overcast day at local noon.

If the equipment is outdoors, very high contrast situations can occur where direct sunlight and shadows fall across the frame. This can result in situations where the shadowed areas have zero pixel saturation and bright areas are full of over-saturated pixels. The MAV can be corrupted because of loss of information. Use of shading and supplemental lighting can be necessary to flatten the overall lighting to better match the capabilities of the image sensor.

For indoor equipment, the light level is often insufficient to obtain proper exposure. In these cases, it is necessary to use supplemental lighting. There are many choices of LED panels and spots that have been developed for the video industry. Note that these lights are not typically rated for use in the hazardous environments commonly associated with industrial machinery and structures.

When insufficient light is available, there are other options to increase pixel saturation. Frame rates can be reduced to allow longer exposures per frame. The *f*-stop can be decreased to allow more light to enter the lens. Of course, reducing frame rates decreases the maximum frequency that can be detected and decreasing the *f*-stop will reduce the depth of field. The analyst must decide how to re-frame or otherwise adjust the shot to balance these parameters.

It is also possible to increase the gain of the sensor. However, this can be undesirable since increasing gain also increases noise. Increased noise changes the individual pixel values so that speckles appear in the image, rather than uniform gradation. The MAV algorithms can further intensify the speckles to unacceptable levels. As an analogy, consider increasing gain on an accelerometer signal. Distortions about the mean of the data (noise) will increase along with the desired signal. In the time domain, "painting" occurs, while in the frequency domain, the base will be raised. Data that was in the noise level before increasing gain remains in the noise level.

Camera Stability

A stable camera platform is needed to prevent distortions of the resulting MAV. For an arbitrary video, it is not possible to distinguish between camera shake and object motion. Image stabilization algorithms applied to the video prior to MAV processing interfere with motion magnification. Applying such techniques after motion magnification can help but will not remove all camera motions.

A stable camera platform is not always achievable. Many machines are on elevated platforms that themselves are vibrating. The following can improve camera stability.

- High quality, heavy tripods.
- Low elevations are best – don't raise the tripod to its full height.
- Use isolation pads at the tripod feet.
- Use frequency filters – the MAV can be filtered narrowly. The frequency responses of the tripod should not be similar to the frequencies of interest, if possible.

Platform stability will also affect composition. It may not be possible to obtain the required shot composition and have a stable platform. For instance, a plan-view shot is not usually possible because mounting a camera at the required elevation and orientation presents significant stability challenges.

Video Frame Rate

A video clip consists of several images in sequence at a constant rate. This is called the frame rate and is expressed in frames per second (fps). Typical frame rates for standard video are 30 or 60 fps, but much higher rates are possible.

Since the object of an MAV is to represent vibration, the frame rate must be chosen to represent the highest vibration frequency present. If the frame rate is too low, aliasing can occur. This concept will be examined in some detail in the **Examples** section. Unfortunately for the analyst encountering an unknown machine or structure, the frequency of the highest vibration present may not be known. Consequently, it is good practice to test a few locations with an accelerometer to determine the frequency content of interest prior to selecting a frame rate.

A frame rate of at least twice the highest vibration frequency *present* is required for alias-free representation. To create a smooth animation video, frame rates should be several times faster than the frequency *of interest*. For example, to prevent aliasing of an object that is known to have vibration at 30 Hz, a frame rate of 60 fps or more should be chosen. If the vibration of interest is at 10 Hz, 60 fps will be sufficient for smooth animation. However, if the vibration of interest is 25 Hz, a frame rate of at least 100 fps should be used.

It should also be noted that at higher frame rates, the exposure time available for each frame is less. Consequently, there must be more light available for higher frame rate videos. Higher frame rates also incur significant processing time and data size penalties.

Video Length

A video source clip can be very short (only 2-3 seconds) to be able to visualize motion. Longer video times increase analysis times. Additionally, a longer video sequence increases the possibility that external influences will corrupt the video. However, if frequency analysis of the time-domain amplified motion is desired, video length may need to be increased to obtain a useful frequency resolution. Discrete Fourier Transform (DFT) analysis specifies the following relationships. For a given sample rate, the maximum frequency ($f_{\max}$) is:

$$f_{\max} = \frac{\text{Sample Rate}}{2} \qquad \text{(the Nyquist Frequency, Hz).} \qquad [1]$$

The time between samples (Δt) in seconds is the reciprocal of the Sample Rate:

$$f_{\max} = \frac{1}{2\Delta t} \qquad . \qquad [2]$$

Since a time history is finite for a DFT, define the period of the sampled time history to be T (sec). At the selected Sample Rate, $T = N\Delta t$, where N is the number of points acquired. A real valued DFT produces frequency-domain trace having $\frac{N}{2}$ points. Therefore, the spacing between frequency bins (the frequency resolution, Δf) will be

$$\Delta f = \frac{f_{\max}}{\frac{N}{2}} = \frac{\frac{1}{2\Delta t}}{\frac{N}{2}} = \frac{1}{N\Delta t} = \frac{1}{T} \qquad \text{(Hz)} \qquad , \qquad [3]$$

which indicates that the frequency resolution from a DFT of a sampled time history will be a function of only the length of time of the time history.

Equation [3] also applies to MAV analysis. The frequency resolution of the magnified motion is a function of only the length of the video. Video frame rate does not matter. For example, if the desired frequency resolution of the measurement is 0.1 Hz, a 10 second video length will be required.

MAV Analysis

Once a quality video is obtained, analysis proceeds depending on the capabilities of the software. The most widely used system for MAV allows for filtering to concentrate on specific frequencies and reduce overall noise, generation of plots of vibration amplitude (time or frequency domain), image stabilization, and production of annotated video files. The specifics of various software packages are not within the scope of this tutorial.

EXAMPLES

Several examples of MAV analysis compared with ODS testing are provided from real world installations to highlight when to consider MAV alone, ODS alone, or a combination of both techniques. Links to animation files are embedded, or all files can be accessed with this link. Note that ODS animations must be viewed in Acrobat (not a clone), and the file must be "trusted" to view. The animations can be rotated and zoomed as needs require. Prior to showing these comparisons, a more detailed look at the concept of aliasing is warranted.

Aliasing

Digital data are by definition sampled at intervals. Consequently, frequency information derived from sampled data can be visually and mathematically ambiguous. Energy at a frequency higher than one-half the sampling frequency can "alias" at a lower frequency. For example, if analog data containing energy at 45 Hz and 60 Hz are sampled at 100 points per second, a frequency analysis would produce a peak at 45 Hz and another aliased frequency at 40 Hz. To eliminate this problem, analog data are low-pass filtered *prior to sampling* to remove energy that would cause aliasing[1].

A movie or video is also sampled information and can alias. A familiar example of aliasing in video occurs when imaging rotating wheels or airplane propellers. When the rotation speed is faster than the one half of the frame rate, the wheels or propeller can appear to

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[1] To accommodate the analog filter slope at the cut-off frequency (as well as power of 2 FFTs), analog sample rates are typically set to be (2.56) f_{max}

go backwards or at a different speed than reality. Unlike the situation for analog signals, low-pass filtering techniques for analog images prior to “sampling” into videos have not been developed. It is therefore not currently possible to anti-alias video data. Either the frame rates need to be high enough to avoid aliasing, or the actual frequencies present should be understood so that aliased information can be ignored.

A laboratory test is used to illustrate the aliasing effect (Figure 5). An accelerometer was attached to a variable frequency shaker, and a video camera was positioned directly in front of the arrangement.

The vibration signal from the accelerometer was connected to data acquisition hardware and processed with typical frequency analysis software. A signal generator configured with a distorted sinusoidal waveform was connected to the shaker input and repeated at 34.5 Hz. A spectral plot from the accelerometer data is shown in Figure 6. Vibration at the accelerometer was measured to be 16 mils peak—peak at the fundamental frequency, with lower amplitude harmonics at 69 Hz, 103.5 Hz, and higher frequencies.

Figure 5: Shaker with Accelerometer

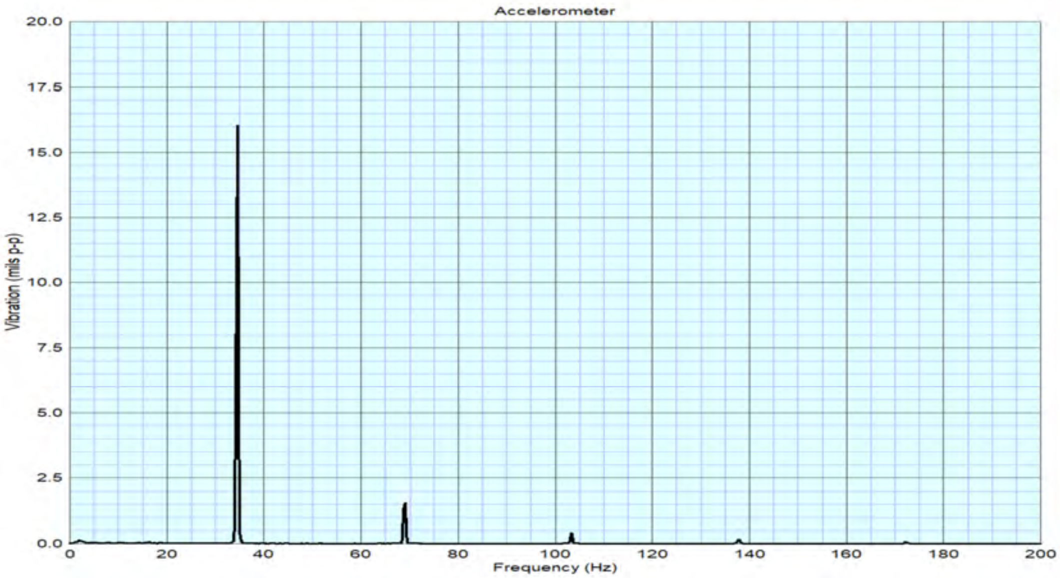


Figure 6: Accelerometer Vibration Data

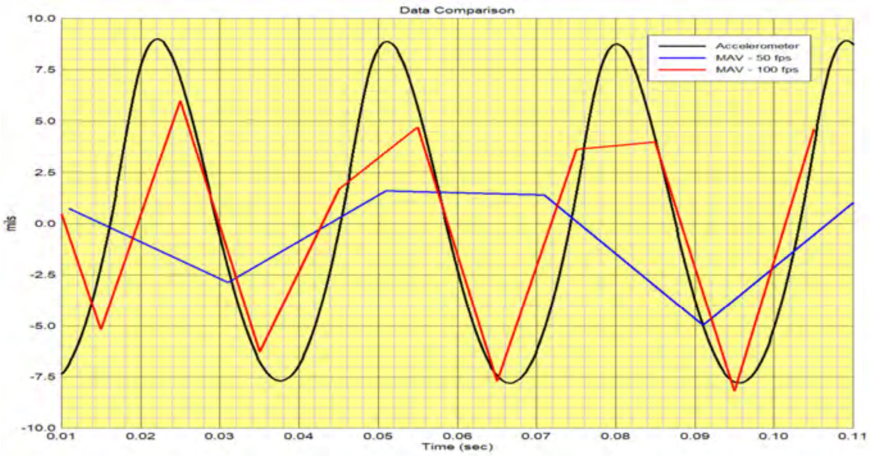


Figure 7: Comparison of Time-domain Data

Two MAVs were created with a frame rate of 50 fps and 100 fps, without changing the shaker input signal. The amplified videos files are at [34 Hz 50 fps] and [34 Hz 100 fps] Although similar in appearance, the MAV appears to be much slower in the 50 fps video versus the 100 fps video.

Time domain signals from the accelerometer signal and the MAVs are shown in Figure 7. The black trace shows the accelerometer signal sampled at 2 kHz. The blue and red traces are MAV derived displacement data obtained at 50 fps and 100 fps, respectively. The blue trace is obviously completely under sampled. The red trace has enough points to get the proper frequency, and over a large number of cycles, the amplitude should be correct as well. However, a video produced with this wave would probably appear to be choppy.

Frequency spectra of the 50 fps and 100 fps data are shown in Figure 8.

A frame rate of 50 fps is insufficient to prevent aliasing of a 34.5 Hz signal since at 50 fps, the highest frequency that can be represented accurately is 25 Hz. The expected alias frequency can be computed by “wrapping” about the Nyquist frequency. A 34.5 Hz signal would be expected to wrap to (25 – (34.5 – 25)) = 15.5 Hz.

The aliased frequency is clear in Figure 8. The 34.5 Hz input signal was aliased to 15.5 Hz. Note that there are other peaks at 19 Hz and 3.5 Hz. These peaks are continued aliasing of the harmonics of the shaker vibration.

19 Hz = 69 – (2*25) – 2nd wrap, positive direction
3.5 Hz = 103.5 – (4*25) – 4th wrap, positive direction

A frame rate of 100 fps produces the correct 34.5 Hz frequency in the MAV derived frequency plot (Figure 8). However, there is also a frequency peak at 31 Hz. This peak is an alias of the 69 Hz energy (50 – (69 – 50)).

These data show that without prior knowledge of the vibration frequencies present, it would be easy to confuse aliased frequency peaks with actual data. Video frame rates must be set at least twice as high as the highest frequency present to prevent fictitious peaks.

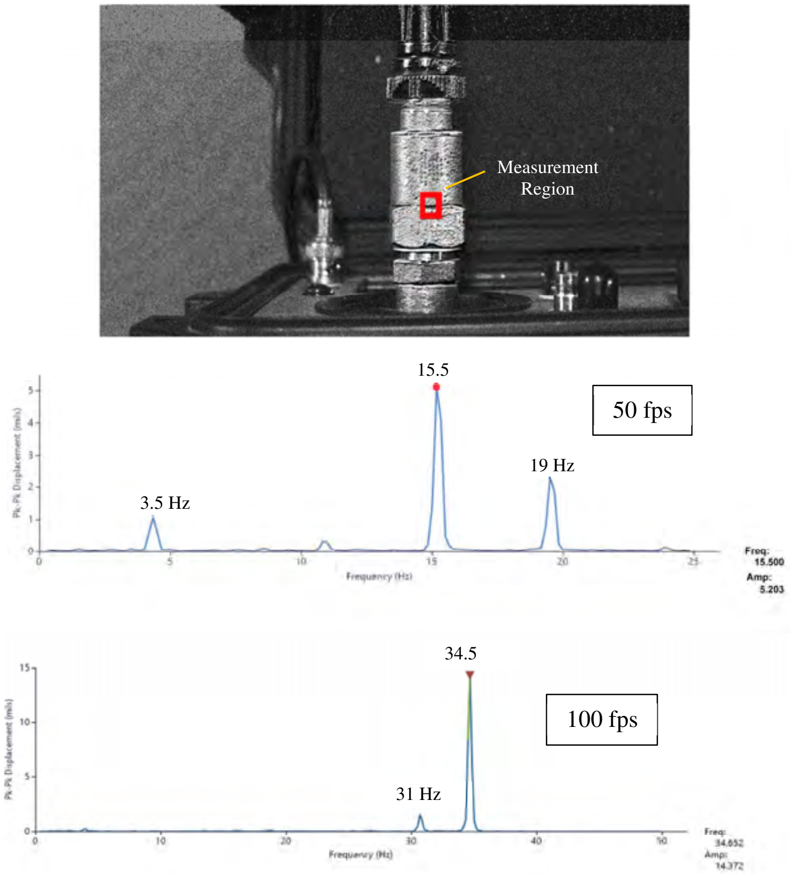


Figure 8: MAV Results at 50 fps and 100 fps

Camera limitations, data size limitations, and data processing requirements can limit frame rates such that it is not possible to avoid aliasing. In this case, the aliased values of the higher frequencies should be understood and computed so that they can be ignored in the MAV spectra or filtered from the final MAV video.

Hyper Compressor

Reciprocating compressors used to feed ethylene into polyethylene reactors are called Hyper Compressors. Typical discharge pressures are approximately 3000 Bar (43,500 PSI). A frequently encountered design utilizes outboard cylinders with tie-rods and pull-rods to accommodate the amount of cylinder stretch that occurs at these extreme pressures. One such machine was experiencing failures of the tie rods. As part of the field investigation, an ODS of the entire machine was made (Figure 9).

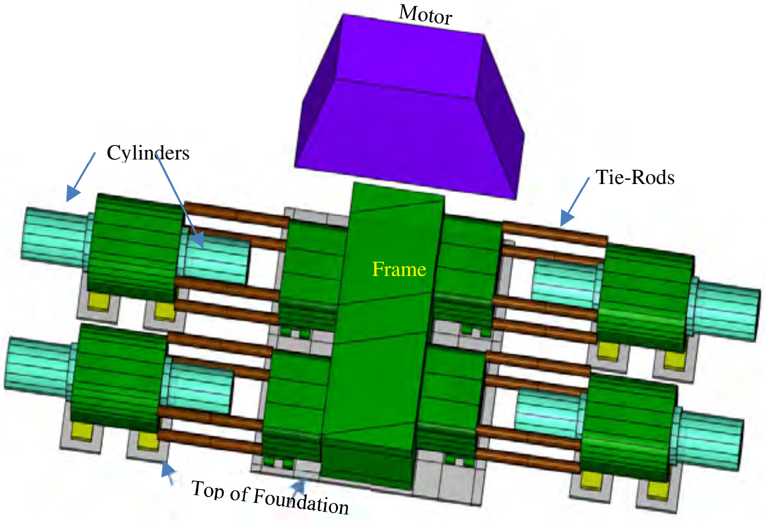


Figure 9: Hyper Compressor ODS Model

A once-per-revolution mark was available at the motor shaft to use a phase reference. Data were acquired using a tri-axial accelerometer at each of the 300+ locations in the model, which resulted in approximately 1000 total measurements. Approximately 5.5 hours were required to obtain a complete set of data. The ODS that resulted was very helpful in identifying deficiencies with bolted joints, foundation, anchor bolts, and tie-bar deflection. The software allowed rotation, zooming, and annotation, as well as trimming of sections of the model to aid in understanding the data. Tabulated vibration amplitude and phase data for each point and direction was also available. The ODS animations were distributed using three-dimensional, rotatable PDF files for each of the running speed orders.

MAVs were also made for this machine. Since it was not possible to obtain a complete view of the compressor due to inadequate sight lines, platform stability, and lighting issues, several MAVs from different angles were obtained. Comparisons of the MAV and ODS animations can be obtained from Hyper Throw 1 and 3 MAV.mp4, Hyper Throw 1 and 3 ODS.pdf, Hyper Throw 2 and 4 MAV.mp4, and Hyper Throw 2 and 4 ODS.pdf. A few static shots are provided as a representation in Figures 10-12. The ODS and MAV for the cross-head guide, tie-rods and cylinders agreed well with each other. However, the complexity of the photographic image presents too much extraneous infromation. In this case, the MAV was not useful at determining vibration amplitudes, because of the large number of camera-to-testpoint distance measurements that would have been required. However, the MAV did elucidate the nature of the tie-rod bending much better than the ODS.

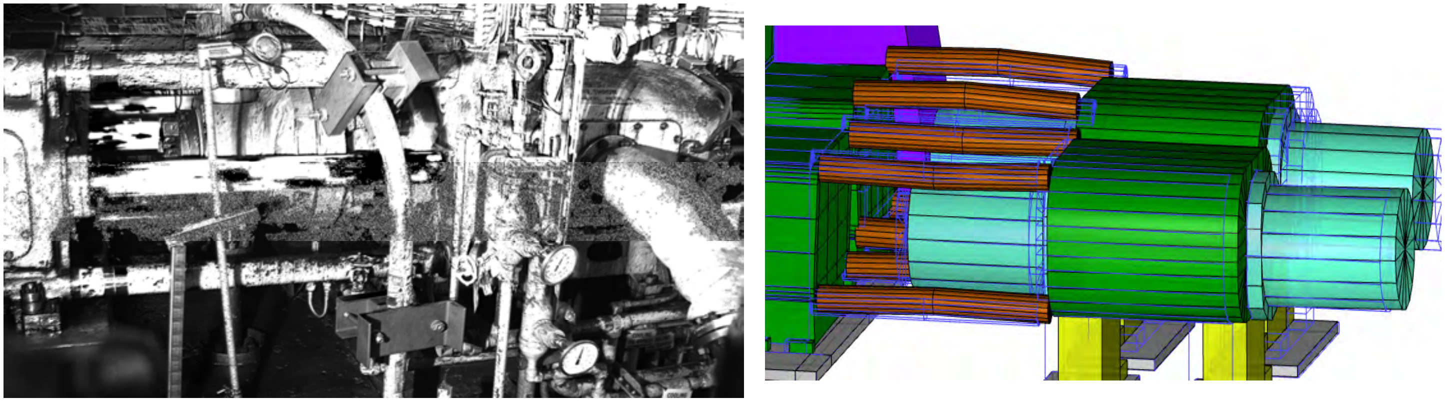


Figure 10: MAV and ODS - Throw 2 and 4 Side

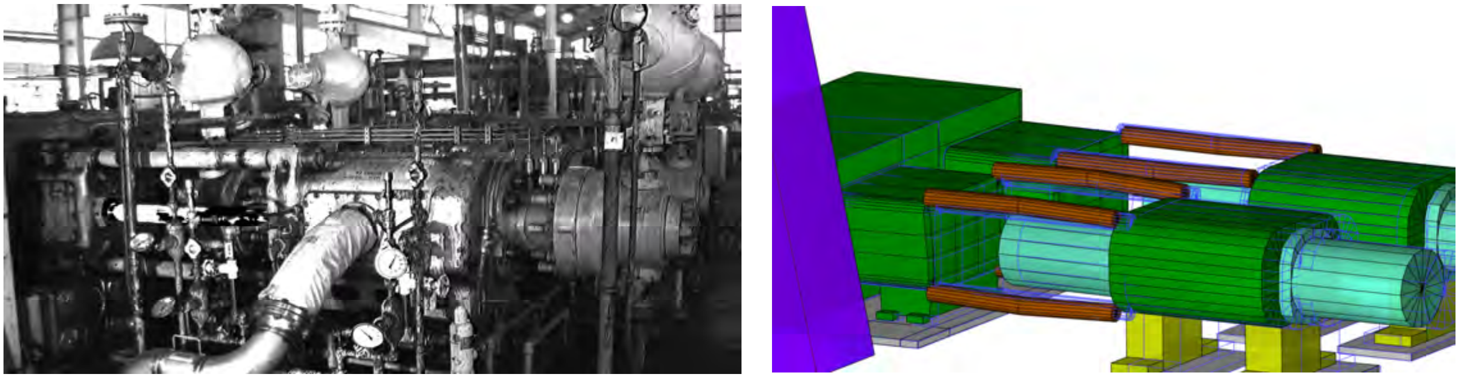


Figure 11; MAV and ODS - Throw 1 and 3 Side

The ODS identified a few cross-head guide to frame connections that appeared to have frame deflection and possibly a dynamic gap across the joint. As shown in the ODS in Figure 12, the blue lines (static position) are well separated from the green surfaces. This behavior can indicate loose bolts or broken internal structure. The MAV, however, did not show such gaps appearing. Instead, the MAV showed that the frame, crosshead guide, and attachment bosses were deflecting and stretching. No loose attachment bolts were observed.

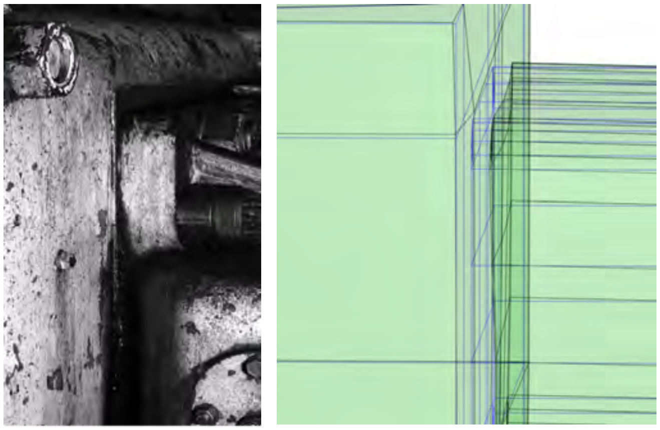


Figure 12: Cross-Head Guide to Frame Connection

Foundation Damage

Concrete foundations for machinery can develop cracks over time. Much of the time, the cracks are superficial with little or no differential motion across the visible crack. ODS studies have been used successfully to help quantify whether a foundation crack should be repaired or ignored. Furthermore, the ODS or a subset of points can be repeated at multi-year intervals to track whether a crack is propagating.

To assess the foundation using ODS techniques, a method of attaching accelerometers to the foundation is required. One such method is to glue a grid of steel washers to the foundation, then use magnetically mounted accelerometers to obtain the vibration data. This is usually a time-consuming and messy proposition. However, if properly applied, the washers will remain for many years, facilitating continued monitoring.

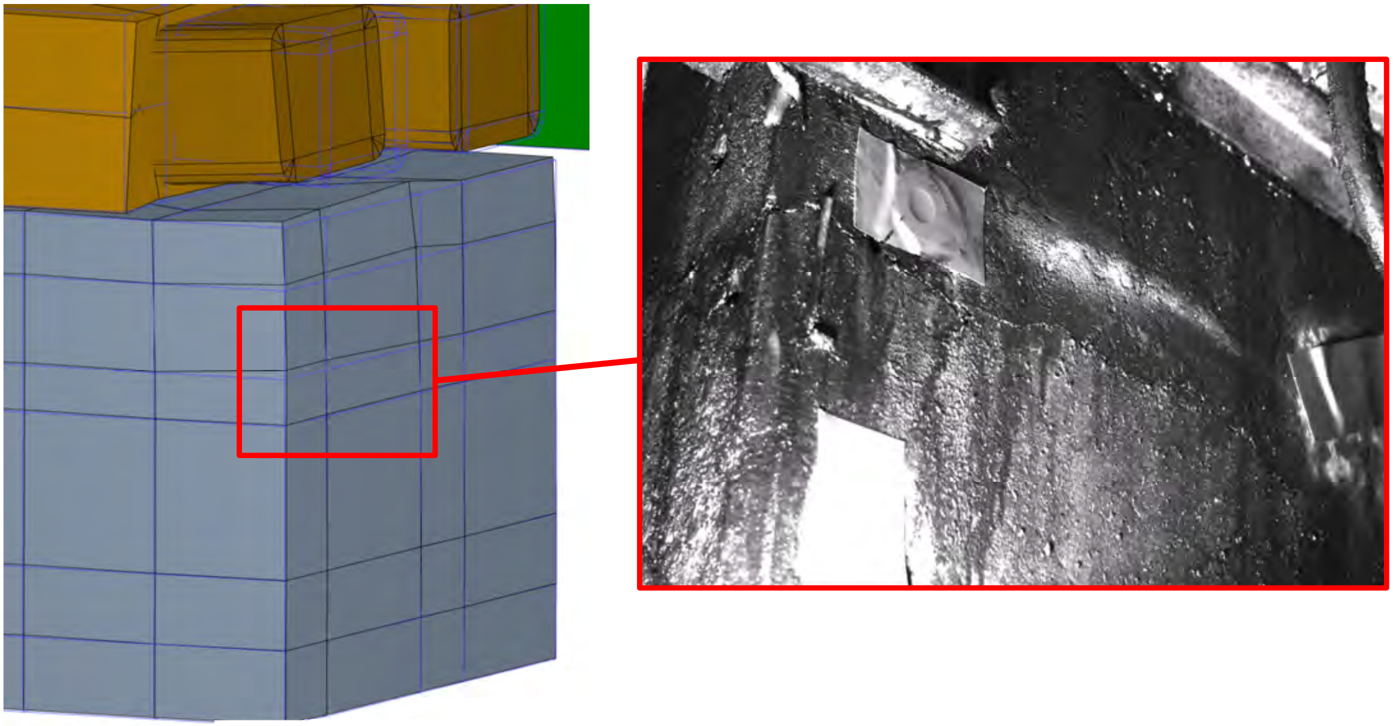


Figure 13: Foundation Integrity ODS and MAV

MAV can also be used to evaluate foundation integrity. The technique is quite adept at enhancing the motion at a crack. Obtaining a usable video is often problematic, however. Sight lines can be obstructed by piping and structures surrounding the foundation. Lighting is also a challenge.

A comparison of ODS animation and MAV are provided in Foundation Crack ODS.pdf and Foundation Crack MAV.mp4. Static representations are shown in Figure 13. The ODS shows differential motion across the foundation between the 3rd and 4th horizontal grid line from the top of the foundation. It is clear from the animation that the vertical foundation deflection causes vibration of the crosshead guide and frame attached to the foundation.

The MAV shown is a closer view of this region of the ODS. Note that it would have been desirable to obtain an MAV of a similar region as the ODS covered, but it was not possible to obtain video through the floor grating. The MAV is, however, quite instructive. The region above the crack clearly separates as a more or less rigid body from the foundation below. This foundation needs repair.

MAVs of many foundation cracks have shown that the technique is almost too effective at enhancing foundation cracks, especially if oil is present in the crack (as it almost always is). A sparkling effect is produced by changes in light as the oil vibrates. Consequently, the vibration amplitudes on either side of the crack should be determined from the MAV data to ascertain whether the differential motion is excessive.

Balanced Opposed Compressor

One type of reciprocating compressor is a balanced-opposed type where all cylinders are at the end of their throw at the same time. This design requires tie-bars to limit frame flexibility across the top of the compressor. If significant frame motion is allowed, the cylinders and piping can experience excessive vibration.

An ODS was done for this type of machine to assess whether the vibration being experienced was due to faults with the frame, foundation, or bolting. Animations are provided in BalOp Compressor ODS.pdf. Furthermore, since a similar ODS had been done 15 years earlier, an assessment of potential degradation could be made.

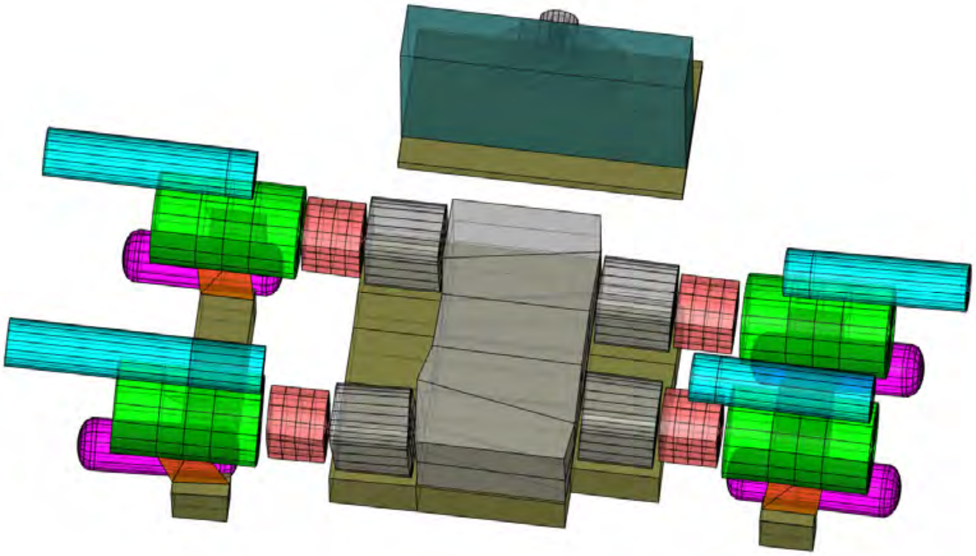


Figure 14: Balanced Opposed Compressor ODS

A static representation of the ODS is shown in Figure 14. The compressor frame is grey, the cylinders are green, the distance pieces are red. Suction and discharge pulsation bottles are cyan and magenta. The static image shows the forced mode shape at running speed when the throws are fully extended. A kink in the frame at the non-drive end appeared to be excessive, as well as the separation between the components of the last throw (bottom left corner). One hypothesis from these data is that an internal tie-bar was loose.

These data were compared to the ODS that had been obtained 15 years earlier. The comparison showed vibration was nearly identical. It was therefore concluded that since the machine had operated successfully in this fashion for over 15 years, the current vibration amplitudes were acceptable. Even so, there was still concern by the owner that joints were separating, or frame damage had occurred. The MAV technique was suggested to evaluate this idea further.

It was not possible to obtain an MAV of the entire machine. Therefore, several MAVs of smaller regions were produced where there were specific concerns. Videos are available in Frame and Joint MAV.mp4 and Frame Defl.mp4. The static representations follow. Camera stability and lighting were a challenge. A narrow time window was available during the day during which bright sunlight and dark shadows were minimized. Even so, shading panels to block the sun and supplemental panel lighting underneath had to be provided to flatten the light acceptably. Mass and damping were added to the camera platform to discourage camera shake.


Figure 15: Frame Deflection and Joint Separation MAV

The MAV showed that the kink represented in the ODS was due to deflection of the frame casing. The two videos clearly show metal deformation. Similarly, the apparent joints between cylinder, distance piece, and frame were not gapping open, but instead were experiencing stretching of the metal on either side of the flanges.

Turbocharger

Two turbochargers for a 13,000 HP engine had repeated failures of multiple components due to excessive vibration. The source of the vibration was pulsation from engine exhaust, but there was no practical way to attenuate the pulsation. An ODS shaker study was performed for each turbocharger along with FEA in an effort to develop effective bracing strategies. MAVs were also obtained with both turbochargers operating. Animations and MAVs are available from the following links: Turbo ODS.pdf, Turbo Left MAV.mp4, and Turbo Right MAV.mp4. Static representations are shown in Figure 16. While the MAVs are interesting, there is not a lot of usable information presented. Camera stability was compromised in one video beyond all possibility of after-the-fact stabilization. The other MAV shows the overall motion of the turbocharger and the waste-gate piping, but a sight line to the turbine side piping was unavailable. So many things are moving in the MAV (conduit, instrument tubing, etc.), the result is more confusing than helpful. The ODS on the other hand provided very clear information. Additionally, since the ODS data was created from speed sweeps of a shaker, a full set of modal properties could be estimated that was valuable in developing the FEA solutions. The MAV techniques cannot yet process such data.

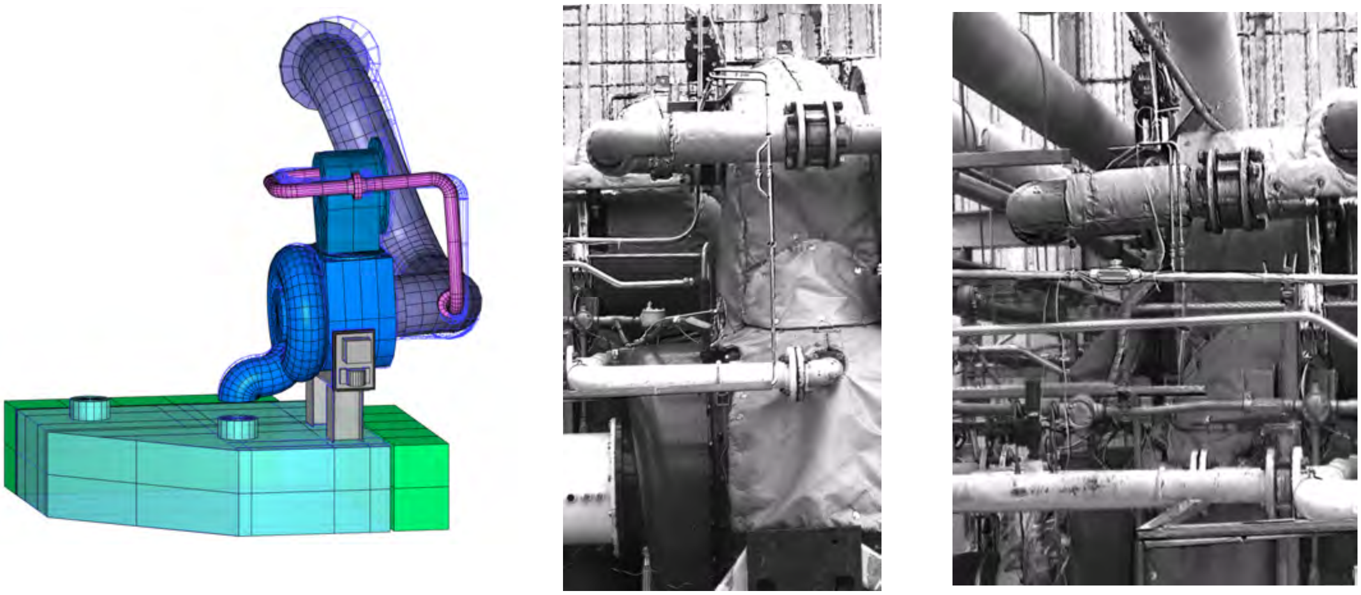


Figure 16: Turbocharger ODS and MAV

Piping Vibration

A large reciprocating compressor had experienced numerous failures of piping. An MAV of one side of the entire machine and piping was done to visualize overall piping vibration. Available sight lines required camera placement to be on elevated floor grating. Consequently, there was no stable platform available to obtain the video. Efforts at image stabilization after the MAV process was performed were ineffectual, despite the fact that several different stabilization software packages were used. The "stabilized" video is shown in Unstable Platform.mp4.

Clearly, this MAV representation was of no value. Additionally, the range of distances represented in the photo would have made it impractical to obtain accurate piping vibration data. For this case, the ODS was the preferred technique for visualization and quantification of vibration.

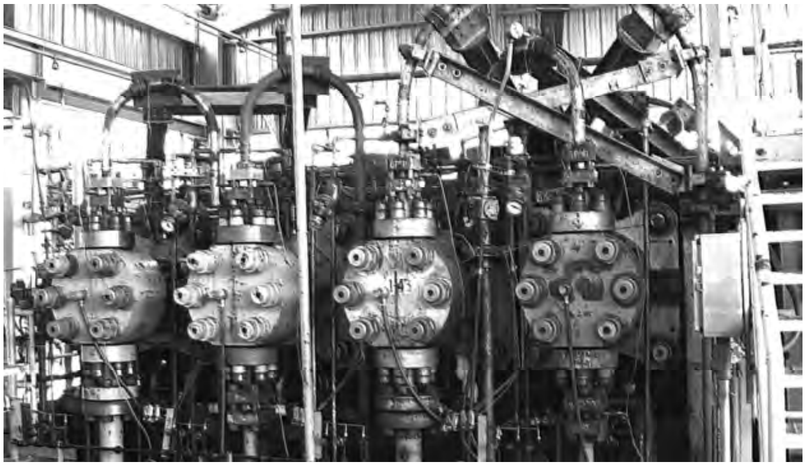


Figure 17: MAV of Side of Compressor

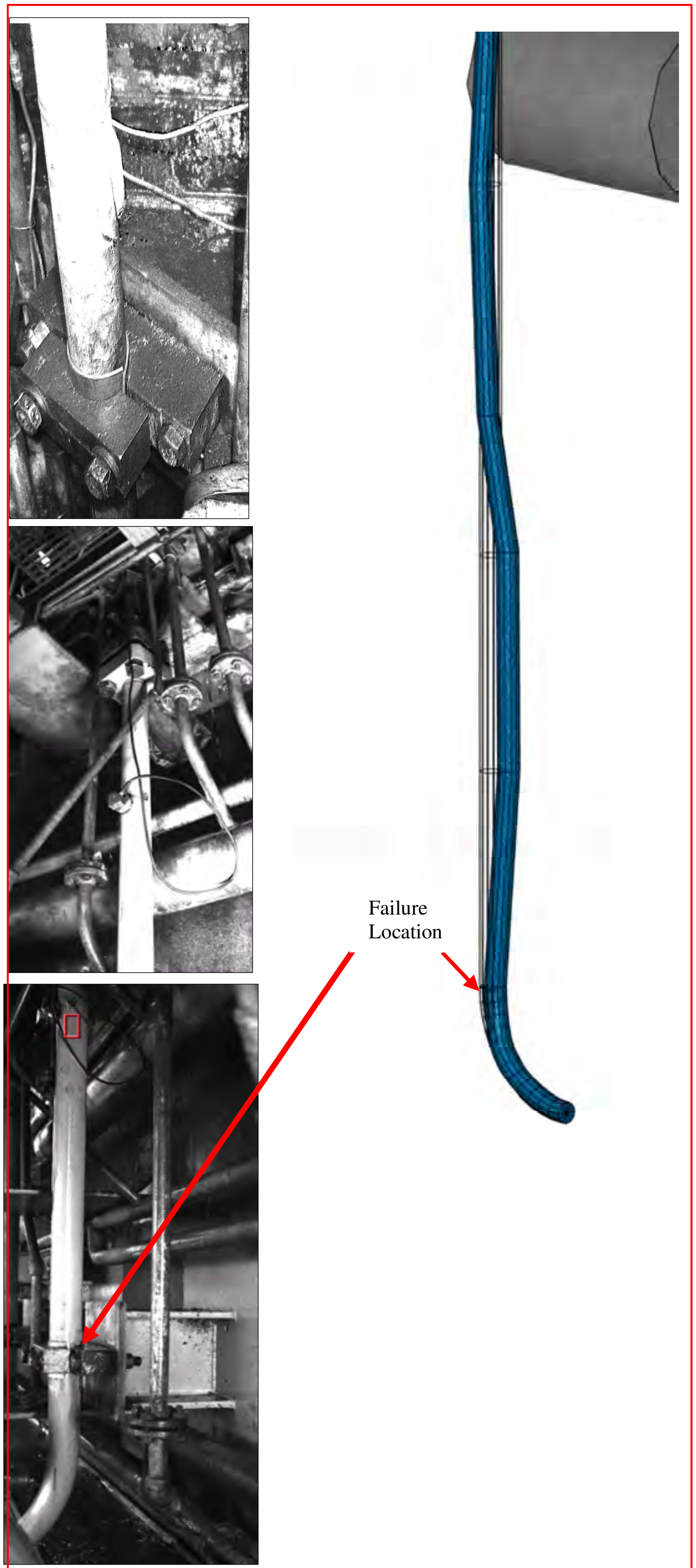


Figure 18: ODS and MAV of Cylinder Discharge Piping

An ODS model was made that included the frame, cylinders and piping local to the machine. A part of the ODS for one cylinder and discharge piping is shown at the right of Figure 18. Deflection between clamps is obvious. Combined with the measured vibration amplitudes, it was apparent why that failure had occurred. An additional clamp for this span was required to de-tune the span natural frequency from pulsation excitation frequency.

To replicate the ODS data for this span, a total of four MAVs (three of which are shown in Figure 18) were required to represent the piping. The pipe span was both above and below grating level, and numerous other obstructions prevented optimal sight lines. Videos for these are presented in 1.mp4, 2.mp4, 3.mp4, and ods.pdf.

The MAV results were much more intuitive than the ODS. The very fine detail available revealed loose clamp bolts but attachment plates to concrete were not moving. Excessive deflections of supports and clamps intended to restrain dynamic response were also observable.

In this case, obtaining the MAVs required more time than creation of the ODS due to lack of suitable sight lines with stable camera platforms, and problems configuring appropriate lighting. The enhanced understanding provided by MAV was deemed worth the additional time, however.

Transient Analysis

Some vibration issues are not related to repetitive cyclical forces but are instead caused by transient phenomena such as water-hammer or slug flow. The ODS animation capabilities can be used to help understand how structures respond to such forces. As with traditional ODS analysis, a geometrical representation of the structure is created with the ODS software. Time-domain data are then used at every point on the model to provide animation. Obviously, this technique can require many channels to be obtained simultaneously. MAV can also be used, but without the high channel count and setup time of the ODS.

A fin-fan cooler structure at a compressor station was experiencing high vibration when one compressor was shut down and another was started. This action generated a pressure pulse that traveled through the piping and to the cooler, causing a transient force. To quantify the vibration characteristics, a time-domain ODS and a pre-triggered MAV were obtained.

The ODS geometry is shown in Figure 19. A total of 22 triaxial accelerometers were used to define various points in the geometry. Data were recorded during the transient event and processed to remove high-frequency components. The resulting animation can be viewed here Time-Domain ODS.

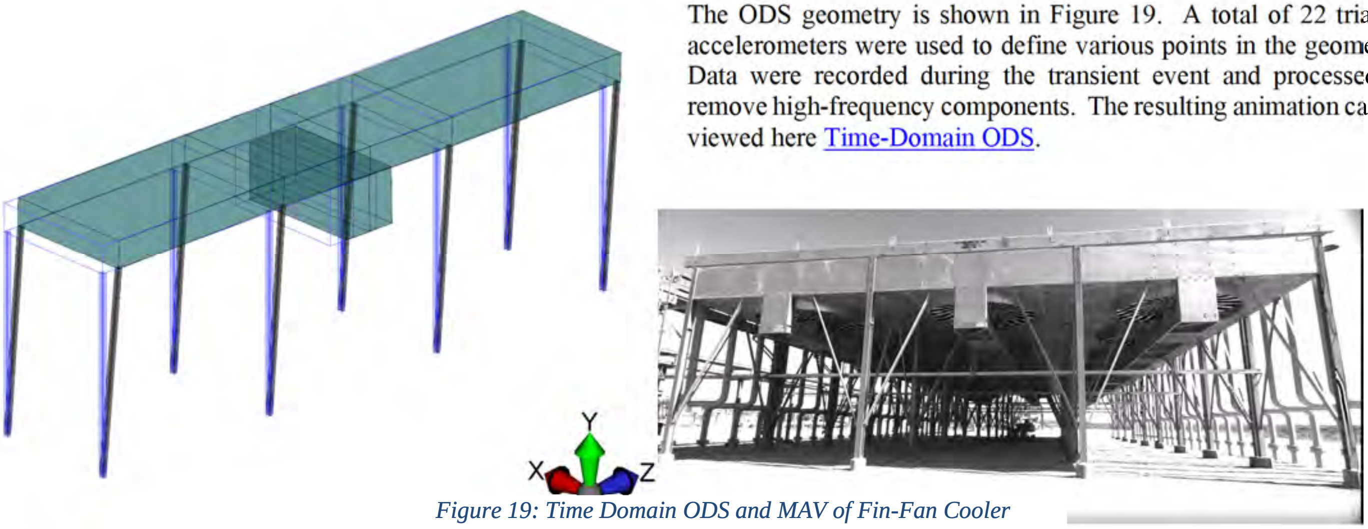


Figure 19: Time Domain ODS and MAV of Fin-Fan Cooler

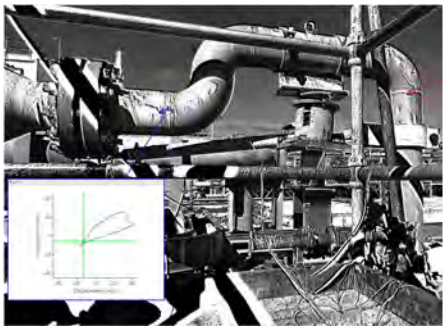
The MAV camera was arranged at the end of the cooler structure. The video sequence was configured to acquire 3 seconds of “pre-trigger” data. When the shutdown event was initiated, the camera was triggered. This allowed the beginning of the transient event to be captured, without needing to know the exact time that the event would occur. The resulting MAV can be viewed with this file.

Thermal Analysis

ODS and MAV can also be utilized to evaluate thermal growth. Similar to transient (time-domain) ODS analyses, a large number of transducers can be required. Additionally, because of the nearly static behavior, transducers somewhat more exotic than accelerometers (laser displacement sensors, proximity probes, slide wire potentiometers, etc.) are needed. These instruments require stationary reference points from which to measure. For elevated or complex systems, such mounting points may not be practical.

Because a video camera can acquire frames very slowly – 1 frame per second or even slower – the MAV technique is naturally capable of capturing near-static data. When these “time-lapse” sequences are amplified, a detailed view of thermal growth behaviors can be obtained. Many of the same caveats for MAV still apply (stable platform, proper angle, lighting). For outdoor situations, lighting can be challenging since over the long time scales involved, ambient lighting can change significantly.

Some examples of thermal piping growth using MAV can be viewed from Stage 3, Stage 1 Structure, and Stage 1 Lead. Note that the video sequence is more easily understood by manually scrolling forward and backward through the sections where motion is occurring. In this case, it was discovered that the thermal growth occurred completely differently than predicted by the thermal analysis. For example, a tension strut that was intended to transfer load to an anchor was found to be loaded in compression.



Summary

Operating Deflection Shape studies and Motion Amplification Video are effective tools for characterizing vibration of machinery and piping. The advantages and disadvantages of each technique should be considered when deciding which tool to use. For the Author's purposes, the ODS tool will provide the highest quality data for large structures and machinery. MAV works well with smaller machines and for some piping vibration. MAV is also extremely valuable at investigating joint separations, loose bolting, and other highly localized phenomena.

Advantages of ODS:

- The ODS procedure produces amplitude and phase at every model point in three directions. Amplitude accuracy is at the limit of the data acquisition and instrument hardware.
- Spectra for every point are immediately available. A table of amplitude and phase can be produced for use in future comparisons to assess progression of damage.
- Since the data are three dimensional and the model is built in three-dimensional space, vibration can be presented from any angle to aid in evaluation.
- Obstructions such as piping, structures, and other machines can be avoided. A small accelerometer can usually be placed at any point desired on the machine or structure.
- Animation files such as 3-D PDFs can easily be created and shared with others.

Disadvantages of ODS:

- It can require a lot of time to create the ODS Geometry and acquire all individual data points. Typically, an ODS of a large machine will require 2-4 hours to complete, or even longer for very complex situations.
- During data acquisition, operating conditions must be constant. The process must be controlled so that forces remain constant.
- At bolted joints, the ODS data can misrepresent whether a joint is failing. Localized metal deflection can appear to be a gap.
- Spatial resolution of an ODS is limited. Resolutions of 1 foot or more are common for large machinery. While adequate for most gross motions, finer details can be overlooked.
- For time-domain ODS, an impractically large number of transducers can be required. Similarly, although thermal analysis can be done with ODS, installation of fixed reference points and more complicated transducers can render this approach impractical.

Advantages of MAV:

- Usually an MAV is less time consuming than an ODS. For non-challenging situations, an MAV will require about 30 minutes to obtain the data. Complete analysis of an entire structure or machine can be less than 4 hours.
- An MAV presentation is arguably more intuitive than an ODS.
- Improved spatial resolution of an MAV provides more information about behaviors at joints, connections and more detailed components. Deflection of metal can be observed.
- Data can be acquired at very low frame rates, allowing near-static behaviors to be investigated.

Disadvantages of MAV:

- MAV is inherently a 2-dimensional representation of a 3-dimensional situation. At a minimum, one spatial dimension will be ignored. It is possible to observe motion in all three directions if a proper angle can be obtained, but the reported vibration amplitudes will be erroneous.
- There is currently no way to prevent aliasing with MAV data. Under-sampled data can misrepresent the actual frequencies present. Traditional vibration measurements (using an accelerometer, for example) should always be made at a few locations to determine an appropriate frame rate, or at least to be able to calculate and understand aliased frequencies.
- The maximum frame rate is determined by the camera used. Additionally, higher frame rates generate higher amounts of digital data and computation time. At the time of this writing, the highest practical frame rate is approximately 500 fps. Even if much higher frame rates could be used, vibration displacement at higher frequencies can be too low for MAV to render.
- It is often not possible to obtain data from certain directions. For example, a top-view is almost always impossible to achieve.
- Sight line and camera placement obstructions further limit the available parts of the machine that can be imaged and analyzed.
- Lack of a stable camera platform can render the obtained video useless for MAV.
- Vibration amplitude accuracy depends on having an accurate distance measurement to *every* point where you may want to obtain vibration amplitude data. After the video is obtained, such information is often unavailable, especially for long shots.
- Supplemental lighting and shading are often required to achieve appropriately flat illumination for successful MAV.
- The "output" of an MAV is a video. As shown by this tutorial, it is difficult to convey such output on a static page.

Acknowledgements

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