High-Speed Measurements of Target-Support Vibrations Using Line-scan Cameras

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Abstract:

The Laboratory for Laser Energetics (LLE) houses the OMEGA 60-beam laser, which is used to carry out inertial confinement fusion (ICF) experiments. The 60 beams delivered by the laser are all focused on a fusion target that is less than a millimeter in diameter. To properly carry out an ICF experiment, the target has to be uniformly irradiated by all 60 of the laser beams. Target vibrations are a critical source of error because they shift the position of the target, disrupting the uniformity of target irradiation. Deviations in target location as little as 20 microns from target chamber center (TCC) can seriously affect the implosion.

Line-scan cameras capture images that represent displacement in one dimension as a function of time, and can therefore be used to capture target movement. Displacement data extracted from the images can then be analyzed using a Fast Fourier Transform (FFT) to identify resonant frequencies of the target. This provides valuable information about the target support structure, its responses to various vibration sources, and the possible effects of engineering improvements.

Optical measurement techniques are superior to other possible options because they do not directly contact the target. However, camera resolution and image quality limit the camera's ability to capture data for targets that are resonating at high frequencies with small displacements.

1. Introduction:

Inertial confinement fusion (ICF) experiments at the University of Rochester's Laboratory for Laser Energetics (LLE) are conducted with both the OMEGA and OMEGA EP lasers. The fundamental concept of an ICF reaction is to compress and heat a target using lasers so that fusion conditions are met and fusion reactions can occur. At LLE, the target is a plastic shell approximately 3µm thick and 860 µm (1µm = 0.001 mm) in diameter that is filled with frozen deuterium (D_2) or deuterium-tritium (DT). The target is suspended from a stalk by spider silks to minimize surface contact and ensure an even surface for fusion (see Fig. 1). The stalk is positioned so that the target is located at the convergence of the beams at the target chamber center (TCC). In order for effective ICF reactions to occur, the target must be evenly irradiated. Otherwise uneven ablation will result in uneven compression and limit the amount of material that effectively fuses, decreasing the yield from the fusion reactions. In order for an even compression to occur, the target must be located very precisely at TCC.

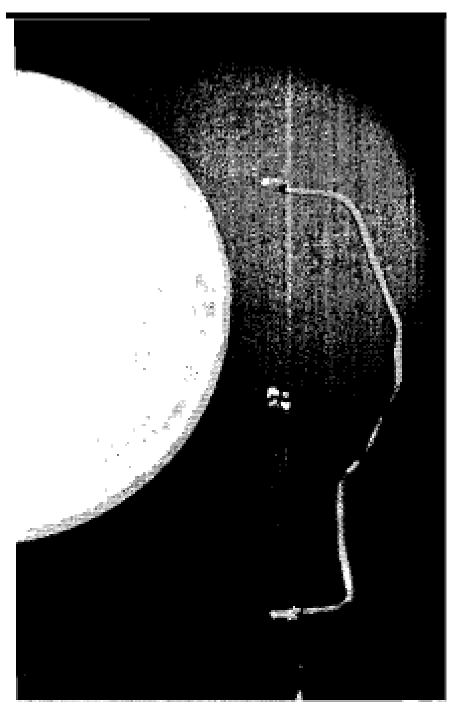

Figure 1: A target mounted on a stalk next to a penny.

The exact positioning of the target is critical. A displacement of as little as 20 μm will seriously impair the compression. Static and dynamic position errors jointly contribute to the maximum allowable error. The target is particularly susceptible to dynamic error because the target mount is susceptible to environment-induced vibrations. Sources including vacuum pumps and machinery attached to the chamber along with machinery in the building and even vehicles driving on the freeway outside the building all contribute to the background vibration that the target experiences. If the resonant frequencies of the target can be isolated, engineering modifications can be made to the stalk to minimize the effect of these frequencies on the target, greatly reducing the dynamic position error of the target.

Scientists at LLE have used traditional two-dimensional (2D) high-speed cameras to observe target vibrations. From vibration data collected by these cameras, resonant frequencies of the stalk can be extracted from Fourier transforms used on position data of the target over time. However, the high expense of the 2D high-speed cameras makes purchasing multiple units for testing purposes costly. In order to minimize the cost, LLE is looking to find an inexpensive camera alternative for use in laboratory development settings. In that regard, the line-scan cameras are highly appealing because of their low costs and variety of capabilities.

2. Line-scan Camera Usage for Vibration Analysis:

Cameras are fundamentally an appealing form of measurement for target vibrations for a number of reasons. The primary reason is that they are a non-contact form of measurement. Unlike accelerometers, which require contact and alter how the stalk reacts, cameras do not require any direct interaction with the stalk, allowing for accurate measurement without disrupting the fusion process in any way. Another important advantage of using a camera rather than an accelerometer or other form of measurement is that a camera naturally measures displacement. An accelerometer however, functions by measuring accelerations. The data gathered from an accelerometer must therefore be double integrated to get displacement. Integration errors are cumulative and do not allow accurate determination of absolute position.

In place of a traditional 2D high-speed camera, it is also possible to use a line-scan camera to capture similar data for analysis. A line-scan camera differs from a normal camera in that an image created by a line-scan camera shows the position of an object along a single dimension as a function of time, rather than showing the position of an object in 2D space at an instant of time. The difference is a result of how a line-scan camera's method of capturing an image differs from that of a traditional 2D digital camera. Both types of digital camera have an image sensor that converts optical data to an electrical signal. Commonly, the image sensor is a charge-coupled device (CCD) with a photoactive region. The CCD captures photons and outputs an electrical signal that is used to create an image. In a 2D camera, the CCD captures photons in a grid of specific height and width and uses the data to compose an image of a certain number of pixels in both rows and columns. A line-scan camera differs in that the CCD has only a single column of photon collectors (pixels). To form a complete image, a line-scan camera collects many individual lines of data. The rate at which lines of data are acquired determines the rate at which position can be measured. The exposure time of each line image is kept very short to minimize motion-induced blur. Each line represents the position of an object along a single dimension in space and as lines are built upon each other, an image is formed which shows how position changes over a period of time (see Fig. 2).

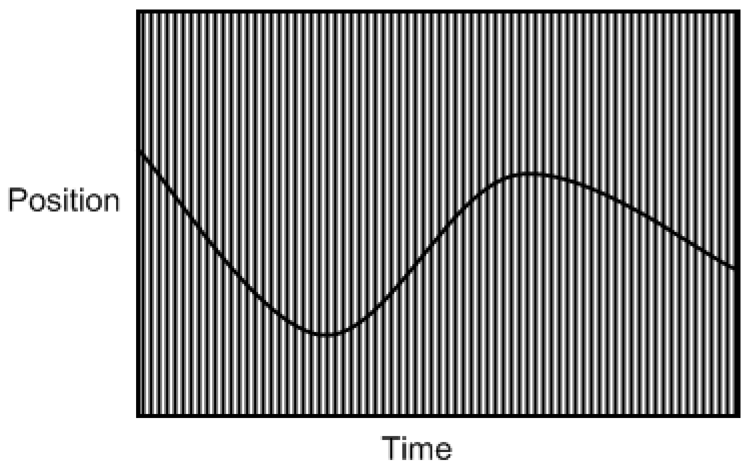

Figure 2: Line-scan camera image. Each vertical line represents a single image capture and the moving line shows position over time.

Line-scan cameras have a major advantage over traditional 2D high-speed cameras in that they cost only a fraction of what a standard camera would. The 2D cameras that are currently being used on the LLE target chamber cost over fifty thousand dollars, whereas a reasonable quality line-scan camera costs less than a thousand dollars. The line-scan camera is also advantageous because it allows the user to easily isolate movement along a single axis, which is highly useful in finding vibration frequencies for that particular axis. The ease of capturing movement, combined with the relatively low cost of each camera, leads to a more advanced usage of the cameras wherein multiple cameras could be used to capture images of the same target from multiple angles, enabling a virtual representation of the object to be built up in three-dimensional space. This approach is feasible in this application because the object of interest is a simple geometric shape, i.e. a cylindrical stalk or a spherical target.

The use of multiple line-scan cameras placed orthogonal to each other would provide a powerful new aspect of target analysis because of the added dimensional information that each new camera would provide. However, there are a number of issues that would have to be resolved individually and collectively before such a setup would be effective. The primary issue is one of lighting, which is a problem when using any high speed camera. If the target is not sufficiently illuminated, the high speed cameras, which have extremely low exposure times, will not be able to collect enough photons to form sufficiently bright images. The problem is exacerbated when multiple cameras are present, because the target then has to be illuminated from all angles to ensure total lighting. Another issue that has to be resolved is line-capturing synchronization for each of the cameras. Because each camera is capturing different information from different angles, the images will not necessarily coincide with each other upon inspection, so it is critical to ensure that the cameras are capturing data at the same time as each other. Furthermore, the cameras need to be capturing images at the same time as the target is illuminated, so a controller is needed to ensure that the light sources are on at the same time as the cameras are capturing information. In order to facilitate these multiple processes, a trigger system was developed to coordinate data gathering across multiple cameras (see Fig. 3).

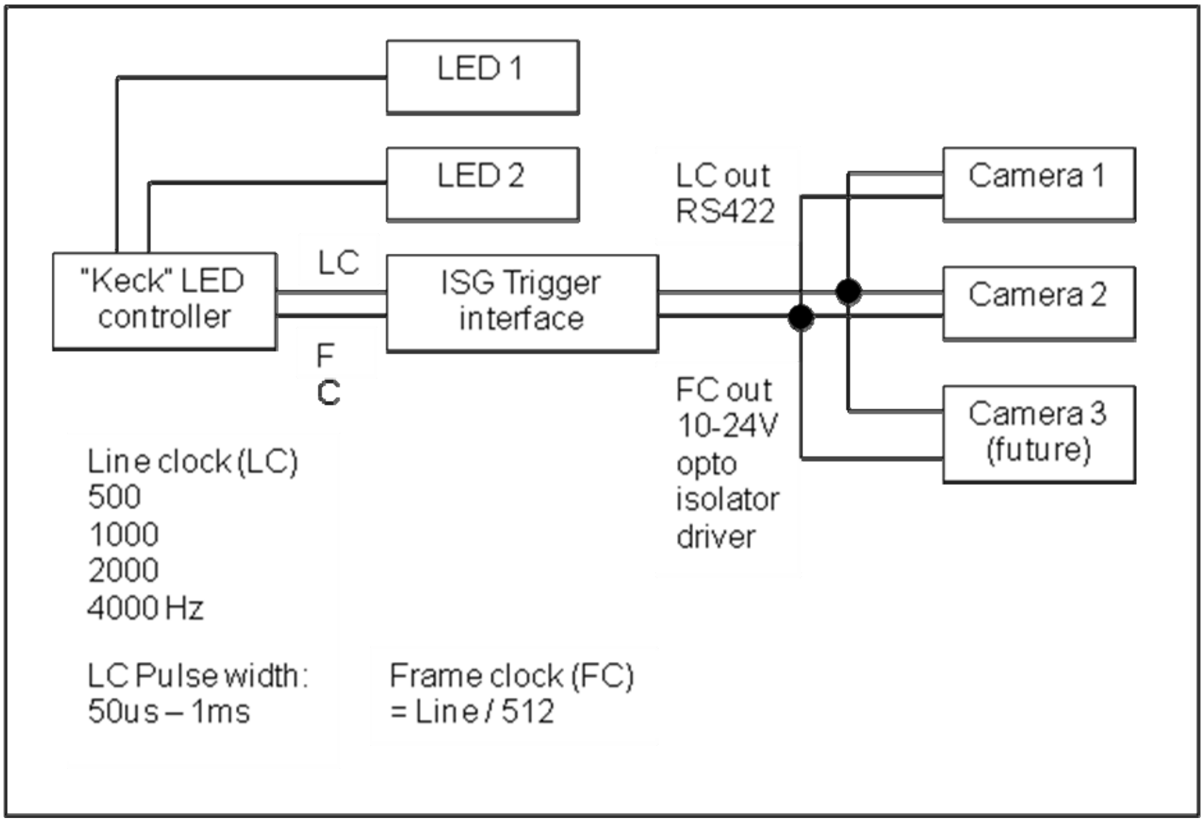

Figure 3: Controller interface for synchronizing camera line acquisition. The "Keck" LED controller illuminates the source at the same time as the cameras are commanded to gather line data. Both can be controlled at a range of frequencies from 500 Hz to 4000 Hz

3. Image Testing with Line-scan Cameras

The use of line-scan cameras for target vibration characterization is an appealing prospect to LLE because of their advantages. However, before the cameras are implemented, they must be tested to ensure that they will provide useful feedback. The first step to testing the line-scan cameras involved simple image collection. First, a sine wave was generated using the Matrix Laboratory (MATLAB) programming environment. The sine wave was then converted to an image with a chosen line thickness, printed on paper, and wrapped around a cylinder of known radius that could be driven at a known number of rotations per minute. The synthesized waveform was then recaptured using a line-scan camera calibrated to the image (see Fig. 4). The image portrayed has time along the y axis, and displacement along the x axis. Initial images captured from the rotating shaft had a number of problems, the primary of which was uneven and insufficient lighting. Additionally, the image was not continuous, as the camera did not capture each line to build an image at a rate directly proportional to the number of rotations of the shaft per minute. Finally, the image captured was not significantly magnified, which made any data extracted from the image noisy and inaccurate. Attempts to recreate the sine wave from this initial test image were unsuccessful.

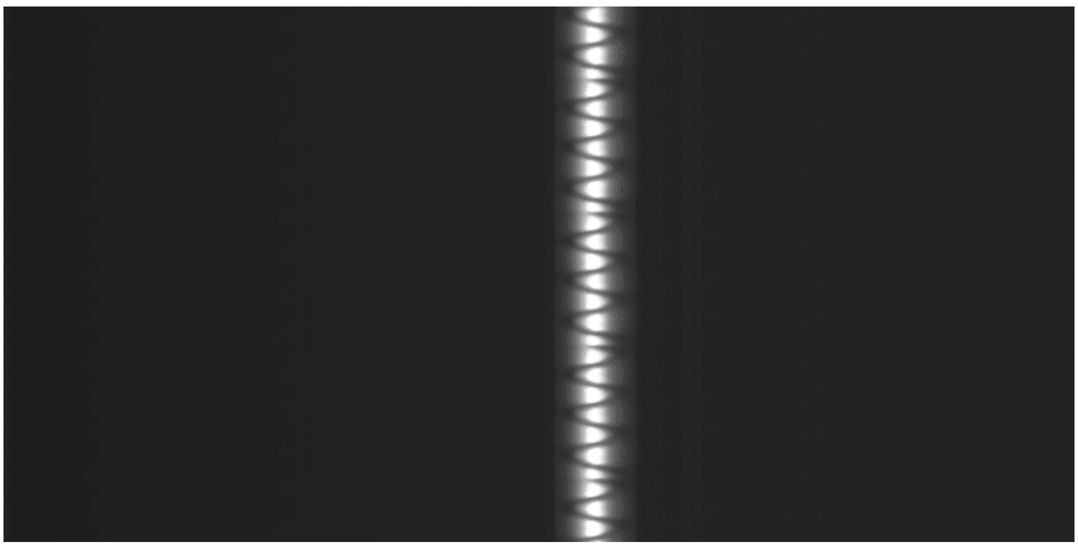

Figure 4: A test image capture from a constructed sine wave rotating on a cylinder driven by a motor. The image is insufficiently magnified, not well illuminated, and discontinuous. The time axis is vertical.

After image capturing with the motor and cylinder proved ineffective, the camera was mounted to a new setup with a lens that increased the zoom. Additionally, by using the “Keck” LED controller, the target could be more uniformly illuminated with a blue LED rather than using a laser pointer focused on the target. Now, rather than focusing on a rotating shaft, the camera was used to take images of an old target stalk, a much more representative situation for how it would be used in actual application. The stalk was mounted to an electrodynamic shaker that could then be driven at a known frequency and amplitude. The stalk itself was attached to a moving table that oscillated in and out based on the movement of a surface which functioned much like a speaker coil. When given a commanded frequency, waveform, and amplitude in volts, the shaker table would vibrate back and forth, and the camera captured that vibration. The results from the shaker table experiments were much more promising, because the images yielded were at a much higher magnification and the object was more evenly illuminated (see Fig. 5).

Figure 5: An example image taken with a line-scan camera of a vibrating target stalk mounted on a shaker table. The stalk itself is magnified to approximately 6 cm in width. The time axis is vertical.

4. MATLAB Analysis Routines

After the collection of data from the electrodynamic shaker table and target stalk, the images were processed in MATLAB to extract useful data on waveforms and resonances. In order, the steps are: cropping, normalization, spline interpolation, binarization, edge pixel finding, and graph analysis.

In the first step, one edge of the target stalk vibration is cropped, to capture only the region of interest and nothing else. The advantage of cropping is that it yields a smaller, more manageable image, and eliminates problems with isolating the desired waveform later in processing. An example of this cropping is show in Figure 6.

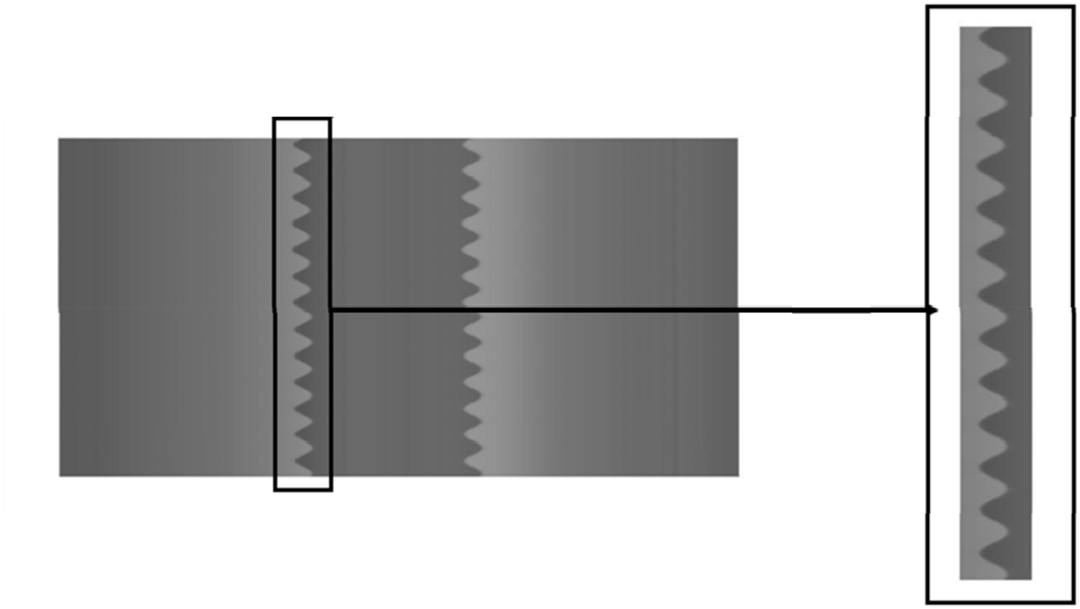

Figure 6: A test image with a cropped region shown. This image takes only the left edge of the vibrations, to ensure that only a single waveform is processed.

The second step, normalization, is only necessary when the image is not continuous and needs to be manipulated to ensure continuity. Because the captured waveform is evenly continuous and has a clear border, this step is not necessary.

Next, the cropped image is spline interpolated to create sub-pixel resolution. The purpose of the spline interpolation is to increase the sensitivity of the camera to vibration, effectively increasing the range of amplitudes that the camera can observe. Figure 7 shows the cropped image before and after a spline interpolation.

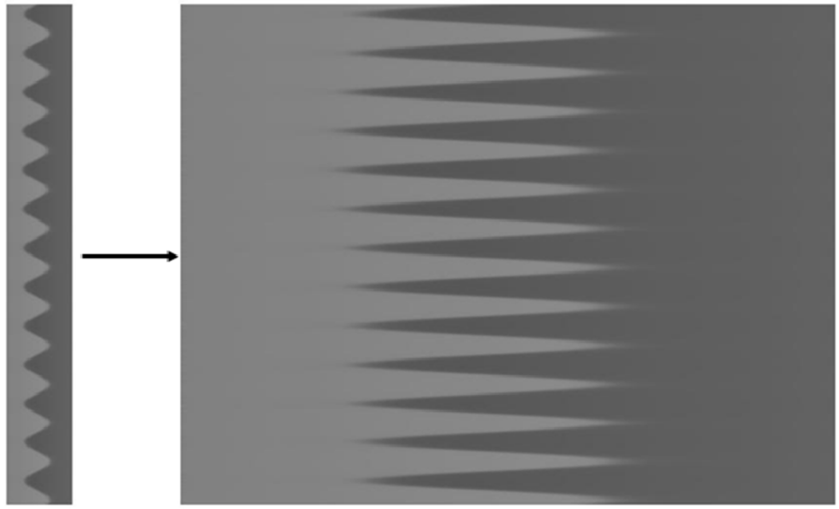

Figure 7: Cropped image before and after spline interpolation. Cubic spline interpolation in the horizontal direction is applied to the graph line by line, so that the resolution can be increased by virtual means. The aspect ratio of the interpolated image is not accurate, because sub-pixel values have to be displayed, so the image appears stretched.

After the image is interpolated, it has to be broken into true and false regions so that the image can eventually be converted into an actual graph. This step involves creating a brightness range, with all values within the range becoming true and all values outside the range false. For the example image, a range of values from 0 to 101 (on a scale of 0 to 255) were set as true. The result of the binarization is shown in Figure 8.

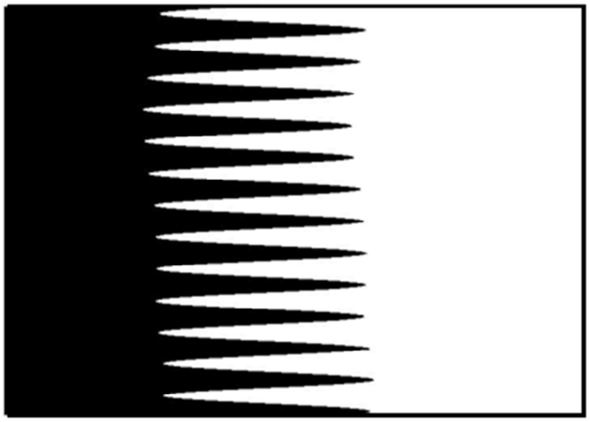

Figure 8: Binarization of the interpolated waveform. The true range is set as values from 0 to 101 (on a scale of 0 to 255).

After the image is converted to a binary map, the edge of each line where the image switches in Boolean value can be considered a data point. Processing each line of the image yields a set of coordinates that create a graph when plotted. The result of edge finding on the binarized image is shown in Figure 9.

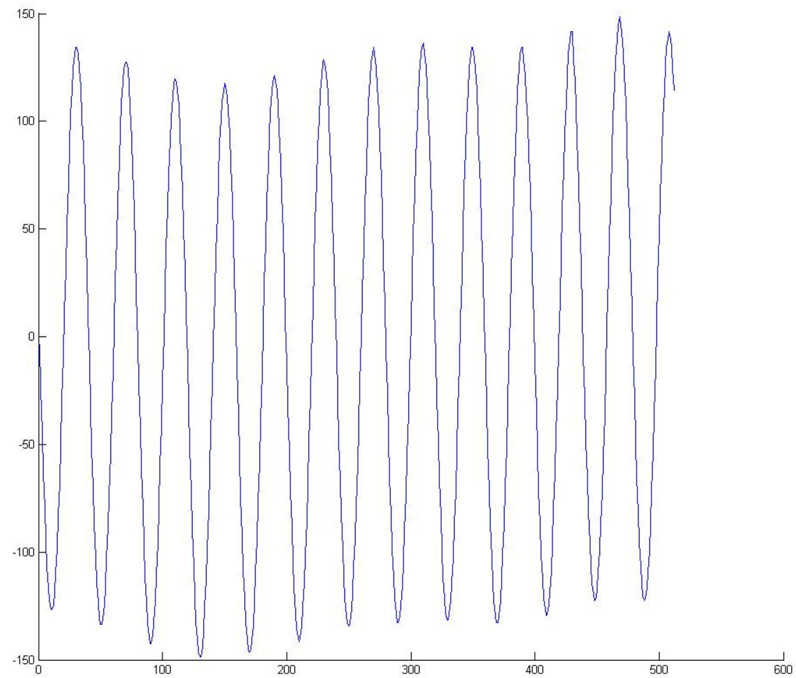

Figure 9: A graph of edge detected points. The X value is the line number from the image (row value, corresponding to time) and the Y value is the displacement from the middle of the image in pixels.

Following the construction of the waveform shown in Figure 8, a critical step is the execution of a Fast Fourier Transform (FFT) to isolate key frequencies present in the waveform, indicating the resonant frequencies of the target stalk. An FFT performed on the test data can be used to calibrate the camera because the electrodynamic shaker's motion can be measured with a calibrated accelerometer. The data taken from the shaker could then be used with results from the image processing to calibrate amplitude and frequency. An FFT performed on an actual target stalk would show the key frequencies at which the target resonates. Following the discovery of such frequencies, the stalk and support structure could be redesigned to eliminate or dampen the effect of those frequencies.

5. Camera Limitations

The major question that needs to be resolved related to the use of the line-scan cameras is exactly how useful they will be at measuring target vibrations in actual chamber conditions. Specifically, what level of resolution can the camera obtain, and at what frequencies? The camera, with magnification, operates at about four microns per pixel resolution. With an added spline interpolation, the magnification can be increased somewhat, though the process of interpolating invites possible error if the interpolation proves inaccurate. As a result, the camera will not effectively record any displacement less than 4 µm.

Past data indicates that the target assemblies resonate at relatively high frequencies, reaching as high as 305 Hz in some cases. Figure 10 shows that if these resonances are observed, the target must be experiencing accelerations in excess of 1g. At resonance, the target motion may be greater than the input excitation by several orders of magnitude, so it is important to be able to measure this response. However, the fact that the target may oscillate at displacements smaller than the camera's optical sensitivity of 4 µm is not of great concern, because only displacements of over 20 µm have a substantial impact on ICF experiments. The camera is clearly able to measure displacements of order 20 µm. During Fourier analysis of the motion waveforms, component frequencies over 100 Hz may not be effectively captured, but the components would fall outside of the frequencies of concern.

An additional capability of the line-scan cameras to strengthen the quality of Fourier data is their ability to store many consecutive frames for processing. By building waveform data from frame to frame, random noise and variation is minimized, yielding a cleaner image with more distinct wave properties.

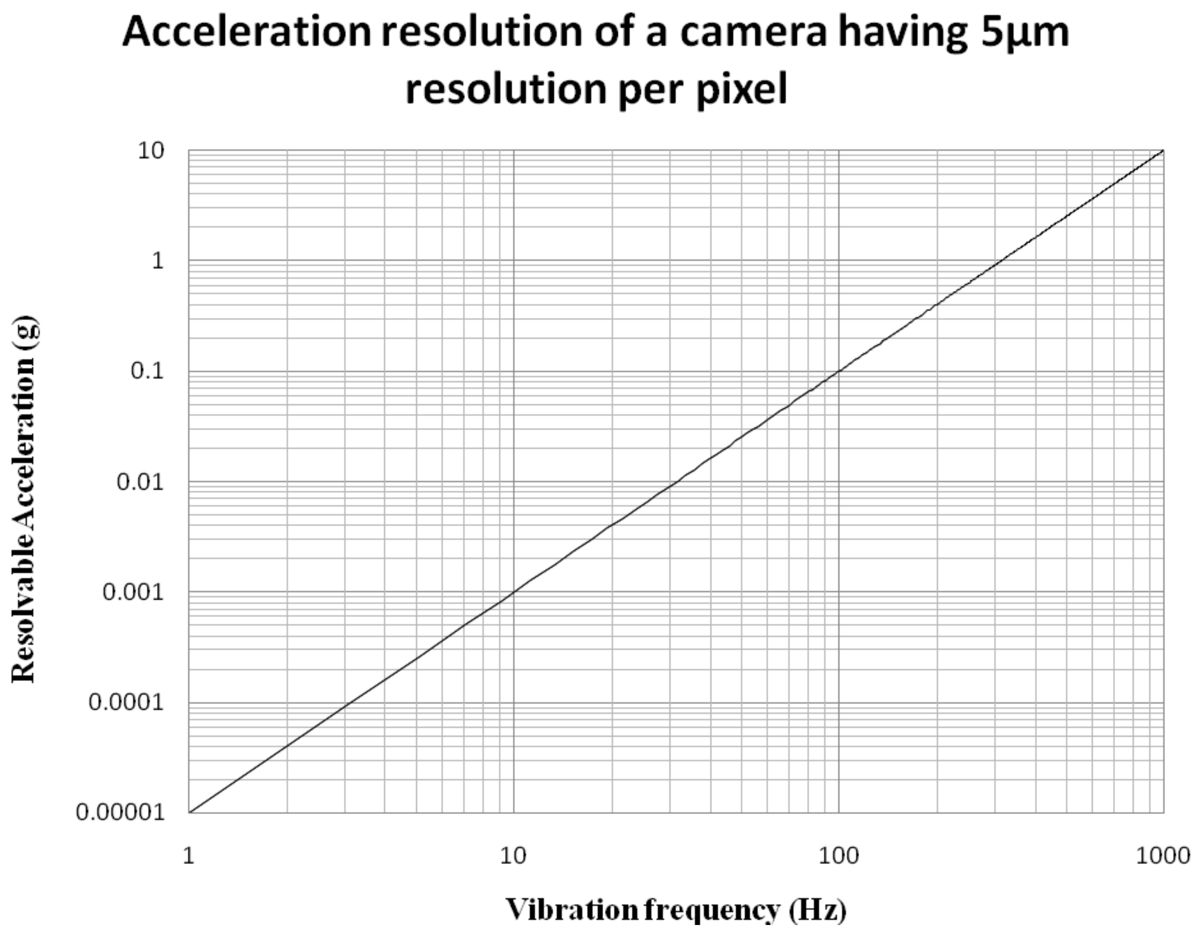

Figure 10: Optical resolution limitations of the line-scan camera. The graphed line shows the acceleration which the camera can resolve for a variety of frequencies ranging from 1 Hz to 1000 Hz. The logarithmic scale shows that the resolvable acceleration increases as the square of the vibration frequency.

6. Conclusion

The fundamental limitation of using optical measurement techniques is that they are only useful in measuring vibrations when the displacements exceed the minimal optical resolution. The issue of optical sensitivity is particularly critical when measuring target vibrations because the displacements may be very small. However, line-scan cameras, with appropriate optical magnification, are able to obtain an optical sensitivity of 4 μm per pixel.

Though the line-scan cameras have definite limitations in measurement capabilities for high-frequency oscillations at low accelerations, they are still useful for characterizing target vibrations relevant to ICF experiments.

Further testing with line-scan cameras inside the target bay and with other optical fixtures may improve the sensitivity of the cameras and provide further data on their functionality for measuring target oscillations. Additionally, the process of networking multiple cameras to build a two or three dimensional representation of the target movement was largely untested and work can still be done in determining the plausibility of such measurements.

7. Acknowledgements

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