Electromechanical Systems
ASE 375

Lecture 20: Optical Vibration Methods and Digital Image Correlation

Vibration related failures

Why is it important to study the motion characteristics of dynamic systems

https://www.youtube.com/watch?v=roN2jvu-Jis

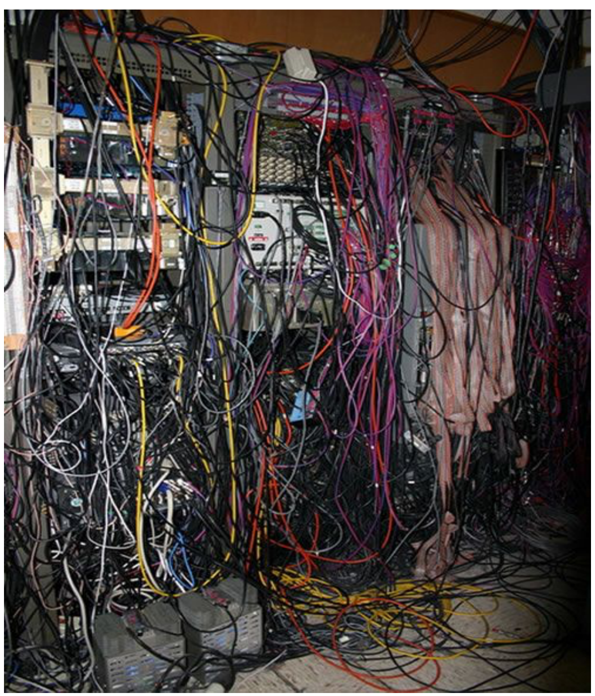
In many situations, optical methods are the easier approach

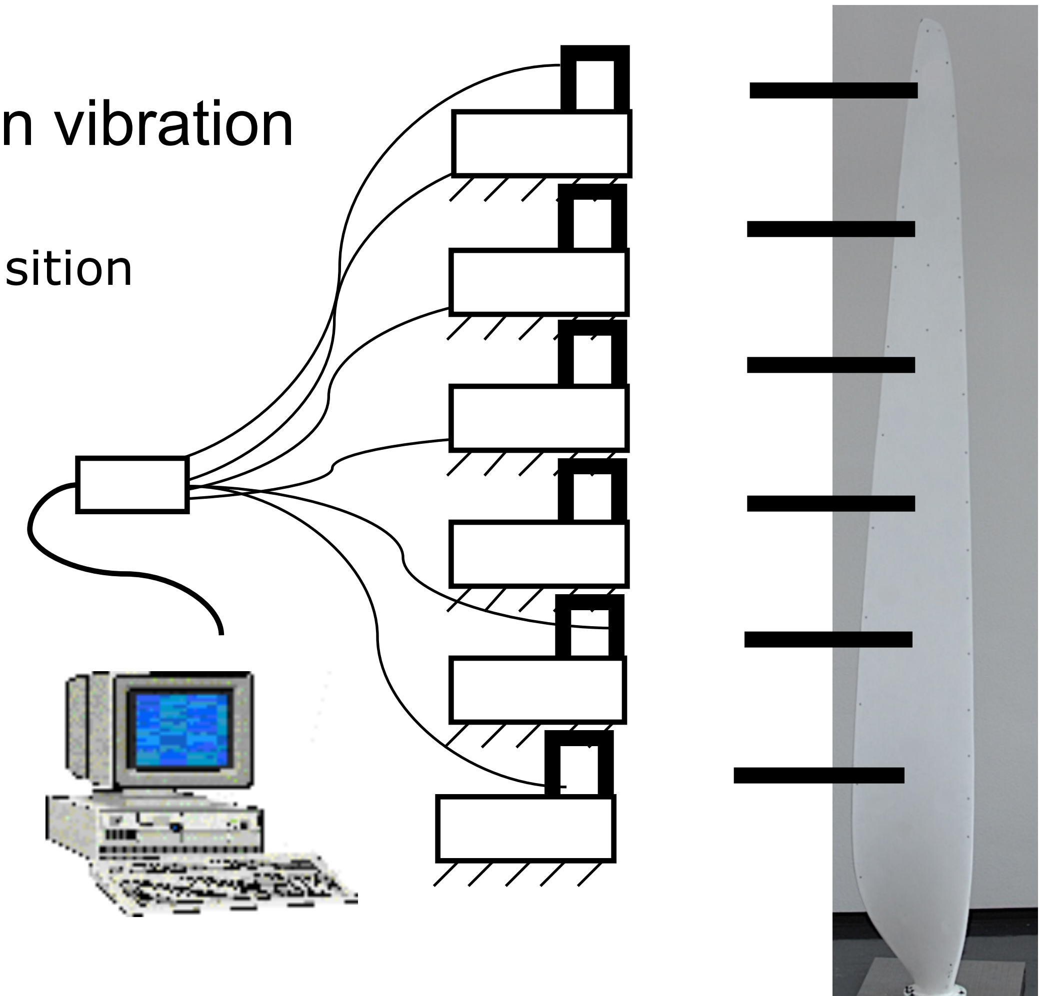
Measuring Vibration on an Entire Rotor Blade

Complicated Setup with Motion Sensor:

- Mounting the Sensor
- Wire up Sensor
- Effect of sensor on vibration

Data Acquisition





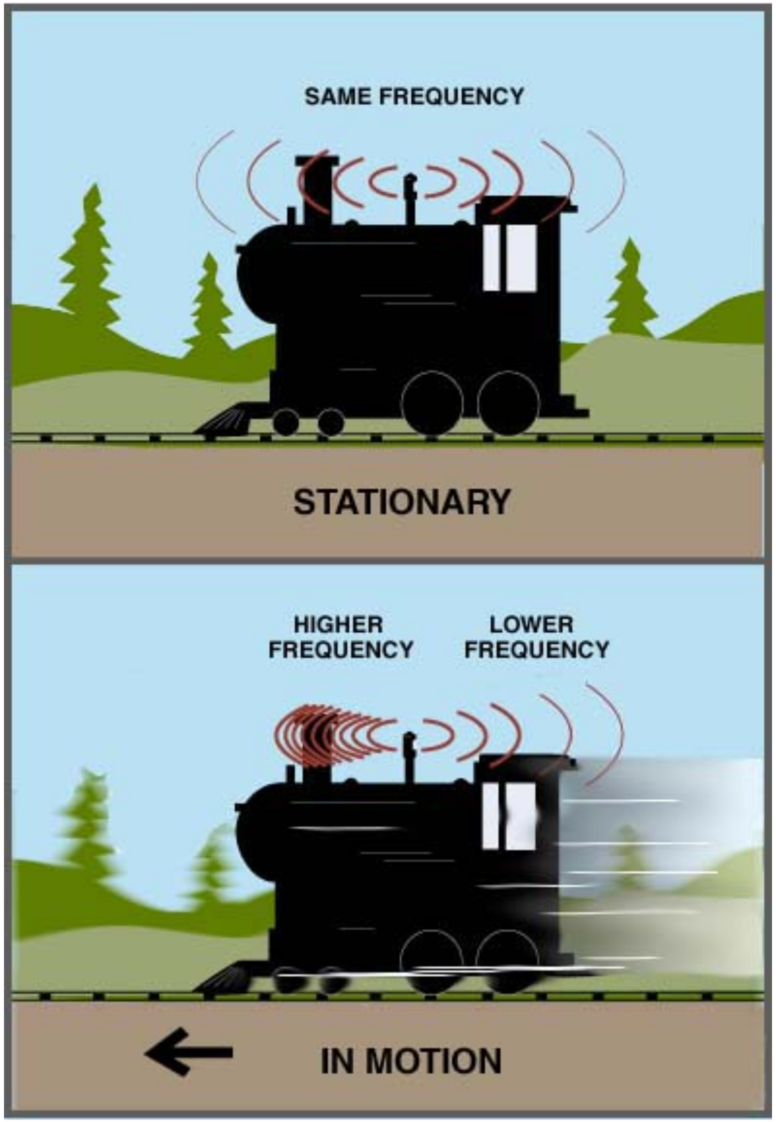
Optical Motion Measurement: Laser Vibrometer

- Laser Doppler Vibrometry (LDV) is a velocity measurement technique, but displacement and acceleration can be inferred.
- LDV uses the principle of the “Doppler Effect”.
- It is used for the analysis of all kinds of vibrating systems
- There are two key advantages of LDV measurement
  - It is non-contact and therefore the tested part stays uninfluenced during the measurement.
  - It is possible to observe dynamics on a very broad scale over large distances down to micron size.
- LDV is nowadays used in a variety of fields.
  - Aerospace –non-destructive inspection of aircraft components.
  - Acoustic – speaker design, diagnose the performance of musical instruments.
  - Architectural –bridge and structure vibration tests.
  - Automotive –structural dynamics, brake diagnostics, and quantification of noise, vibration
  - Biological –eardrum diagnostics and insect communication.
  - Hard Disk Drive Diagnostics –specifically in the area of head positioning.

Doppler Effect

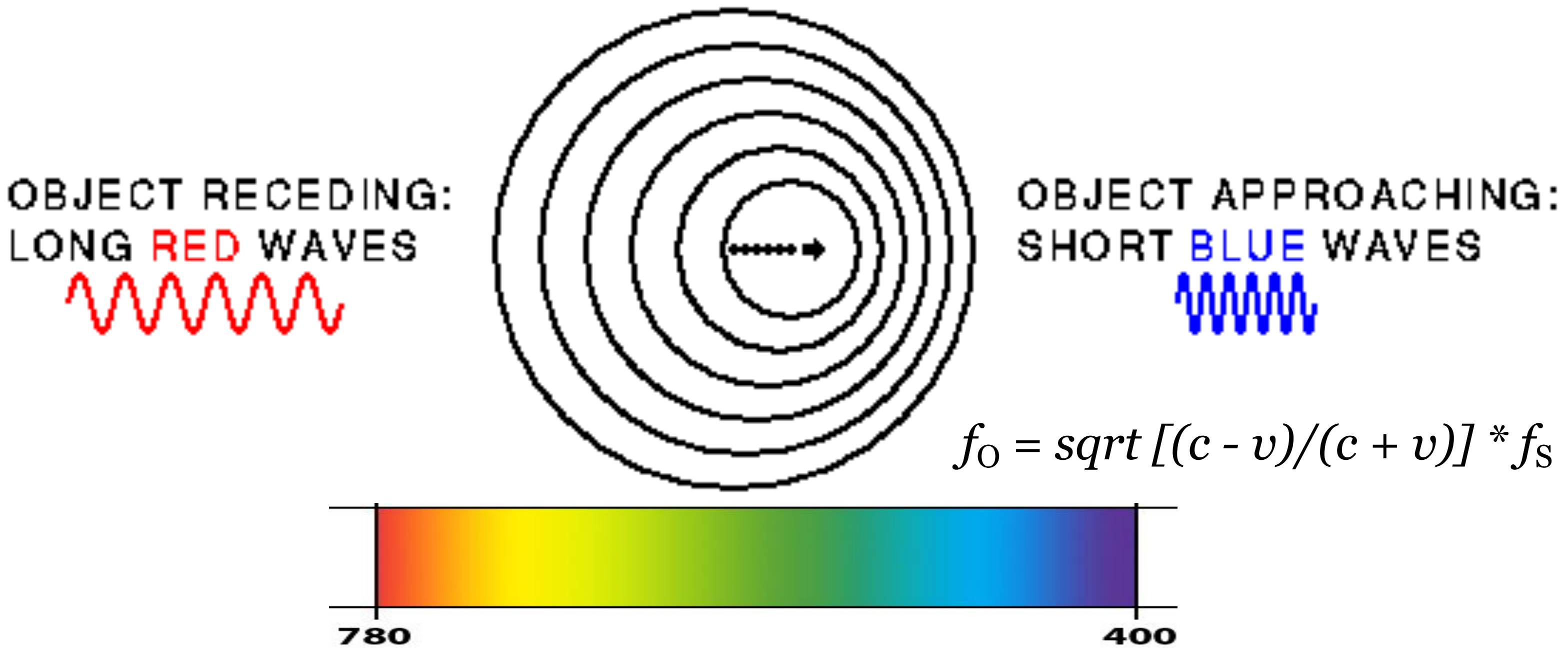
A moving frequency source "appears" to have a different frequency to an observer depending on the relative motion of the source with respect to the observer

- Christian Doppler first proposed the effect in 1842 for light waves.
- Confirmed experimentally by Christoph Ballot in 1845 using sound waves
- Approaching sources gave off a higher pitch, and receding sources gave off a lower pitch.



https://www.youtube.com/watch?v=wrzWAox8NCM

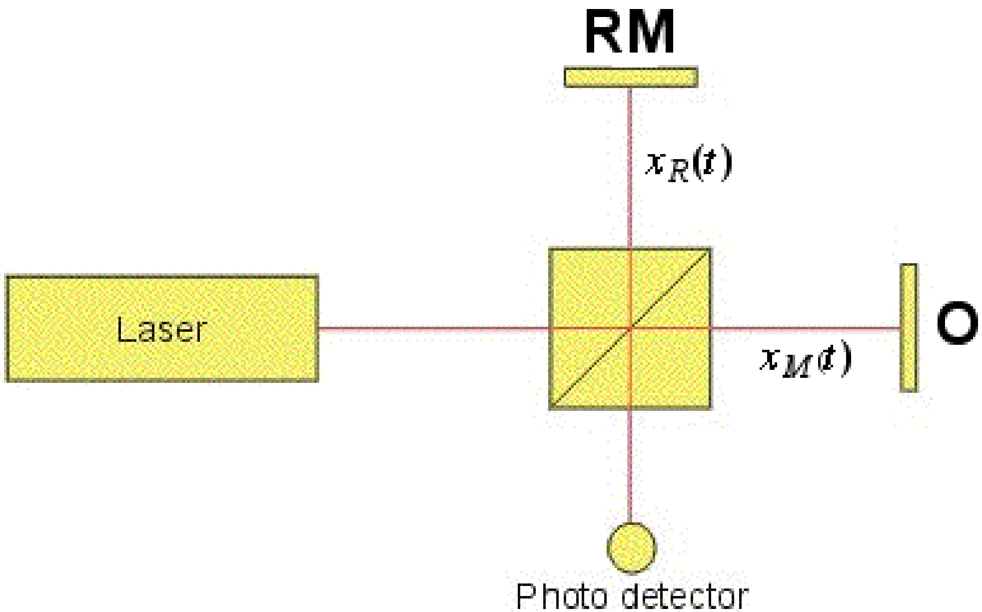
Doppler Effect in Optics



$$f_O = sqrt\,[(c - v)/(c + v)] * f_S$$

- Light waves from a moving source experience the Doppler effect to result in either a red shift or blue shift in the light's frequency.
- The observed frequency, f_O is related to the source frequency, f_S as a function of the speed of light and speed of the source
- A light source moving *away* from the listener (v is positive) would provide an f_L that is less than f_S
- When the light source is moving *toward* the listener (v is negative), then f_L is greater than f_S.
- Hubble used this to prove the expanding universe theory

Laser Doppler Vibrometer Schematic

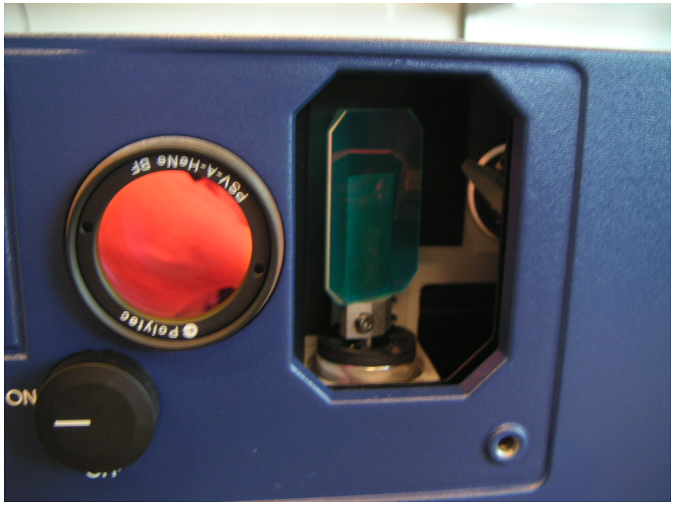


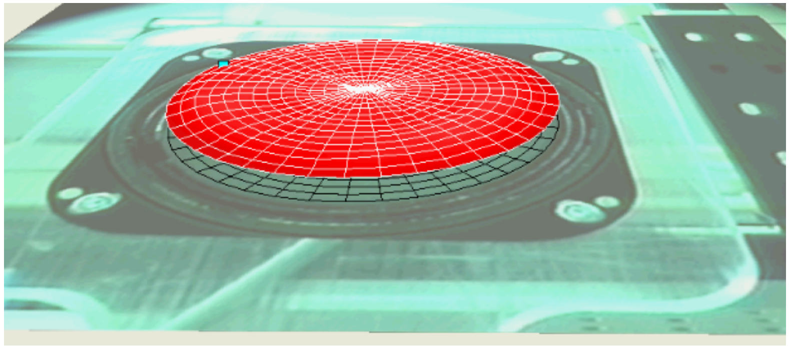
$$f_D = 2\frac{v(t)}{\lambda}$$

- A laser beam is divided at a beam splitter into a measurement beam (passing straight through the splitter towards the tested object "O") and a reference beam, which is deflected 90° upwards and propagates towards the reference mirror "RM".
- Since the path lengths for the returned beams are the same, the phase different between the reference and test beam is directly related to the motion of the object O.
- The rate of change of phase is proportional to the rate of change of position which is the velocity *v*(*t*) of the vibrating surface.

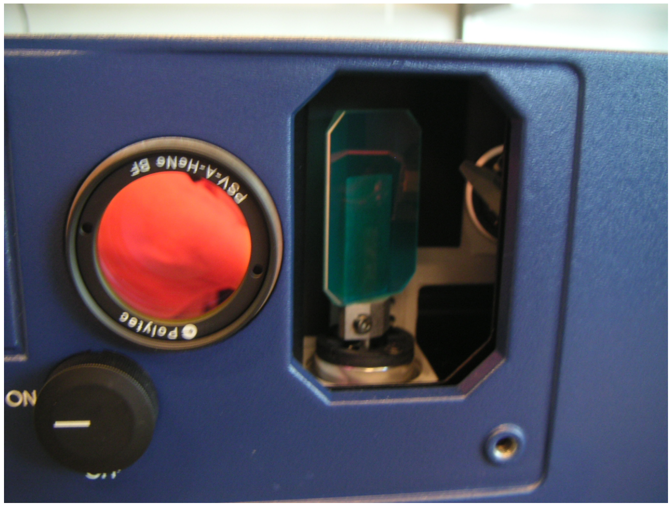
Scanning Doppler Vibrometer

- Many phenomenon cannot be described using single point measurements
- Vibrometers have been modified with rotating mirror arrangements to accommodate scanning multiple points





Scanning Vibrometer



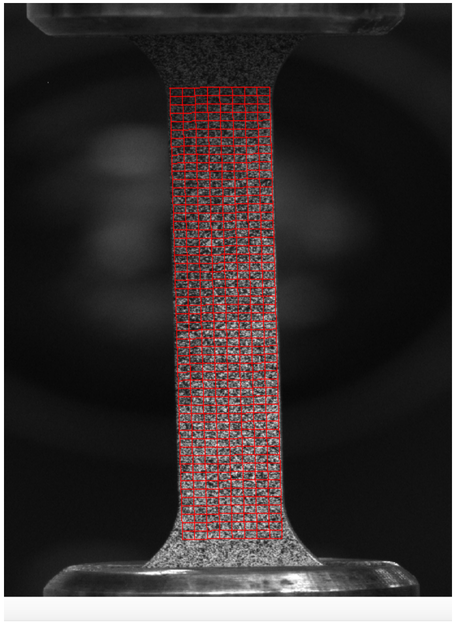
- Can measure grids of 500x500 points
- Measuring rate of 50 pts/second
- High resolution measurement takes 5000 secs (1.4 hrs!!!)

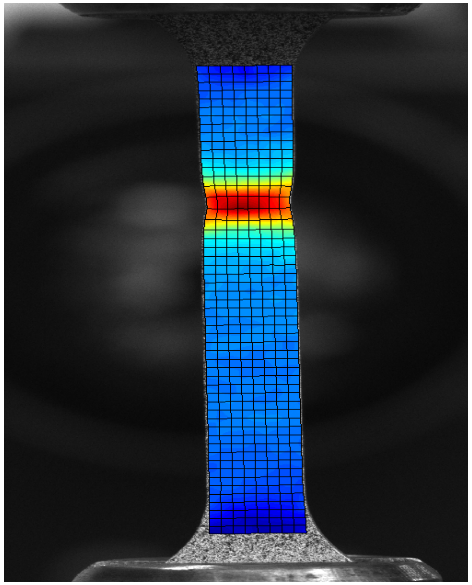
- Most physical phenomenon are spread out over an area
- Some of them might happen in very short time scales
- This is where Digital Image Correlation comes in.

Digital Image Correlation

- Measure & Visualize **Entire Structure's Response**
  - Displacements and strain gradients
  - Complex material types & geometries
  - Non-contact and non-destructive
  - Phenomenon can be captured over timescales from microseconds to years
  - 2D measurements and 3D measurements possible

Ex. principal strain field plotted on top of a uniaxial tension specimen





DIC Principle

- Digital Image Correlation (DIC) systems use the principles of photogrammetry and digital image processing to track features in space and assign their position relative to a predetermined coordinate system

- Photogrammetry (Hardware):
  - Capturing/Measuring a series of images of the phenomenon over timescales from microseconds to years and over an entire surface
  - Triangulation between a stereo camera pair is used to determine location in z-direction (out of plane)

- Digital Image Processing (Software)
  - A mathematical technique of image registration and tracking in order to convert image intensity distribution into displacements and strain

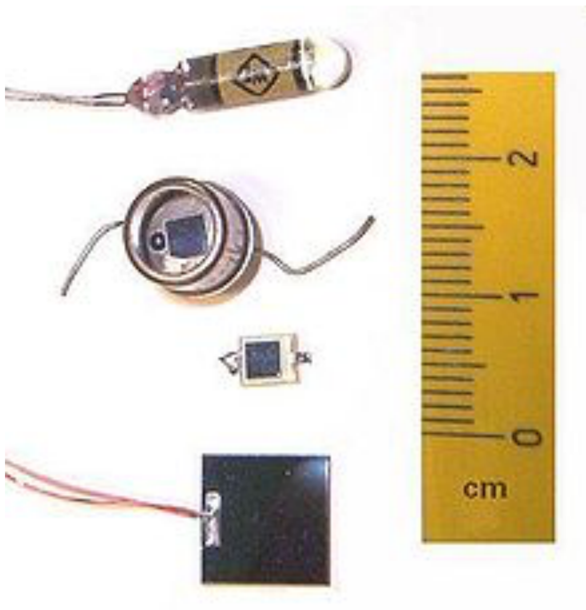
Photogrammetry

- High Resolution CCD Cameras (no internal moving parts) 2MP – 20MP
- Larger Sensors than point and shoot cameras provide better pixel quality with less pixels
- High Light Sensitivity
- Typically Monochrome (Black and White)
- Capable of Image Acquisition Rates from 15Hz to 1M frames per second

- Data Acquisition Controller that triggers cameras to take pictures
- Synchronizes with Test machines and records output signals
- Uploads image information to computer

- Calibration Objects have a dense grid of points at known location supplying in-plane coordinate information
- By moving the calibration object closer or further from the camera, information can be provided to the sensor relating depth of field and out of plane coordinates

Image Sensors



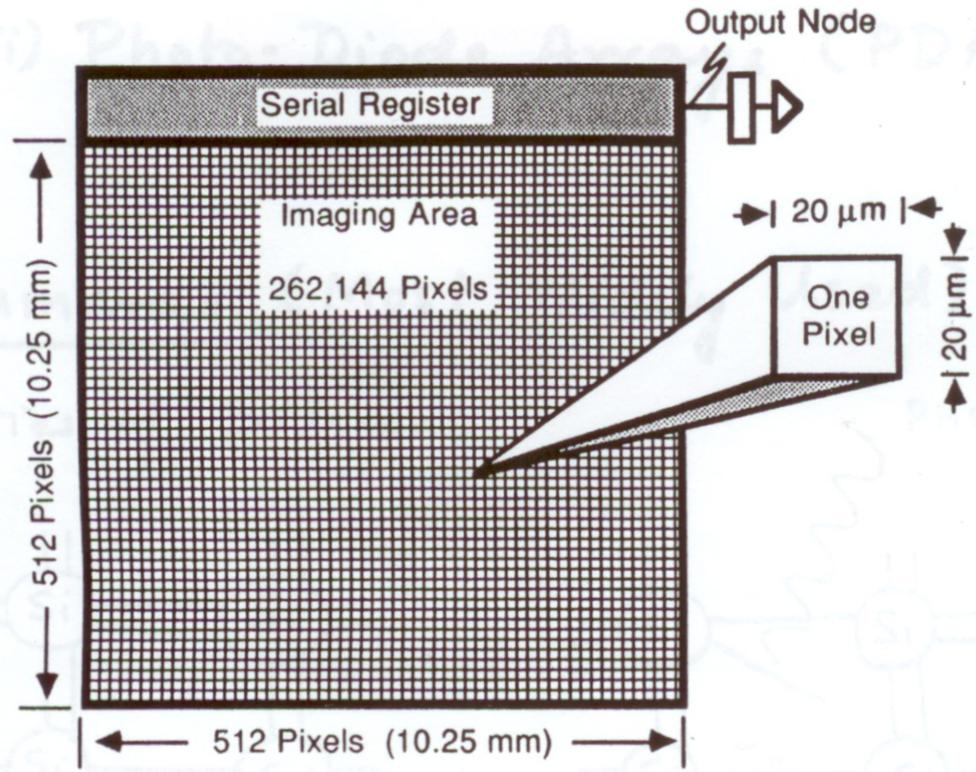


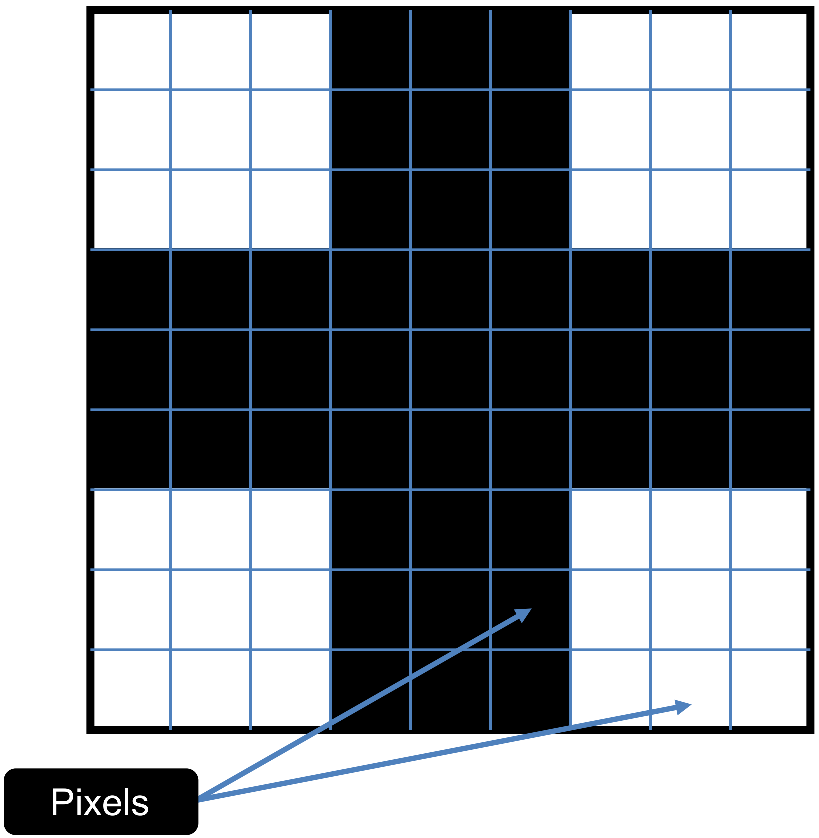
FIG. 4. Typical 512 × 512 CCD.

- Imagine a photodiode shrunk down to 20 micro-meter
- Now array nxm (for eg. 512x512) of these onto a substrate
- This array is called an image sensor

Image Correlation

- **Lets consider a simple example**
  - The camera has 9x9 – 81 pixels
  - The specimen is marked with a cross-like pattern

Image, on screen



Image, in memory

100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Image Correlation

Image after motion, on screen

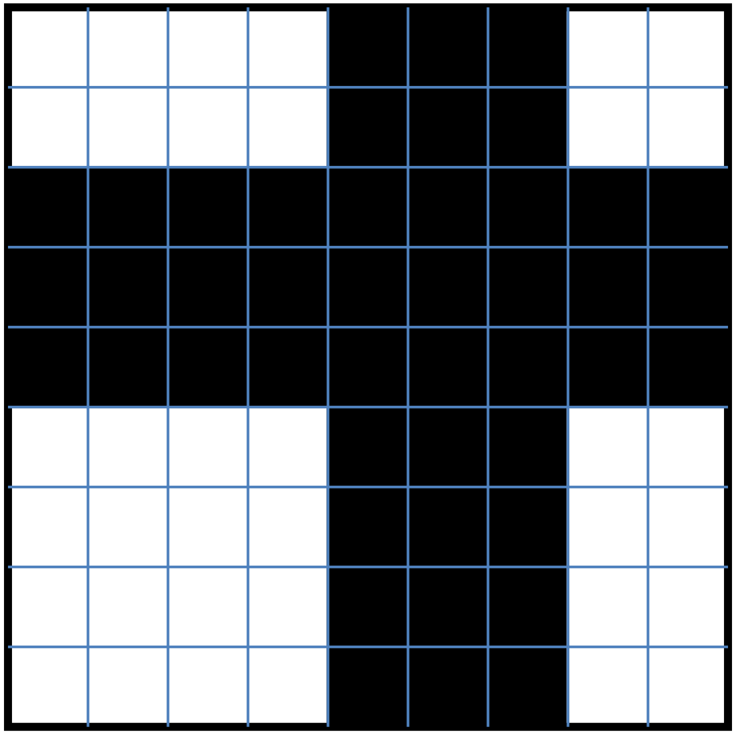


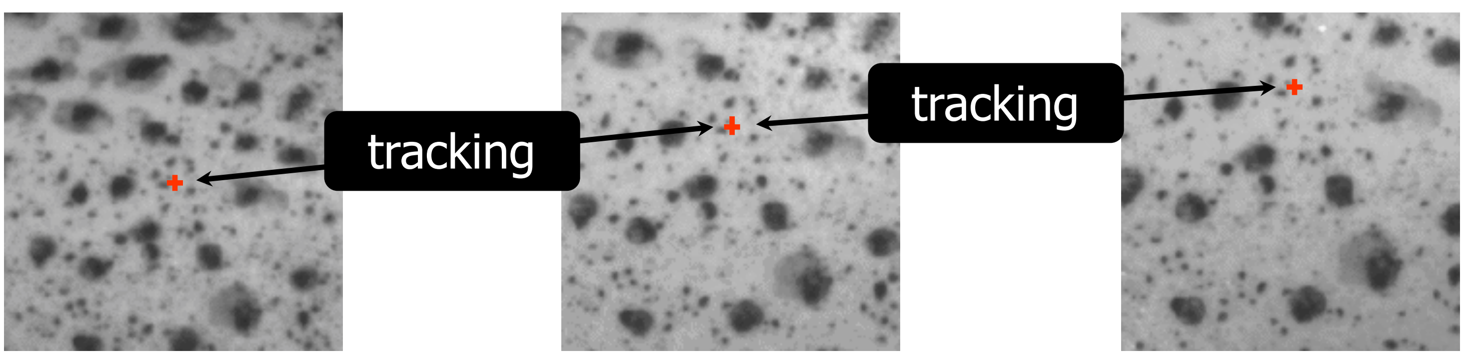
Image after motion, in memory

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

- Since the image is calibrated before the experiment, each pixel has a coordinate location associated with it.
- Based on the before and after images, each pixel can therefore be assigned a displacement
- If the time between the images is known, then the rate of strain is known

Spatial Correlation

- Given a point and its signature in the un-deformed image, search/track in deformed image for the point which has a signature which maximizes a similarity function
- The signature of a point can be anything that discriminates it among any other point signatures
- It can be:
  - Pixel gray-value
  - Gray-value derivatives
  - Color…
- In practice, a single value is not a unique signature of a point, hence neighboring pixels are used
- Such a collection of pixel values is called a subset or window



Spatial Correlation Procedure