Limitations of Vibration Spectra

Presented by: Simon Mills BSc(Eng) CMarEng CEng MIMarEST FInstNDT FISCM

Managing Director, SpectrumCBM Ltd

Chair BSI GME/21 – Mechanical vibration, shock and condition monitoring

Past Chair ISO TC 108/SC5 – Condition monitoring of machines systems

Chair BSI GME/21/7 – Condition monitoring of machines

BINDT PCN Cat IV Analyst and Trainer

Introduction

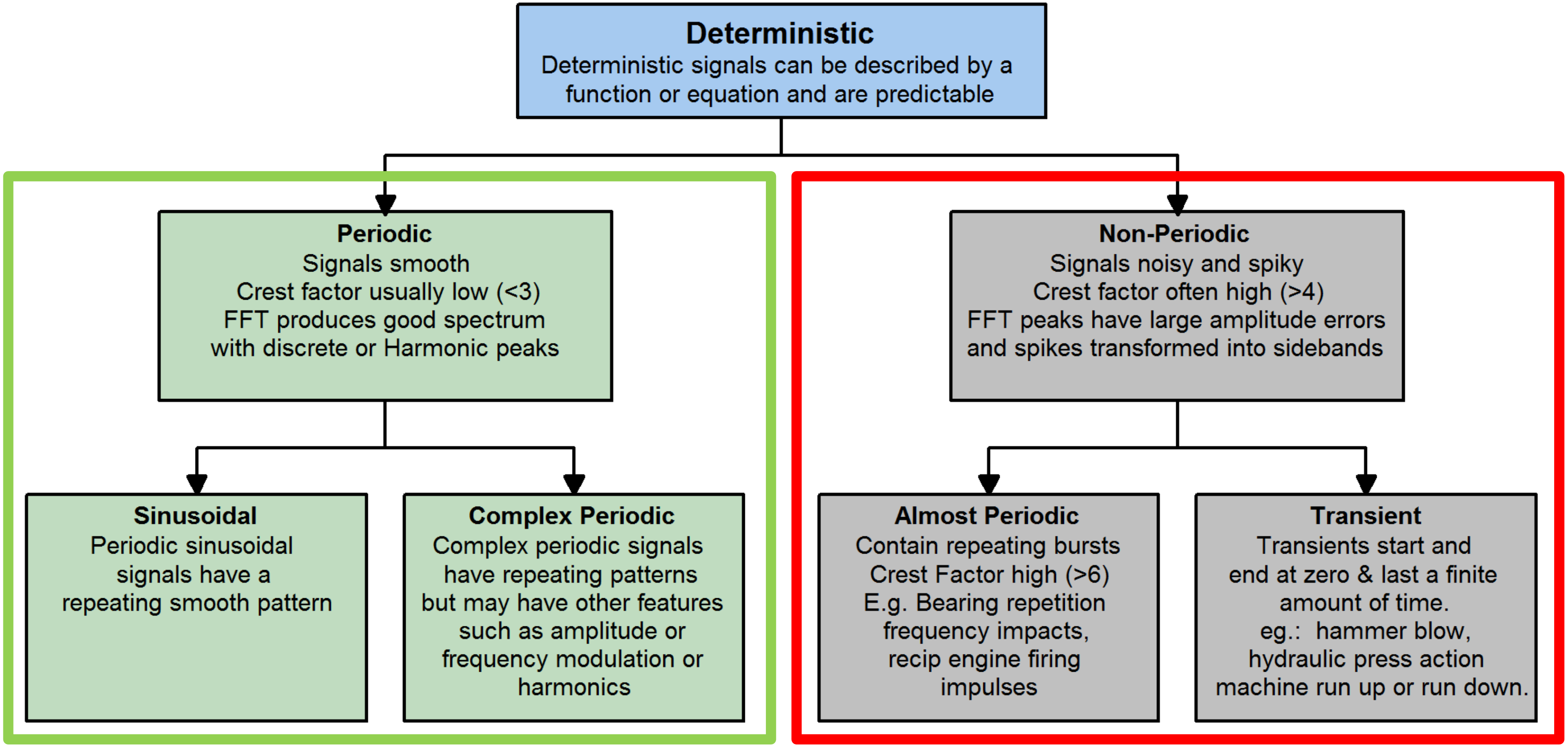
- Vibration spectra are in common use in many vibration monitoring & analysis programs
  - The raw vibration data is usually acquired as a time waveform (time trace)
  - A time waveform will only produce one unique spectrum depending on its sampling and post-processing set-up
  - However the same spectrum could have come from an infinite number of time waveforms
- Spectra underestimate the amplitude of impacts
  - It is difficult to estimate the true peak amplitude if only a spectrum is available
- Care needs to be taken when relying on spectra

Spectrum CBM Ltd

Mechanical Vibration

- Most rotating & reciprocating machines vibrate
- Vibration is generated from factors such as:
  - Unbalance
  - Misalignment
  - Looseness
  - Lack of lubrication
  - Bearing wear and damage
- Each factor contributes to the vibration signal
  - Adding periodic, sinusoidal, and transient signal components

Classifying Vibration



- FFT works best on the data types in the green boxes
- FFT errors are greater for the data types in the grey boxes

Spectrum CBM Ltd

FFT Effectiveness

- *"Fourier analysis can only be used on deterministic and repetitive signals. If signals belong to another class than the deterministic and repetitive one (discrete components) large amplitude scaling errors are likely to happen."*
  - From: *An Automatic Approach for Proper Amplitude Estimation in CBM Applications*, T Lagö and A Boyer, BINDT, COMADIT 2013, Krakow, Poland

Vibration Transducers

- Displacement transducer
  - Typically a non-contacting proximity probe
  - Powered -18V DC, typical output sensitivity 8 mV/μm
- Velocity transducer
  - Typically a seismic moving-coil sensor
  - Self-powered, typical output sensitivity 80 mV/mm/s
- Accelerometer
  - Typically a seismic piezo-electric sensor
  - Integrated Electronics Piezo-Electric (IEPE)
  - Powered 18V DC, typical output sensitivity 100 mV/g

Errors in the Acquisition Process

- Some errors which can occur in the acquisition and A-D process:
  - Sampling rate too low – Limits FFT max. frequency (F_{max})
  - Number of samples too small – Limits FFT lines/resolution
  - Sampling duration too low – Limits lowest frequency resolved
  - Aliasing – Under-sampled frequency gives ghost frequency
  - Clipping – Chops signal top and/or bottom, causes harmonics
  - Truncation – Signal start/finish discontinuity, causes leakage
  - FFT post processing (Digital)
- (Solution: Attend BINDT PCN VA2 or VA3 course)

Vibration Analyst CM Syllabus

Ref	Subject	Cat 1	Cat 2	Cat 3	Cat 4
1	Principles of vibration	6	3	1	4
2	Data acquisition	6	4	2	2
3	Signal processing	2	4	4	8
4	Condition monitoring	2	4	3	1
5	Fault analysis	4	5	6	6
6	Corrective action	2	4	6	16
7	Equipment knowledge	6	4	4	-
8	Acceptance testing	2	2	2	-
9	Equipment testing and diagnostics	-	2	4	4
10	Reference standards	-	2	2	2
11	Reporting and documentation	-	2	2	4
12	Fault severity determination	-	2	2	3
13	Rotor and bearing dynamics	-	-	-	14
	Total hours for each category	**30**	**38**	**38**	**64**

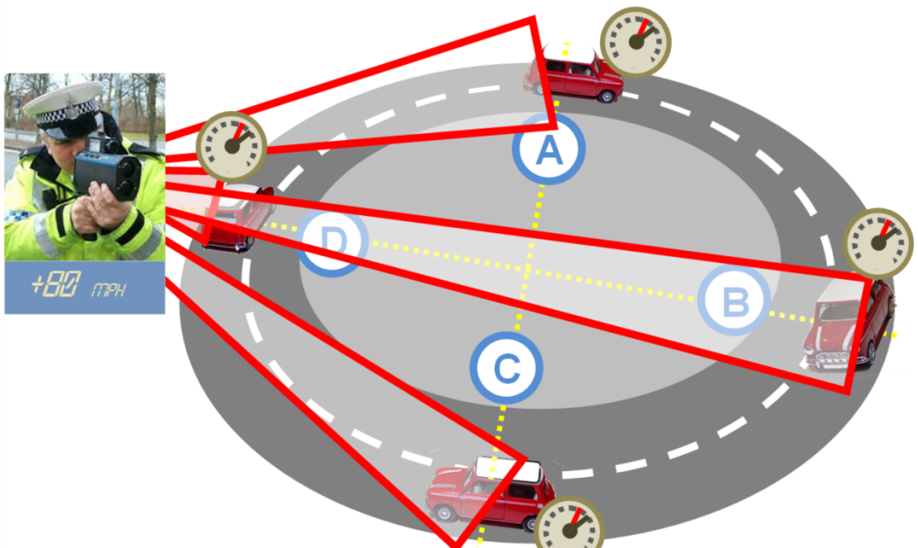
Acquiring Raw Vibration Data

- First an example of measuring speed
- Then some examples of measuring:
  - Displacement
  - Velocity and
  - Acceleration

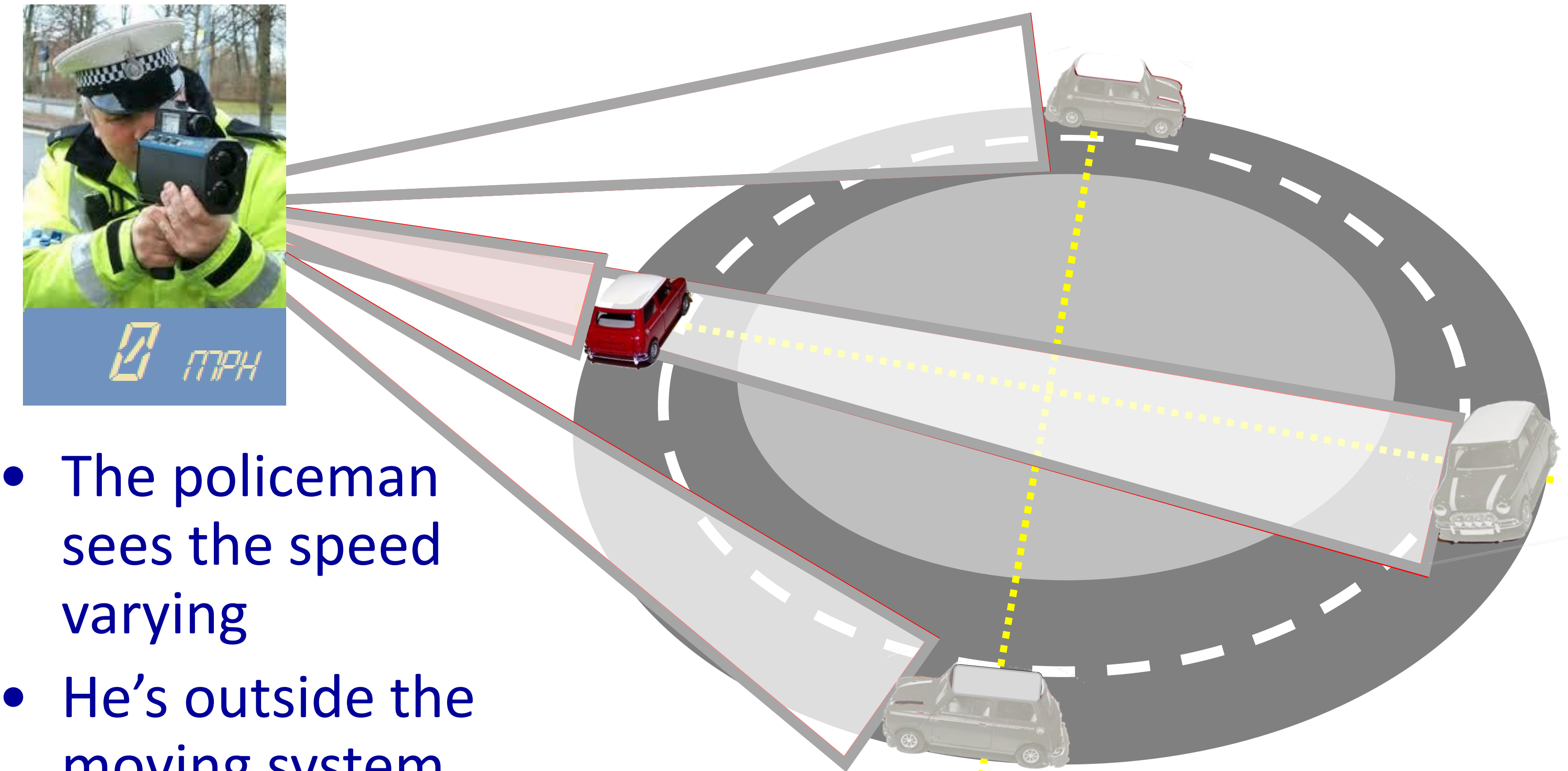
1 *Measuring Speed*

Let’s look at how the policeman's radar gun would indicate the car's speed at the four marked positions.

Assume the car is travelling at a constant 80 mph. Fill in what you think the speedo, and the radar gun would indicate at each marked position A, B, C & D in the table below. Assume that the radar gun indicates speed towards it as being positive, and away from it negative



Task 1: Measuring Speed



- The policeman sees the speed varying
- He's outside the moving system

Task 1: Measuring Speed

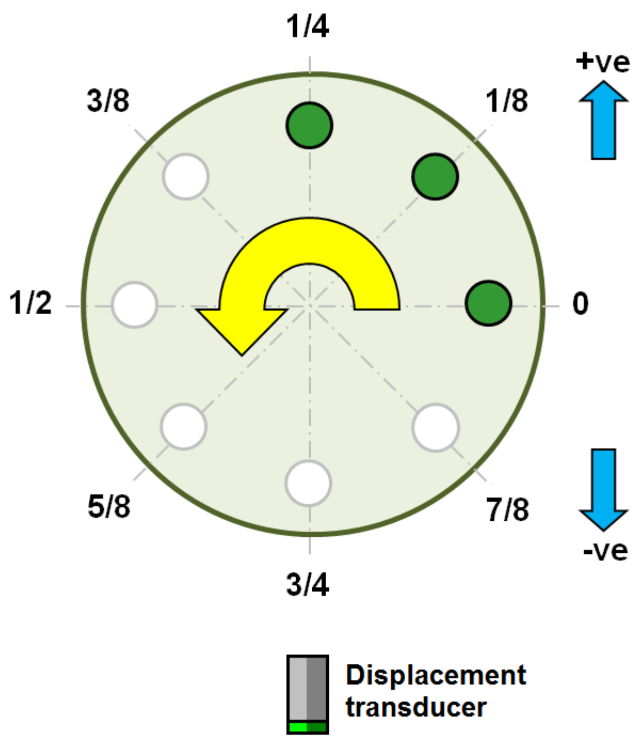
Position	Speedo	Radar Gun Indication	Direction of speed
A	80 mph	-80 MPH	Away from the radar gun
B	80 mph	0 MPH	None
C	80 mph	+80 MPH	Towards the radar gun
D	80 mph	0 MPH	None

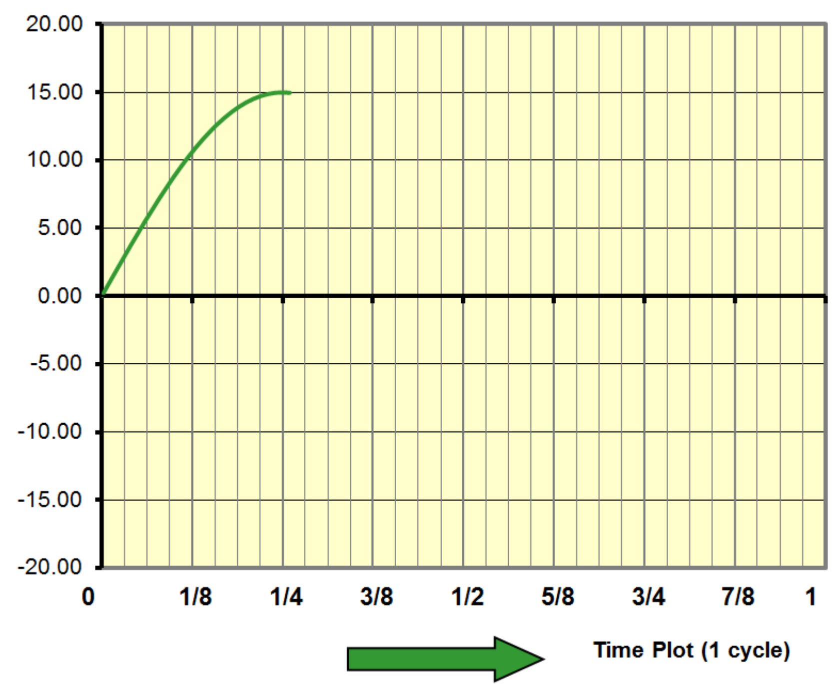
Task 2: Vibration Waveforms

- The simplest parameter to look at first is displacement, or the distance the centre of rotation moves due to the unbalance
- We’ve set up a horizontal zero line, and started the rotor at this position
- Distance downwards is set to be negative, and upwards is positive

Task 2a: Displacement Waveform

- Draw what you would see at each 1/8th of a revolution cycle on the time trace grid provided.
- We've started you off with the first three points
- We've assumed max displacement amplitude is ±15 units peak

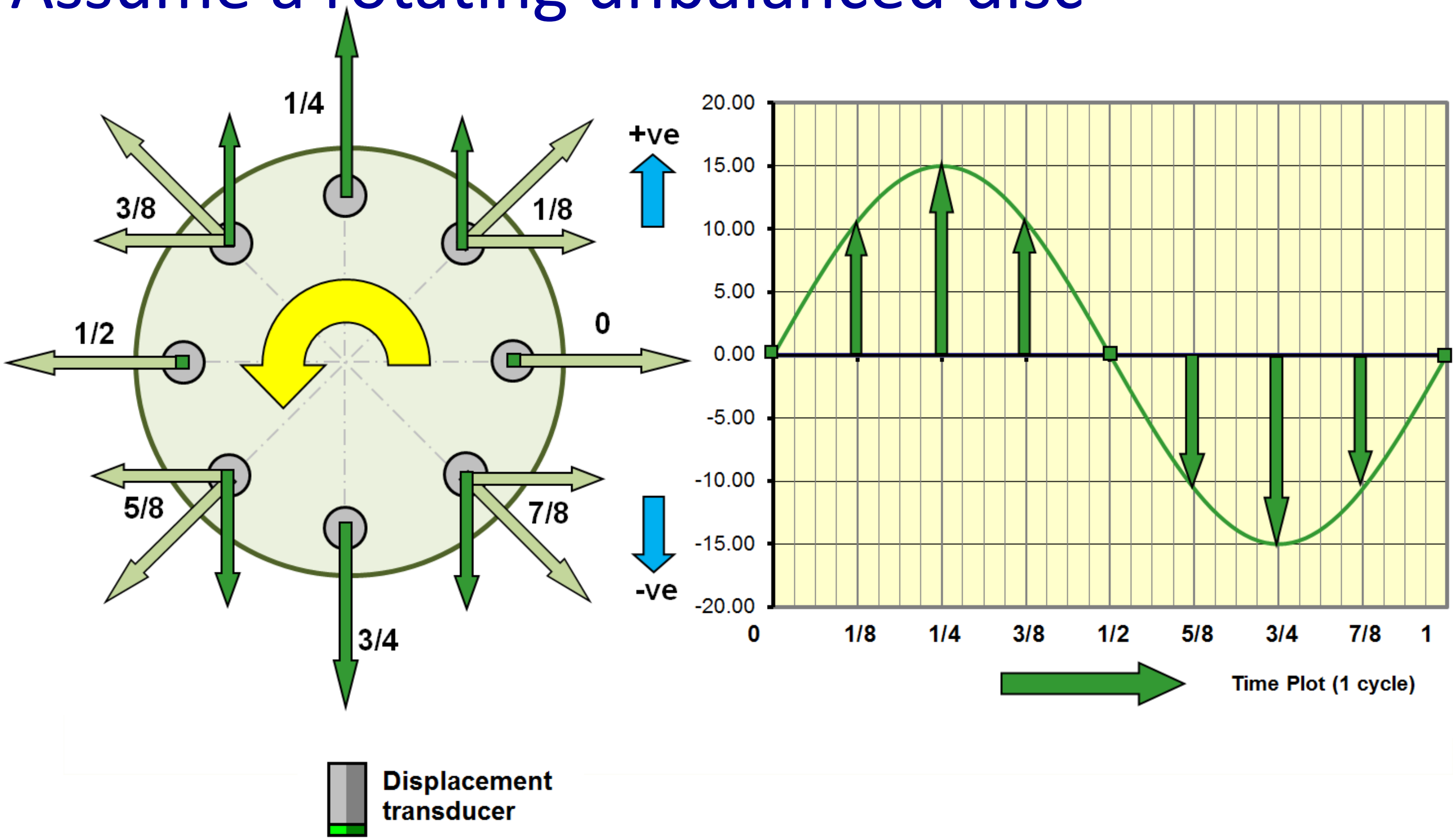




Spectrum CBM Ltd

Task 2a: Displacement Waveform Solution

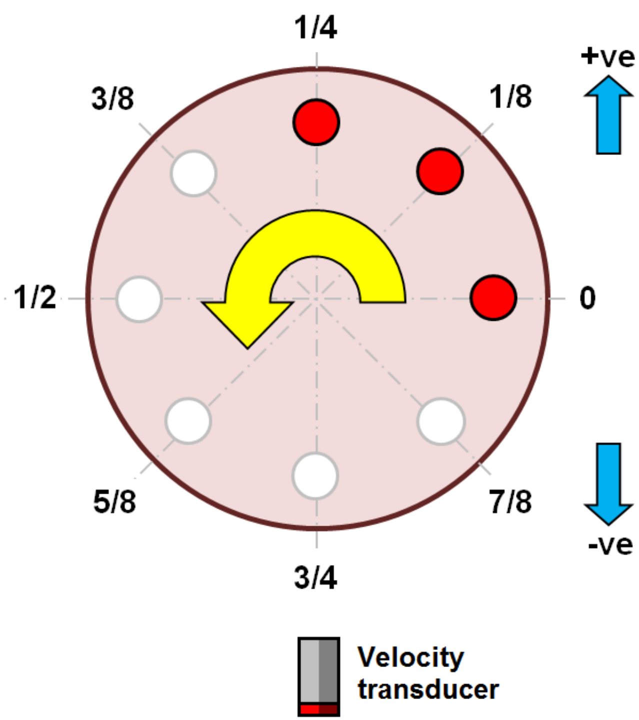
- Assume a rotating unbalanced disc

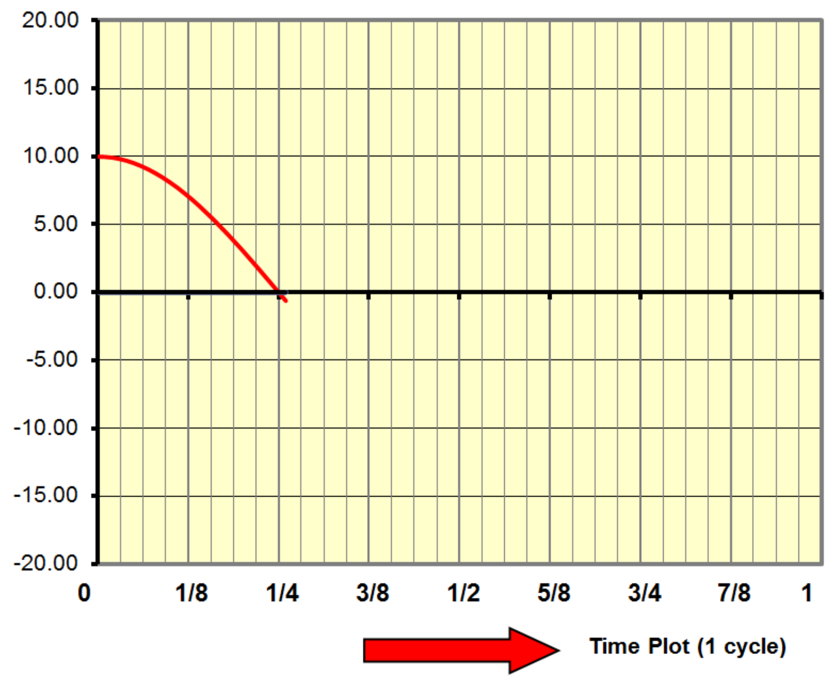


Spectrum CBM Ltd

Task 2b: Velocity Waveform

- Draw what you would see at each 1/8th of a revolution on the time trace grid provided.
- We've started you off with the first three points
- We've assumed max velocity amplitude is ±10 units peak

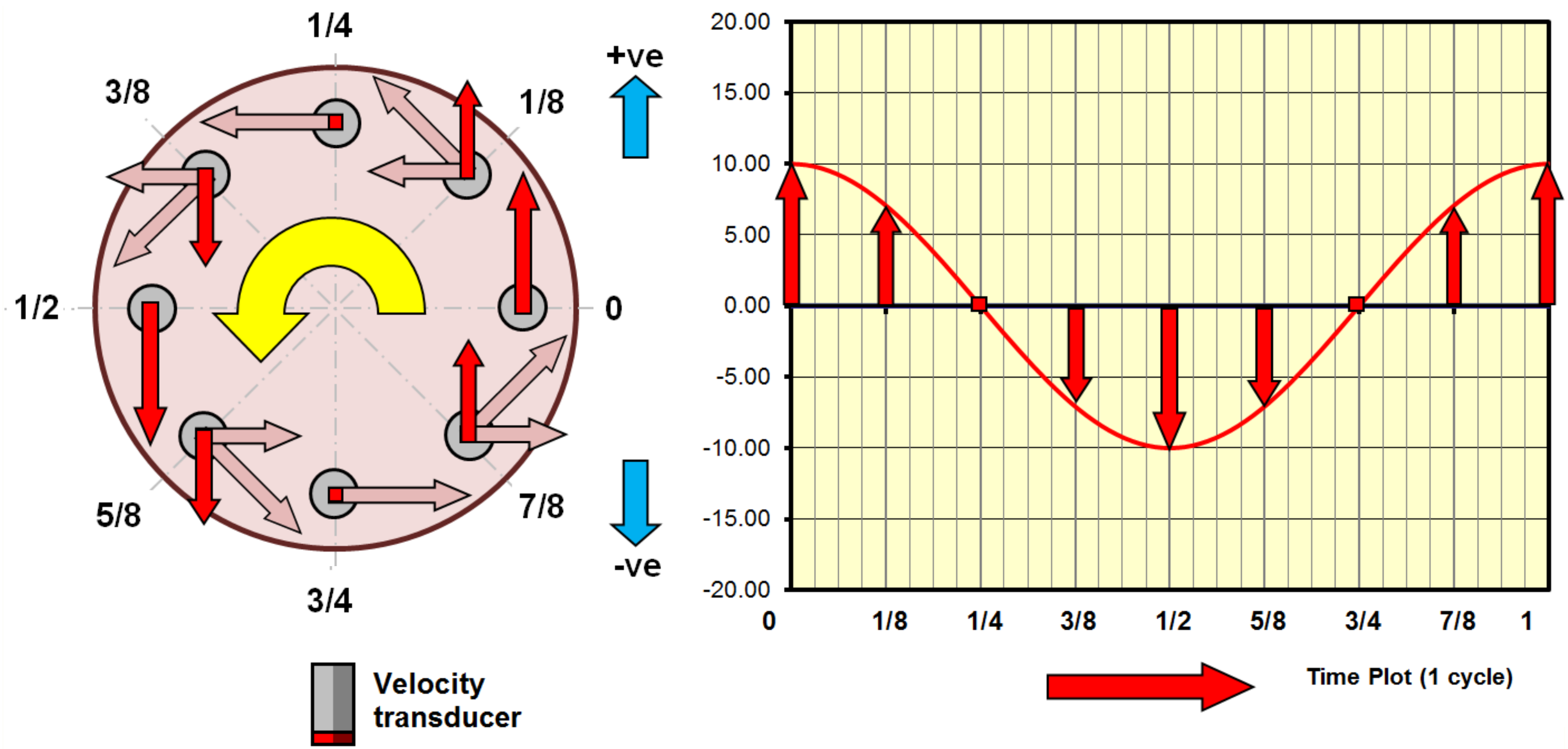




Spectrum CBM Ltd

Task 2b: Velocity Waveform Solution

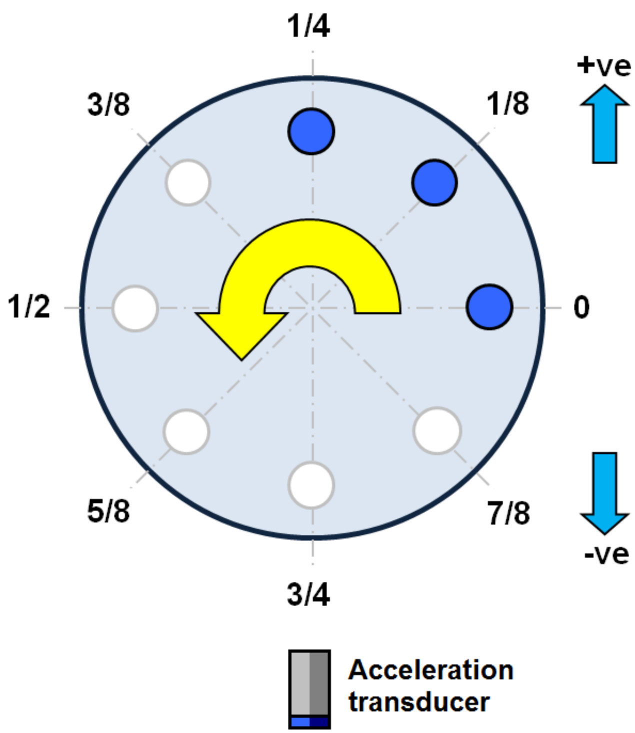
- Assume a rotating unbalanced disc

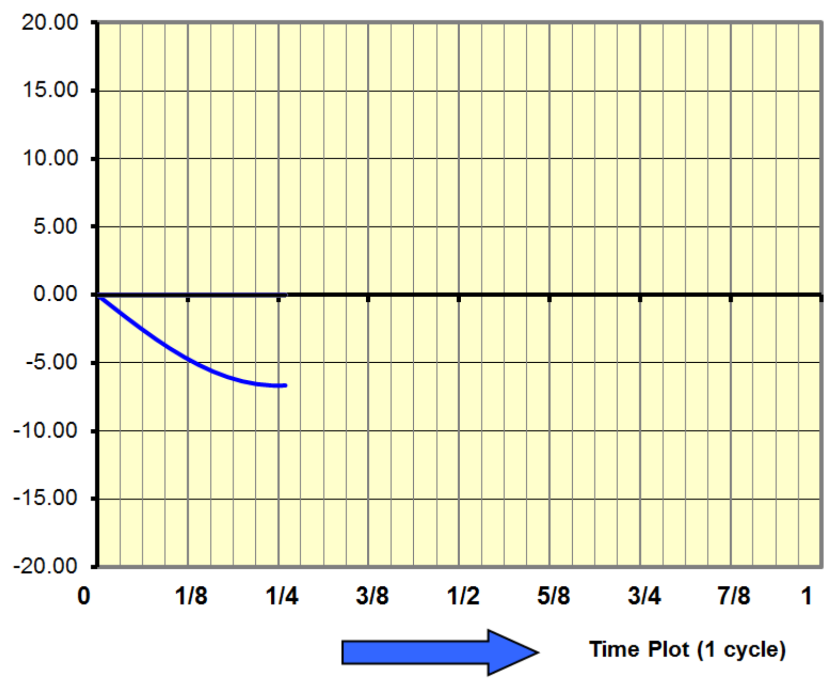


Spectrum CBM Ltd

Task 2c: Acceleration Waveform

- Draw what you would see at each 1/8th of a revolution on the time trace grid provided.
- We've started you off with the first three points
- We've assumed max acceleration amplitude is ±6.67 units peak

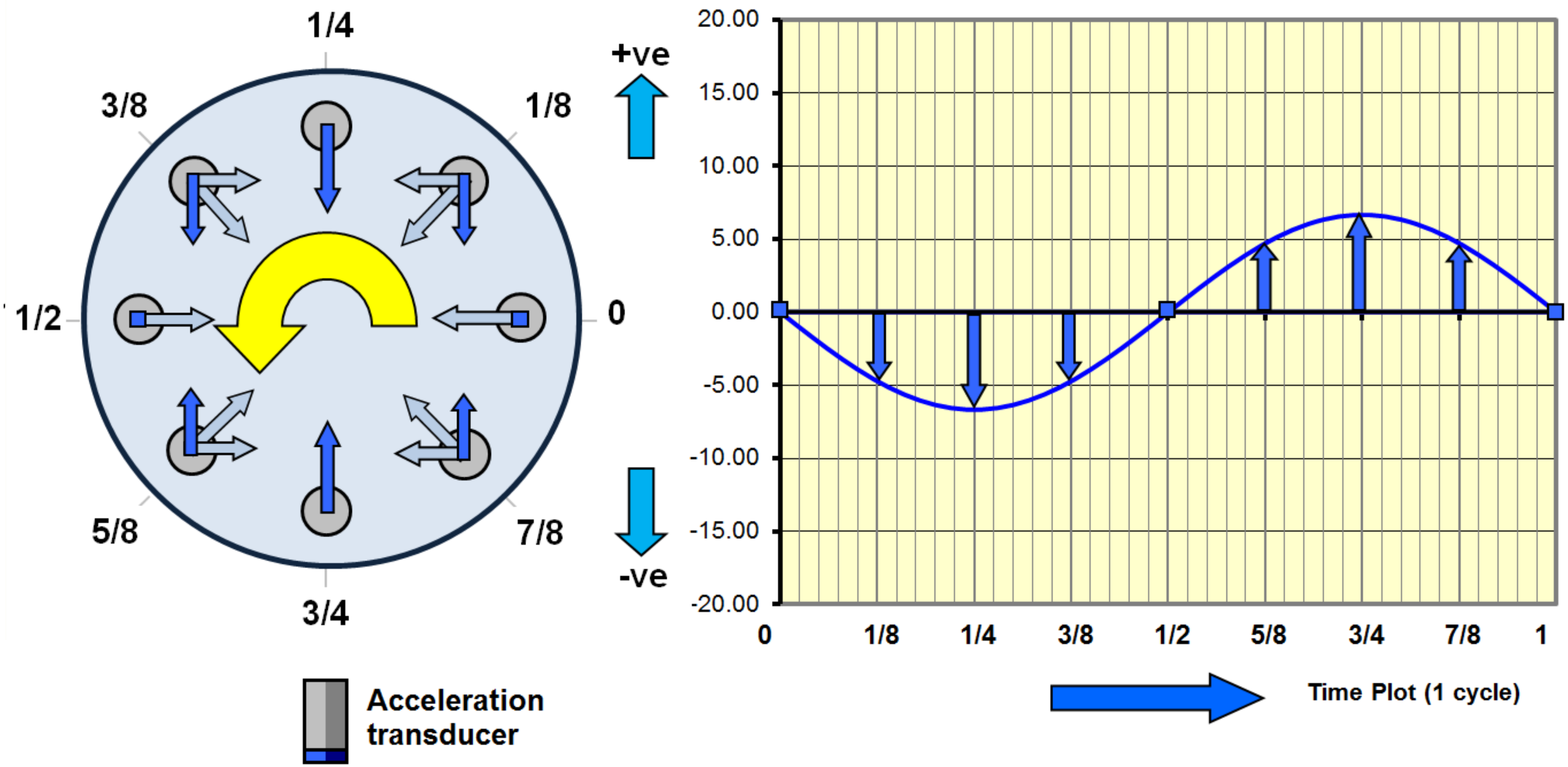




Spectrum CBM Ltd

Task 2c: Acceleration Waveform Solution

- Assume a rotating unbalanced disc



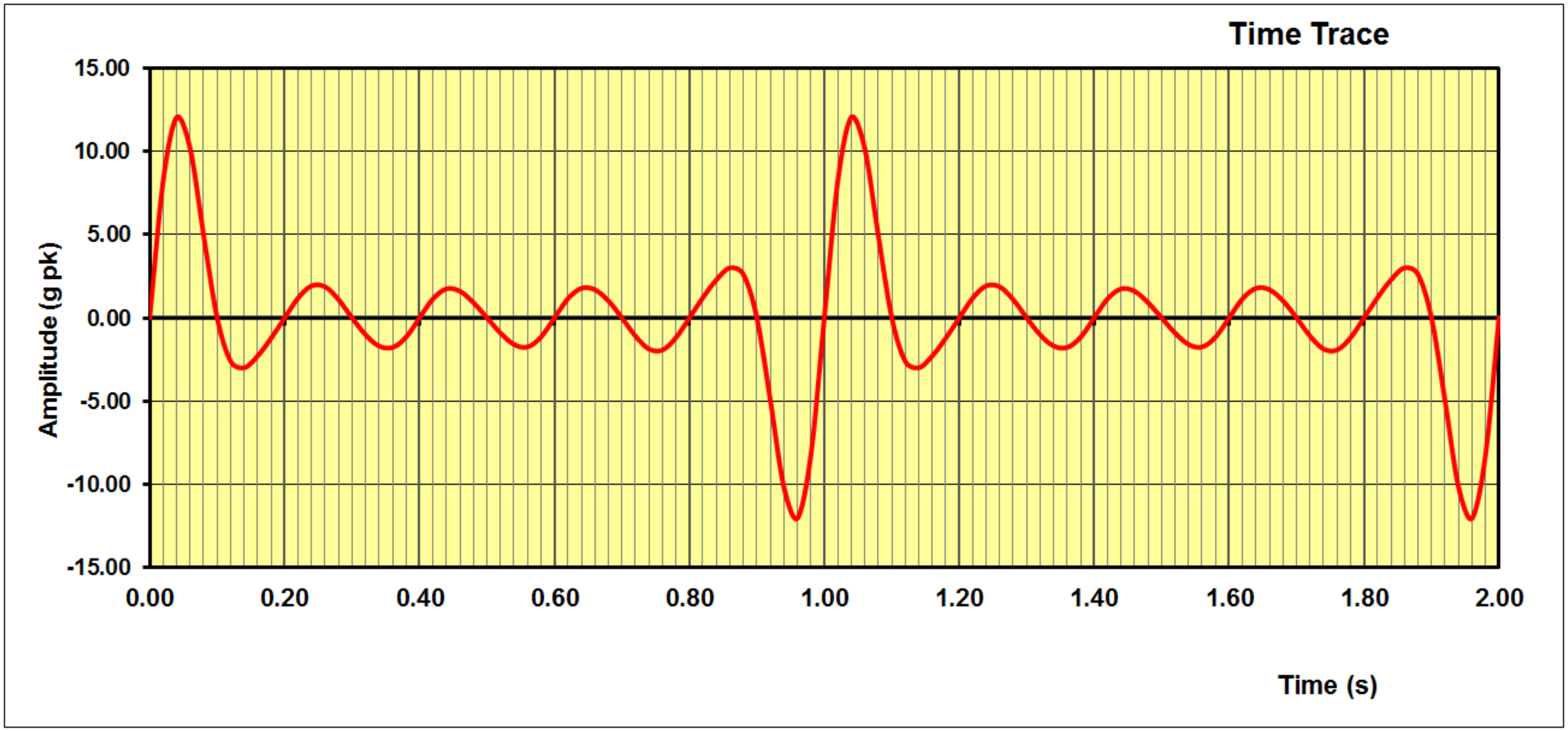
Analysing Smooth Signals

- All the examples so far produce smooth signals
- These are periodic sinusoidal waveforms
- They are ideal candidates for an FFT
- They will produce a clear spectral component
  - Of course, unbalance is a very common fault
  - It produces a large clear 1x component in the spectrum
  - The amplitude of the unbalance component is usually accurately indicated

Spectrum CBM Ltd

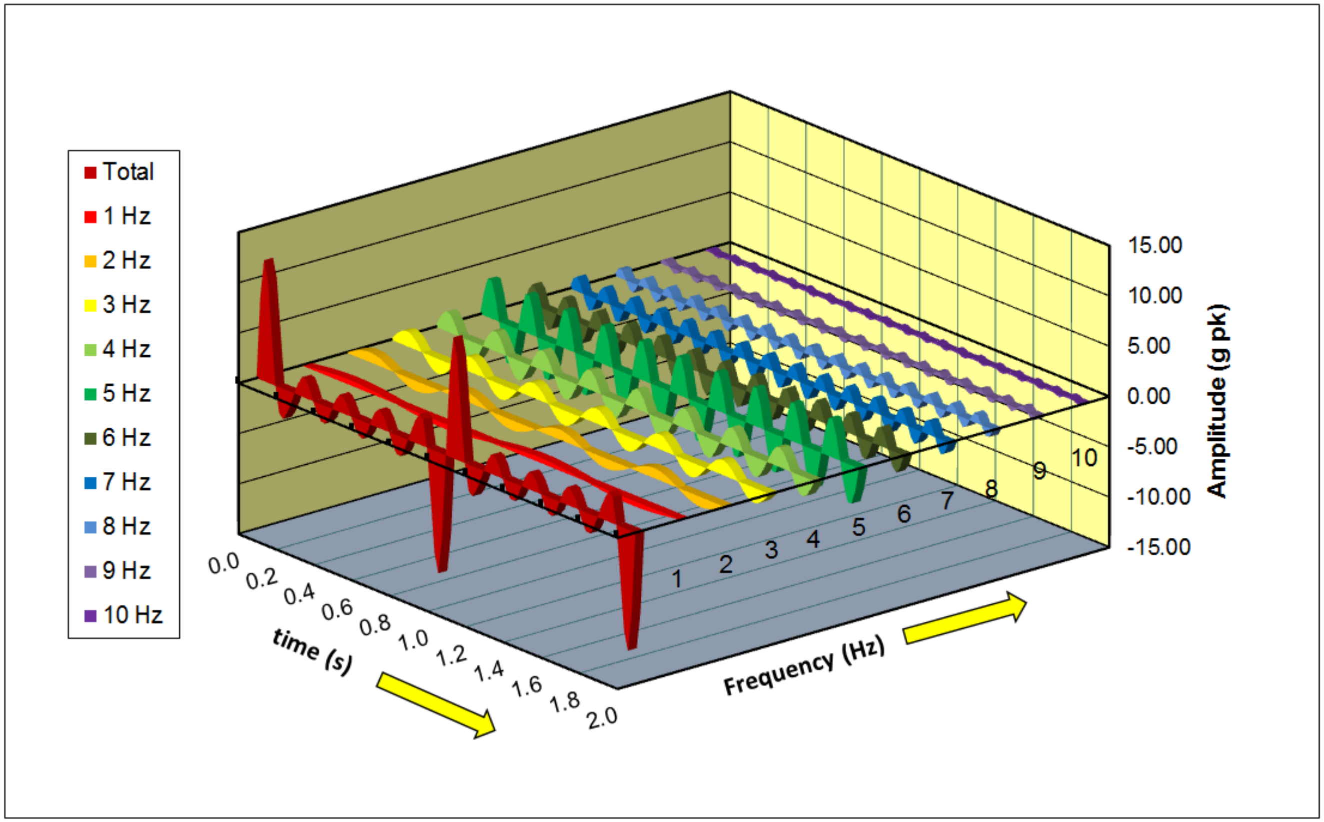
Example Time Domain Plot

- A time trace plot is shown here
- The plot has both positive & negative values of 12 *g* pk, (24 *g* pk-pk)



Time and Frequency Domain

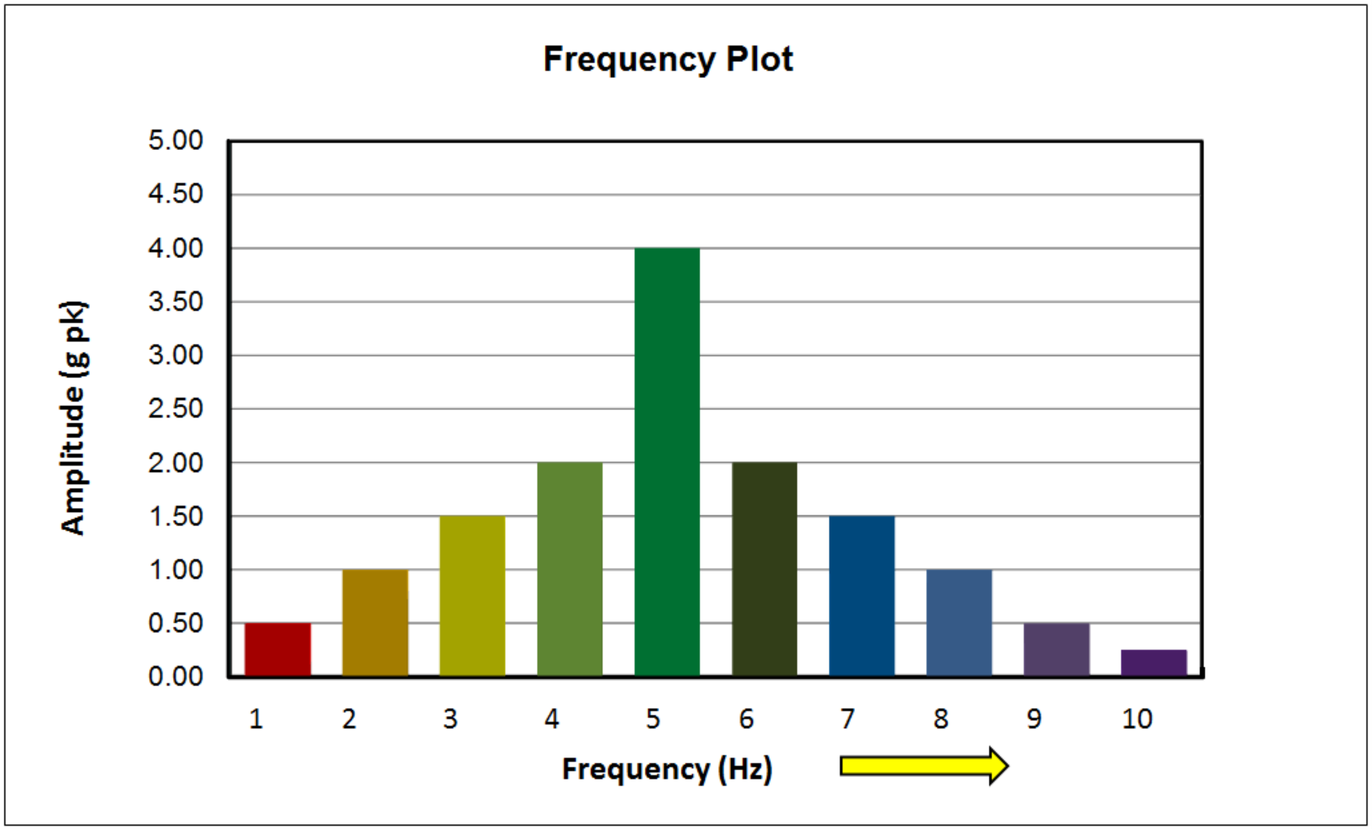
- The left hand **[red]** plot is the original vibration acceleration time signal
- It has a large peak once per second with a value of +12 *g* pk, (24 *g* pk-pk).
- It appears to contain ten components. The largest of the components is approximately 4 *g* pk at a frequency of 5 Hz.



Spectrum CBM Ltd

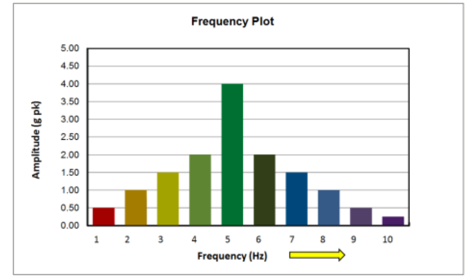
Frequency Domain

- This is a spectrum of the time trace we’ve just seen
- See how the vibration now only has positive values, and a maximum of 4 *g* pk



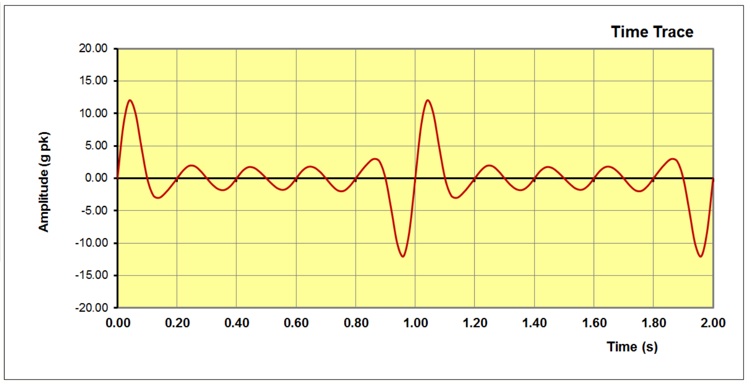
Spectrum CBM Ltd

Frequency Domain

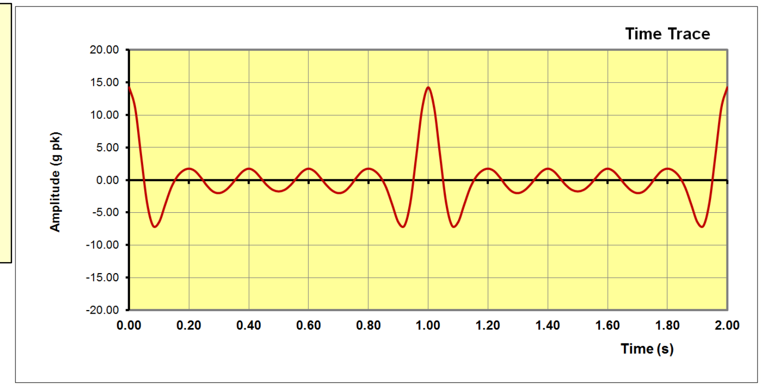


- This spectrum could be from many time traces
- All the signals shown below have this same spectrum

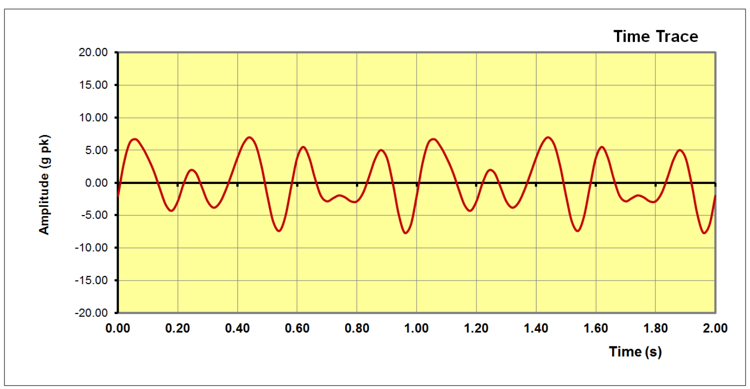
Key values
g pk 12.03
g rms 3.92
CF 3.07



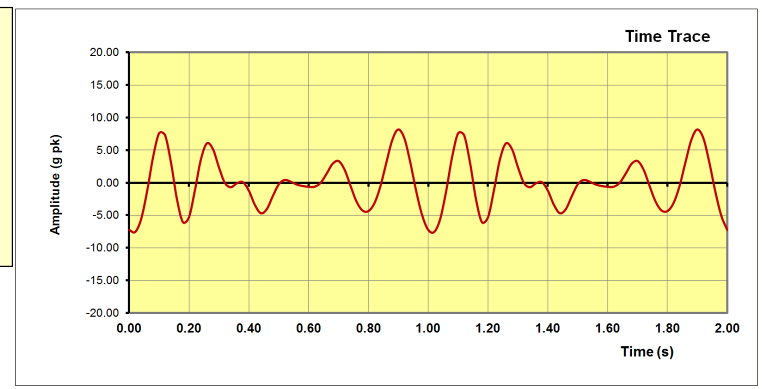
Key values
g pk 14.25
g rms 4.17
CF 3.42



Key values
g pk 6.98
g rms 3.93
CF 1.78



Key values
g pk 8.18
g rms 3.99
CF 2.05

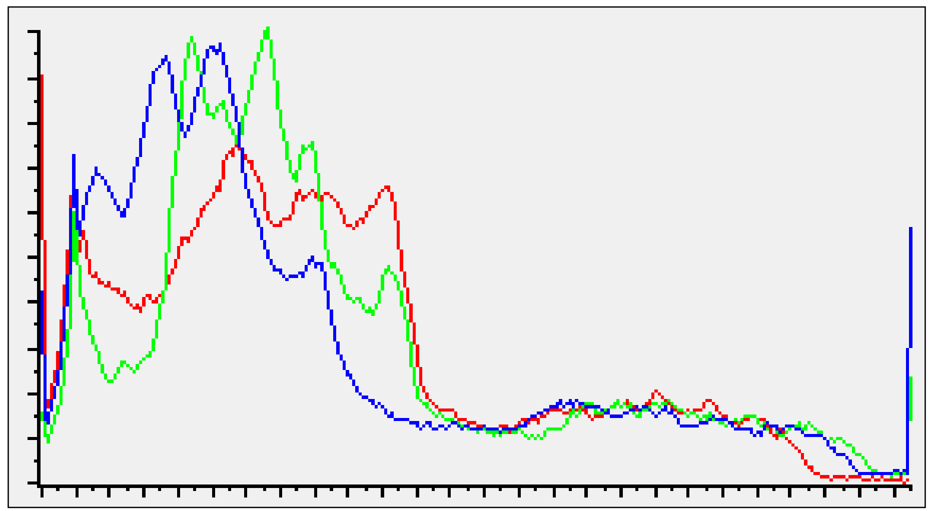


Measuring Periodic Vibration

- Generally FFT works well on periodic signals
- In particularly on single sinusoids
  - Good frequency accuracy
  - Good amplitude accuracy
- With mixtures of sinusoids
  - Good frequency accuracy
  - May be errors on amplitude (<10% to >50%)

Other Types of Spectra

- Here we have a photo, and a spectrum of the 3 primary colours
- The spectrum shows the photo's distribution of red, green and blue, not what's in the picture



Vibration Spectrum – Basic Fault Set

Mechanical: e.g. Unbalance (1x), Misalignment (1x, 2x), Looseness (1x, 3x)

Show as clear peaks

Best viewed in velocity

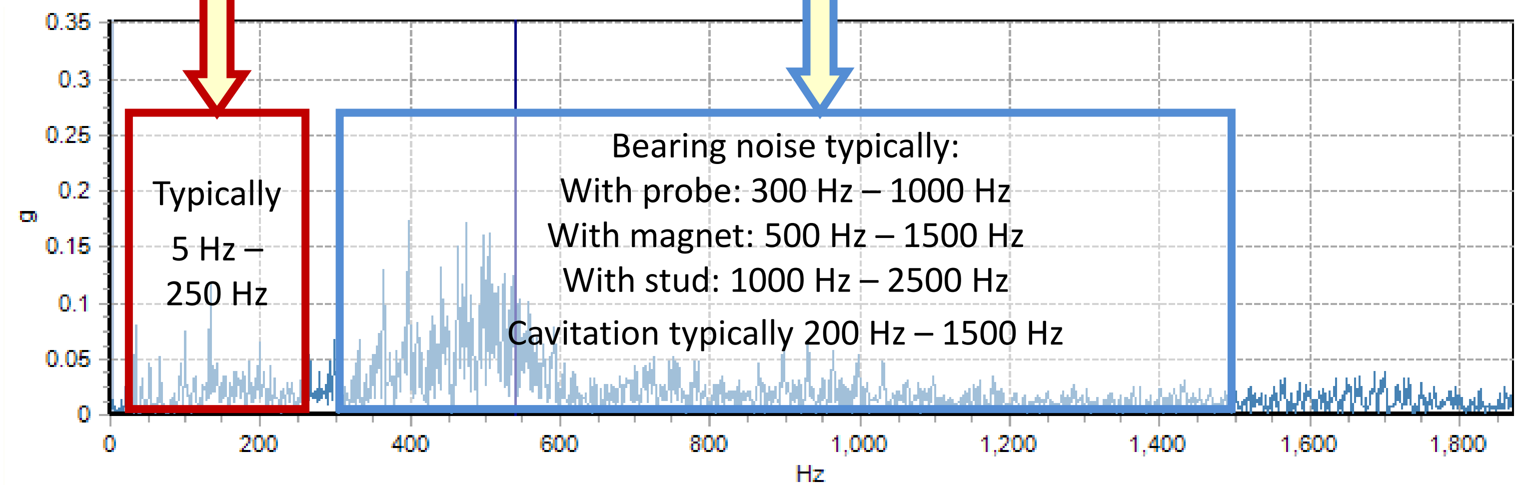
Noise: e.g. poor lubrication, bearing wear

Shows as a broad hump centred on 500 Hz – 1500 Hz

Impacts: e.g. bearing damage

Shows in peaks (harmonics & sidebands) over the hump

Best viewed in acceleration



- Note: VA Cat I practitioners should be able to recognise these basic faults (when set up by a VA Cat II or higher)

Spectrum CBM Ltd

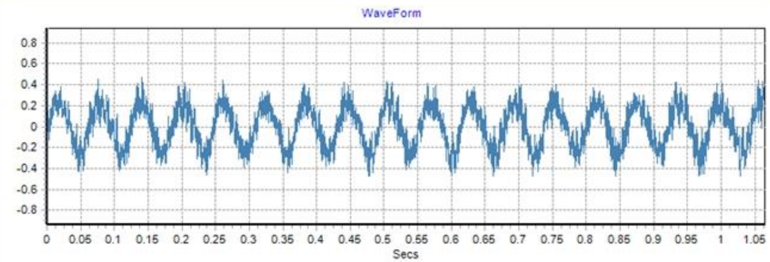
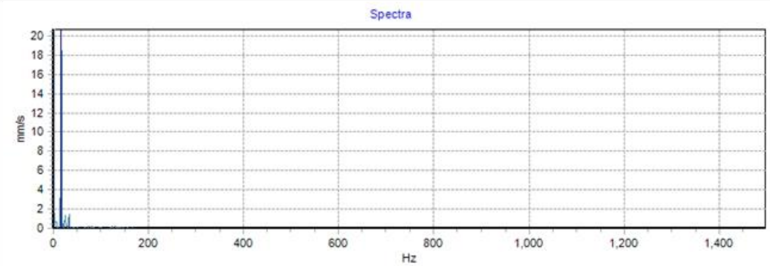
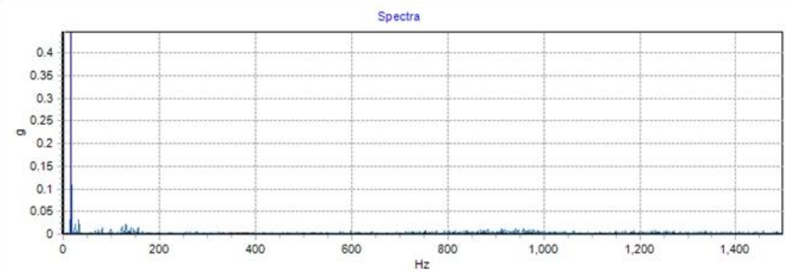
Task 3: Recognising Common Faults

- Here are some details about this example:

Details	Description	Picture / Schematic
Type	Belt driven centrifugal exhaust fan	
Lift Weight	1550 kg	
Rotational Speed	Motor speed: 1430 rev/min (23.8 Hz) Fan speed: 954 rev/min (15.9 Hz)	
Motor Power	135 kW	
Support	Mounted on fabricated steel sub-frame onto spring mounts on high-level steel superstructure	

Spectrum CBM Ltd

Task 3a: Fault Recognition – Exhaust Fan Example 1

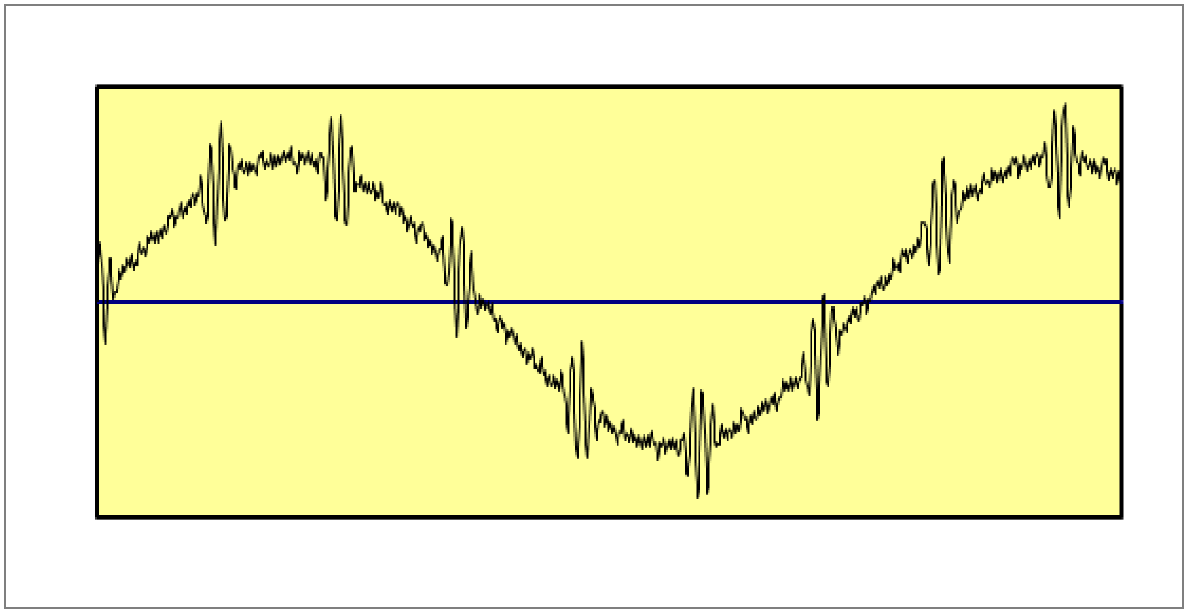
Measurement Features	Time / Spectra
Time Trace: Sine wave. Has some noise overlaid. **Crest Factor**: Low, typically 1.5 – 2.5 In this example: *g* pk = 0.47, CF = 2.45	
Spectra: Large peak at running speed. Highest amplitude radially. **Frequency:** Main component at running speed (1x) **Other Freq:** May have small 2x or 3x harmonics Example: velocity pk = 20.67 mm/s @ 15.94 Hz (956 cpm)	
Accel Spectra: **Frequency:** Main component at running speed (1x) **Other Freq:** May have harmonics and noise Example: acceleration pk = 0.22 *g* @ 15.94 Hz (956 cpm)	

Parameter	Units	Status	Fault Diagnosis
Velocity:	v r.m.s	High	*The fan vibration velocity is too high* *The fan is probably unbalanced*
Acceleration:	*g* r.m.s	Normal	
Acceleration:	*g* pk	Normal	
CF		< 3	

trum CBM Ltd

Vibration Mixtures

- In real life, signals can be more complex
- They may also contain many components including sine waves, shocks, impacts & noise

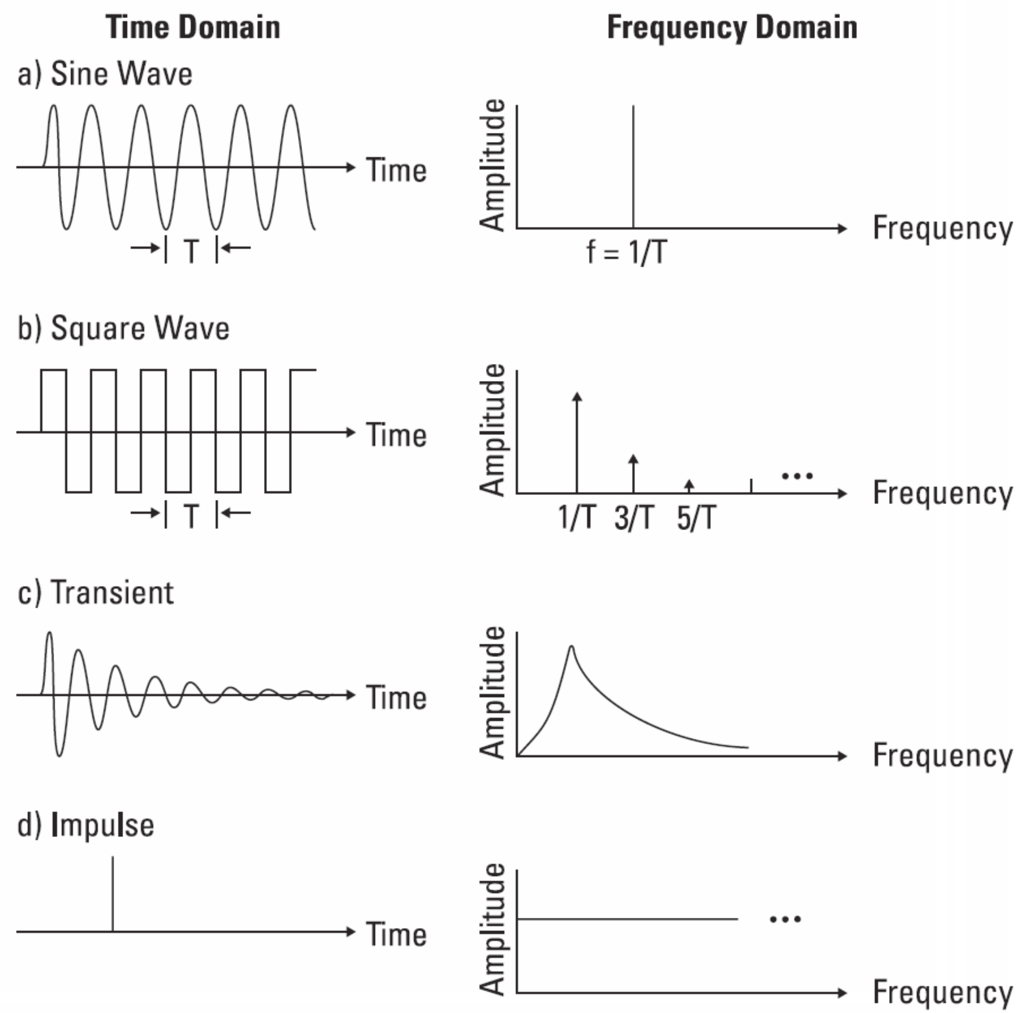


Acquiring Raw Vibration Data

- All transducers output a continuous signal
  - Voltage or current output
  - Continuous signal acquisition (Analog)
- Analog to Digital
  - Discrete data acquisition

Examples of Time to Frequency

- Here are some examples of different types of time domain signal and corresponding FFT
  - Ref: The Fundamentals of Signal Analysis - Application Note 243, Agilent Technologies



Measuring Non-Periodic Signals

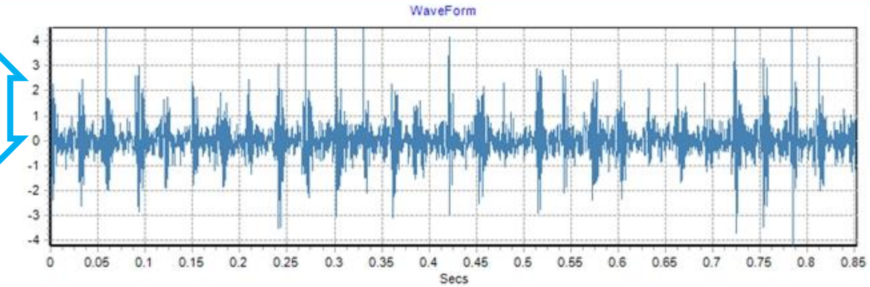
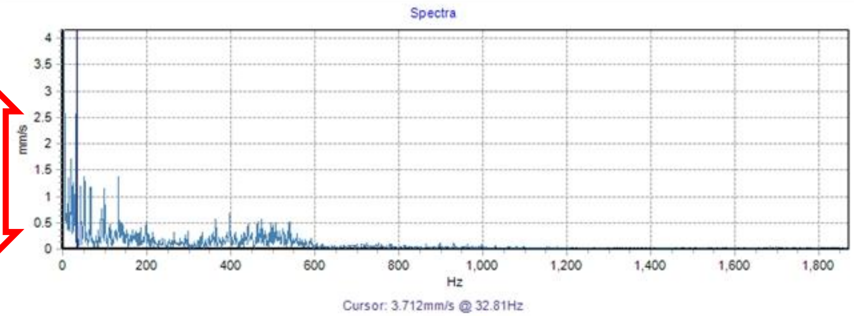
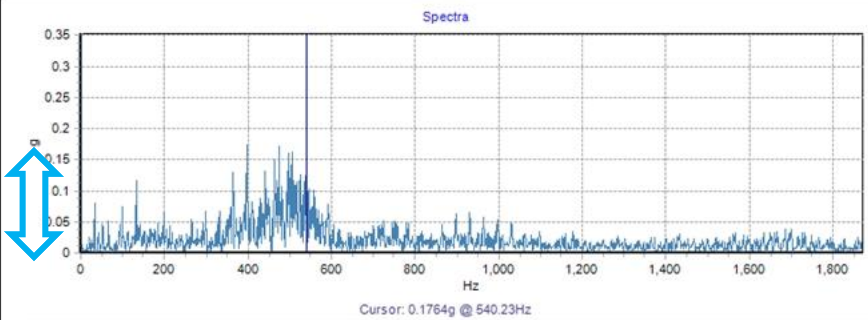
- Non-Periodic signals may contain:
  - Large amplitudes with short duration (Spikes)
  - Bursts of activity
- These are usually not sinusoidal waveforms
  - They are not ideal candidates for FFT
  - They will not produce a clear spectral component
- Bearing noise and damage are common faults
  - They produce many components in the spectrum
  - The true peak is not accurately indicated
  - The humped shape of the spectrum is an important factor

Task 3b: Exhaust Fan Example 2

- Here are some details about this example:

Details	Description	Picture / Schematic
Type	Belt driven centrifugal exhaust fan	
Lift Weight	550 kg	
Rotational Speed	Motor speed: 1430 rev/min (23.8 Hz) Fan speed: 1000 rev/min (16,7 Hz)	
Motor Power	28 kW	
Support	Mounted on fabricated steel sub-frame onto spring mounts on high-level steel superstructure	

Spectrum CBM Ltd

Measurement Features	Time Waveform / Spectra
Time Trace: Impacts may show as large "spikes". Waveform may contain noisy central "backbone", with impact "ribs". Usually has some symmetry. Crest Factor: High >4 Example: *g* pk = 4.54, CF = 6.5	
Velocity Spectra: Amplitude normal, but may have many other peaks **Frequency:** Main components at (1x, 2x etc) **Other Freq:** Small hump around 500 Hz Example: velocity pk = 3.7 mm/s @ 32.8 Hz (1968 cpm)	
Acceleration Spectra: Rounded hump with white space underneath showing noise. Impacts distributed over hump as smaller peaks / sidebands. Spectra amplitude often less than 1/10th true peak. **Frequency:** High frequency hump 500 – 2500 Hz **Other Freq:** Often overlaid with bearing harmonics Example: acceleration = 0.18 *g* pk @ 540 Hz (32400 cpm)	

Parameter	Units	Status	Fault Diagnosis
Velocity:	v r.m.s	**Normal**	*The vibration acceleration is too high* *The bearing is probably damaged*
Acceleration:	*g* r.m.s	**High**	
Acceleration:	*g* pk	**High**	
CF		**> 4**	

Limitations of Spectra

- A time trace produces one unique spectrum (depending on the processing set-up)
  - However the same spectrum could have come from an infinite number of time traces
- It is important to understand that the spectrum contains much less information than a time waveform
- A spectrum loses the original shape (phase) of the signal and contains only amplitude and frequency
- It is difficult to estimate the true peak if you only have a spectrum available

Conclusions

- Spectra Advantages:
  - FFT good for periodic mechanical faults:
    - unbalance, misalignment & looseness
  - These usually show as single or multiple harmonic peaks
  - Modulated signals are indicated by sidebands in the FFT
- Spectra Disadvantages
  - Impact amplitudes are badly underestimated in the FFT
- Tips:
  - Remember time traces will show better information
  - Crest factor is useful especially where there are noise & impacts

Questions

- Thank you for your attention
  - You are welcome to contact me if you have questions about BSI or ISO standardisation

References

- British Institute of Non-destructive Testing (BINDT) – www.bindt.org
- British Standards Institute – www.bsigroup.com
- International Organization for Standardization (ISO) – www.iso.org
- ISO 18436-2:2014, Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 2: Vibration condition monitoring
- BINDT INST397, Vibration Monitoring & Analysis Handbook – S R W Mills – BINDT, ISBN 978 0 903132 39 7
- The Fundamentals of Signal Analysis - Application Note 243, Agilent Technologies, www.agilent.com
- Random Data: Analysis and Measurement Procedures, Fourth Edition, By Julius S. Bendat & Allan G. Piersol, 2010, John Wiley & Sons, Inc.
- An Automatic Approach for Proper Amplitude Estimation in CBM Applications, Thomas L Lagö and Alan Boyer, 17-20 June 2013, BINDT – The Tenth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies

Spectrum CBM Ltd