Twist, Windup, Torque and Torsional Vibrations by Counting Gear Teeth and Encoder Pulses with Considerations to Shaft Angle Domain Analysis

A White Paper

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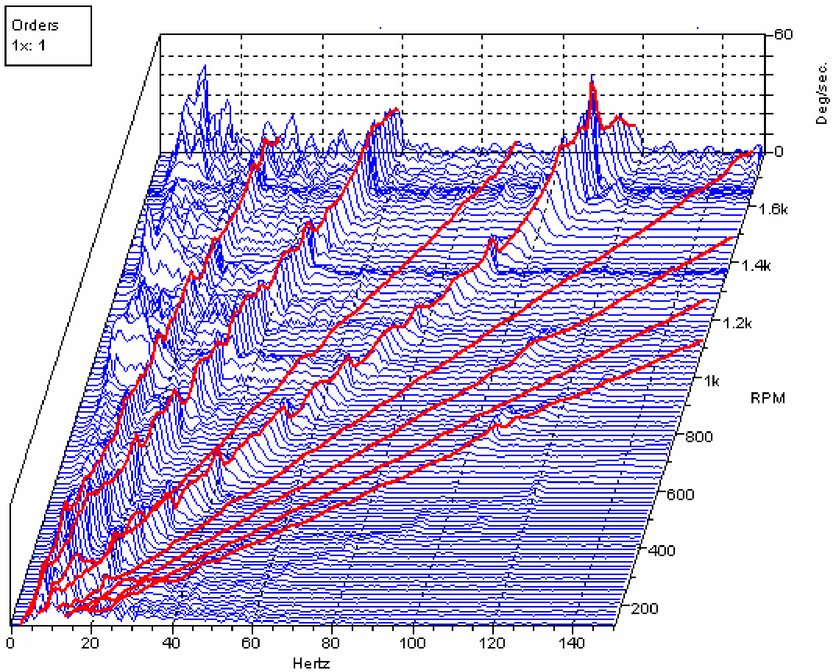


Torsional Vibrations

- What are Torsional Systems?
  - Drivelines
  - Belt Drives
  - Chain Drives
  - Valve Trains
  - Transmissions
  - Gears
- What is their Purpose?
  - To carry Torque from one place to the other
  - To carry Position, Speed and Acceleration from one place to the other
- What is the Measurement Challenge?
  - To measure how Torque and Kinematics are carried across the System and to describe the Nature of the Deviations in terms of Elasticity, Inertia, Torque and Contact.
- What is the main Measurement Obstacles?
  - The System Components are continually moving relative to any reasonable Instrumentation Platform
  - Large parts of the System reside in inaccessible Places

Invasive Sensing Techniques

- Telemetry
  - RF methods with Antennae and Batteries
    - Requires highly skilled personnel
    - High Maintenance
    - Invasive
  - Slip Rings
    - Invasive
    - Unreliable
- Shaft Mounted Sensors
  - Strain Gauge
    - Gives local Surface Strain
    - Requires highly skilled personnel
  - Opposing Accelerometers
    - Gives rotational Acceleration
    - Good for Transmission Error
    - Filters out Shaft Translations
- Discussion
  - Advantages
    - Give direct physical Measurements
      - Strain
      - Acceleration
      - Speed
    - No special Signal Processing necessary behind the Transducer System
  - Disadvantages
    - Invasive
    - Expensive
    - Skill and Maintenance Intensive

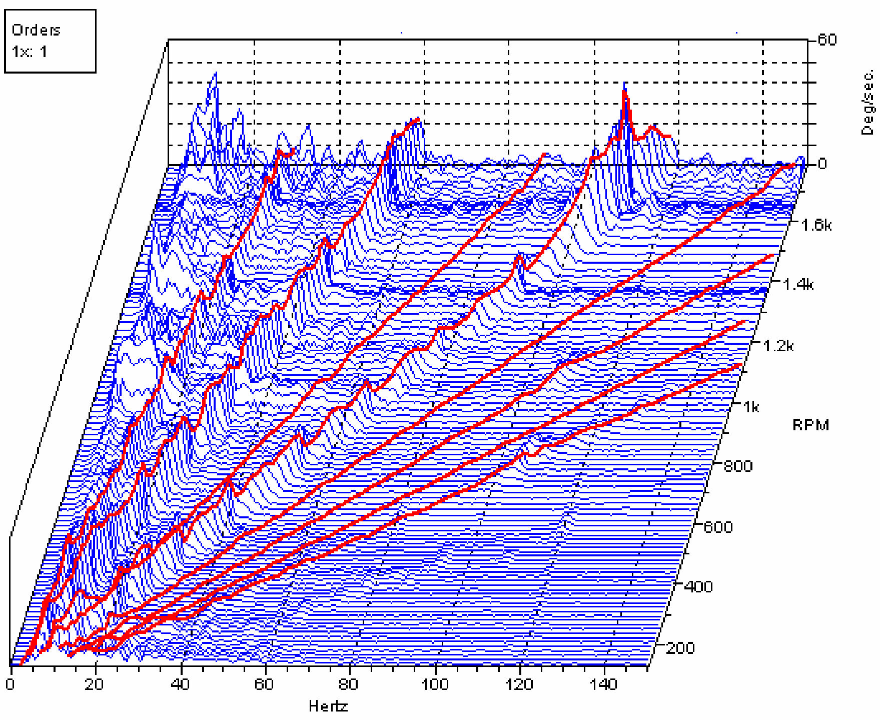
Non Contact Sensing Techniques

- Non Contact Sensing
  - Doppler Laser
    - Measures speed of top and bottom of shaft; subtracts. Same comments as opposing accelerometers. Fixturing is difficult in moving test.
  - Proximity Sensors on Gears
    - Optical and eddy current probes tell of tooth pass events. Instantaneous speeds are easily calculated. Typically 20 to 200 pulses per revolution.
  - Shaft Encoders
    - Ditto. Typically many hundreds and thousands of pulses per revolution. Good ones may be expensive.
  - Roll your own Strap-On Encoders
    - Glue on printed bar patterns observed by optical sensors. Uneven spacing mandates geometric calibration. Shaft and pulley mount.
    - Strap on belts with metal patterns. Observed with eddy current probes. Calibration desirable.

- Discussion
  - Advantages
    - Easier Fixturing, especially in crowded and nasty places
    - Inexpensive
    - Suited for moving tests
    - Ideal for Continuous Monitoring
    - Ideal for End of Line Test
  - Disadvantages
    - Strain must be calculated by information from two adjacent Measurement Positions
    - Requires special purpose Software in addition to normal Analyzer Functions
    - Geometric Calibration and Baselines required for Jittery Encoders

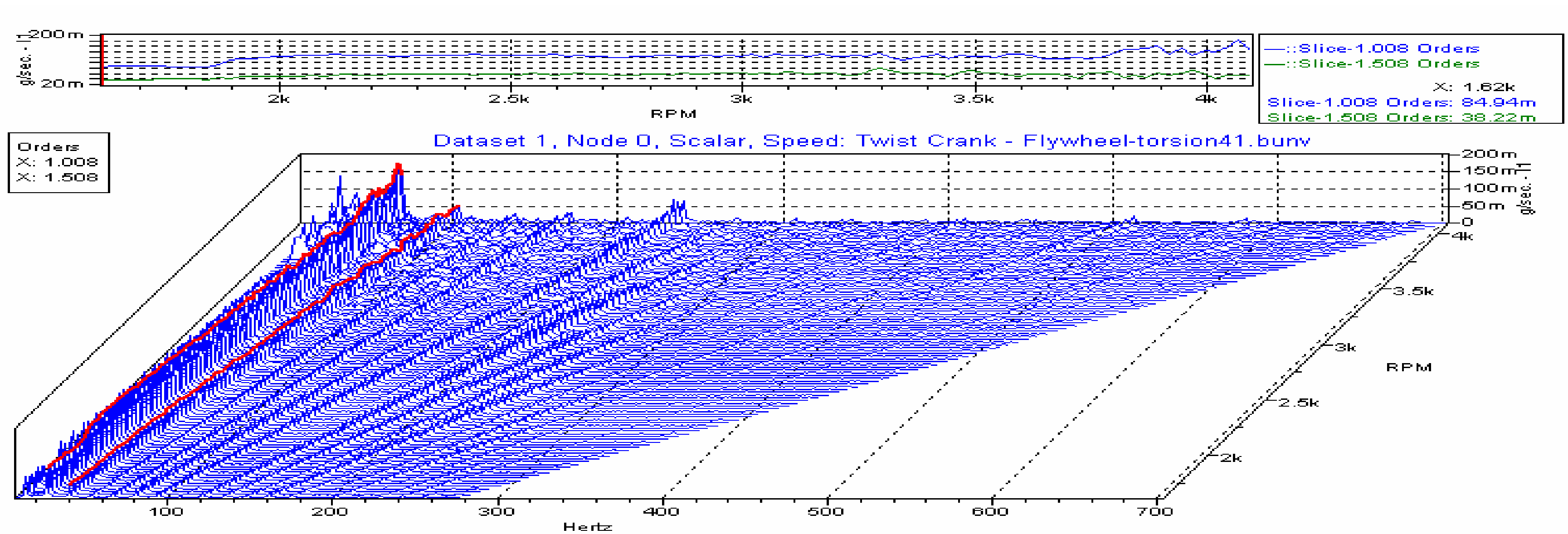
Small Electric Motor

- Encoder with 2000 Pulses per Revolution
- Analog Channel Sampled at 200 KHz
- Four Pole Motor
  - Excitation at 1/rev, 2/rev and 4/rev
  - Resonance at 106 Hertz
  - Sidebands at 0.3333/rev



Crankshaft Twist in 3 Cylinder Diesel

- Eddy Current Probes at Front Crank (72 teeth) and Flywheel (106 teeth)
- Analog Channels sampled at 50 KHz
- Four Stroke Engine
  - Firing order at 1.5/rev
  - Torsional Resonance at 248 Hertz
  - Steady Torque Load at 1/rev and 1.5
  - Twist in degrees by integrating Speed and subtracting Crank and Flywheel



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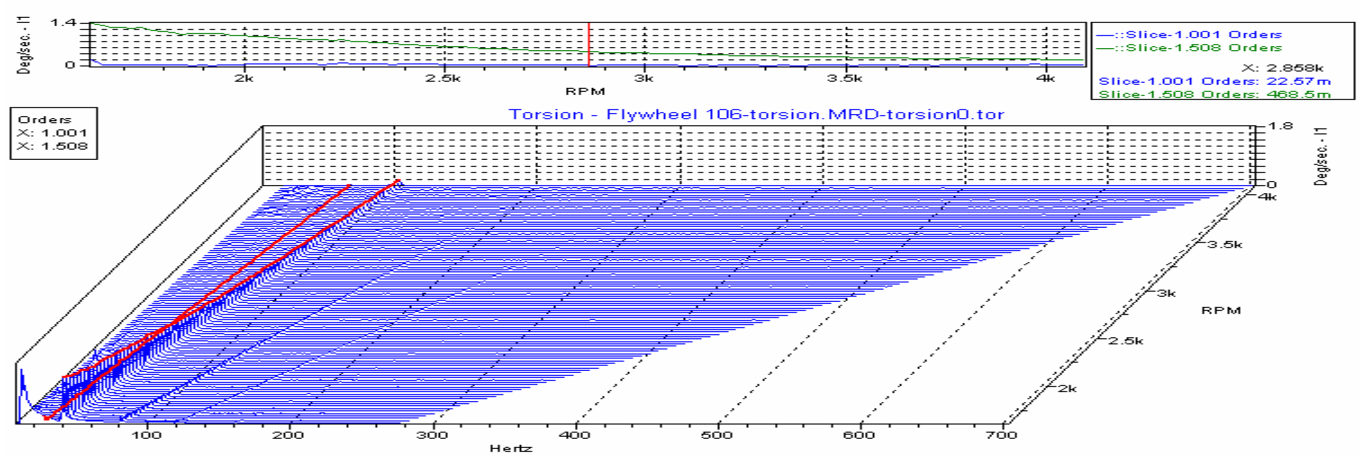
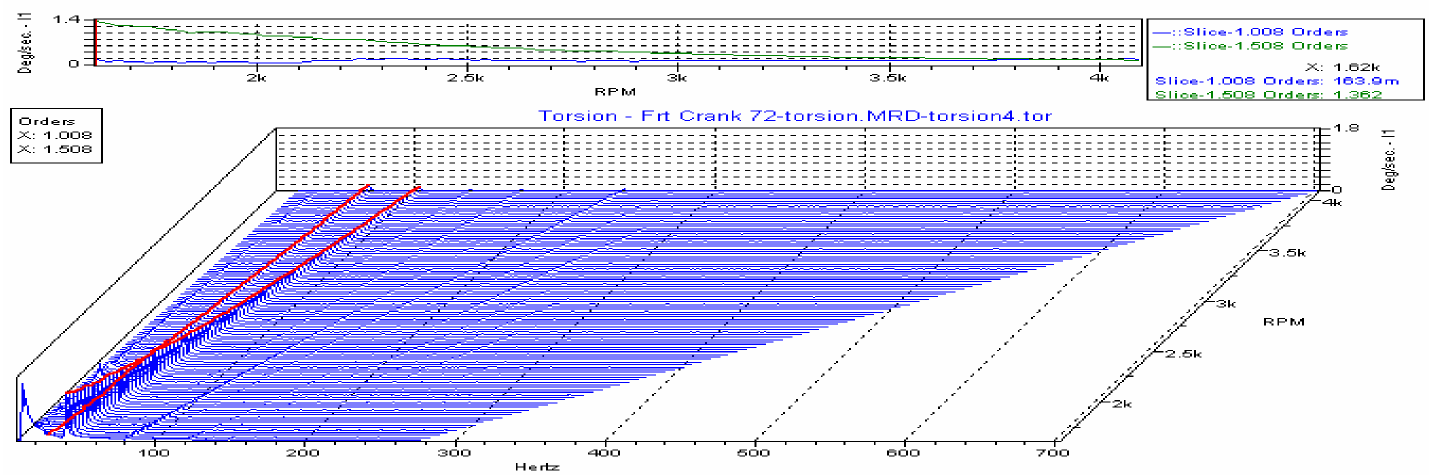
  - Higher Firing Order Torque at Low RPM
  - Twist in degrees by integrating Speed and subtracting Crank and Flywheel





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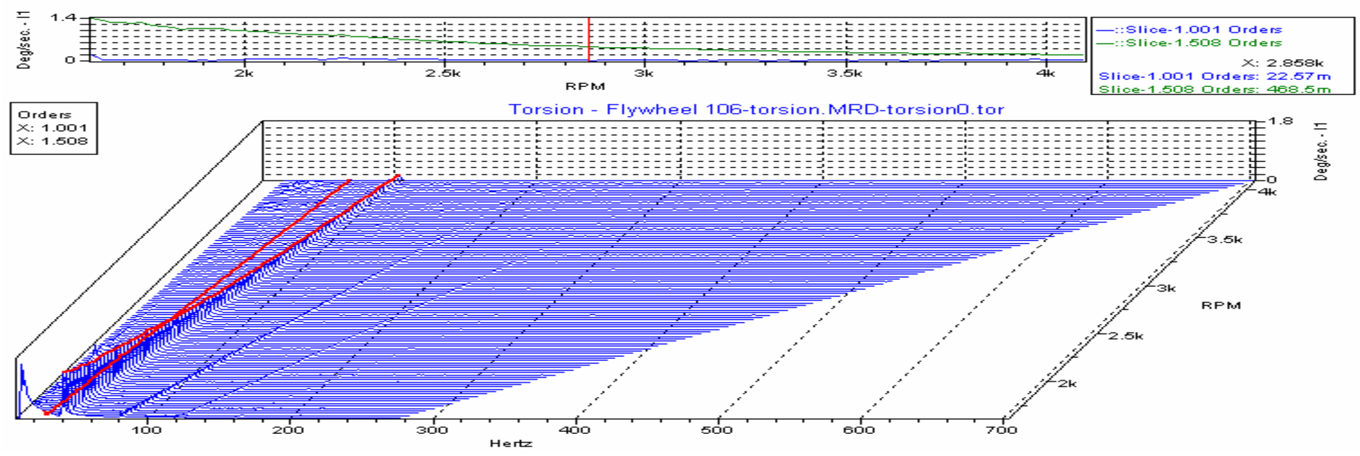
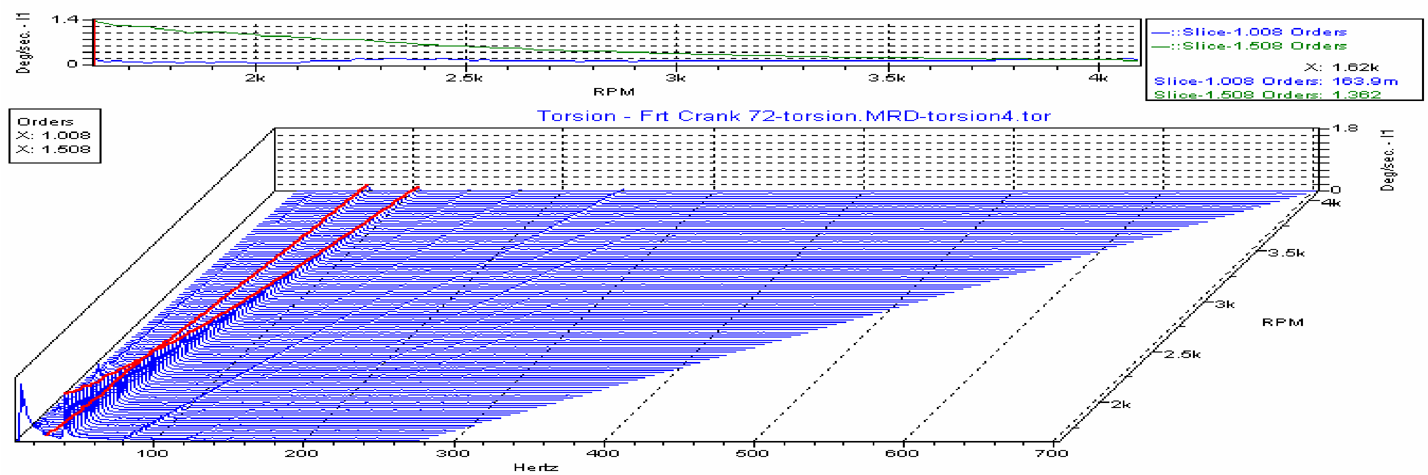
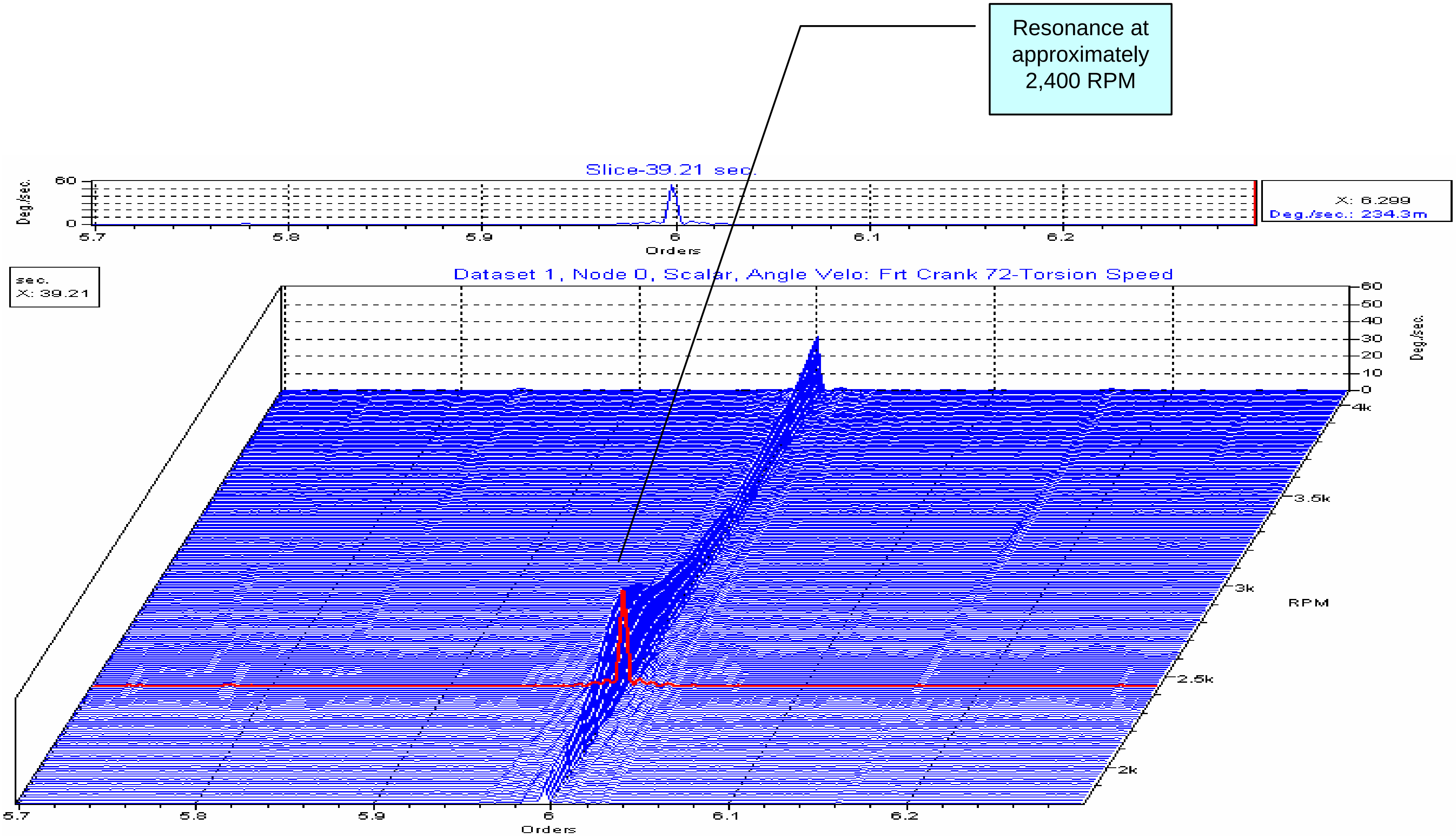


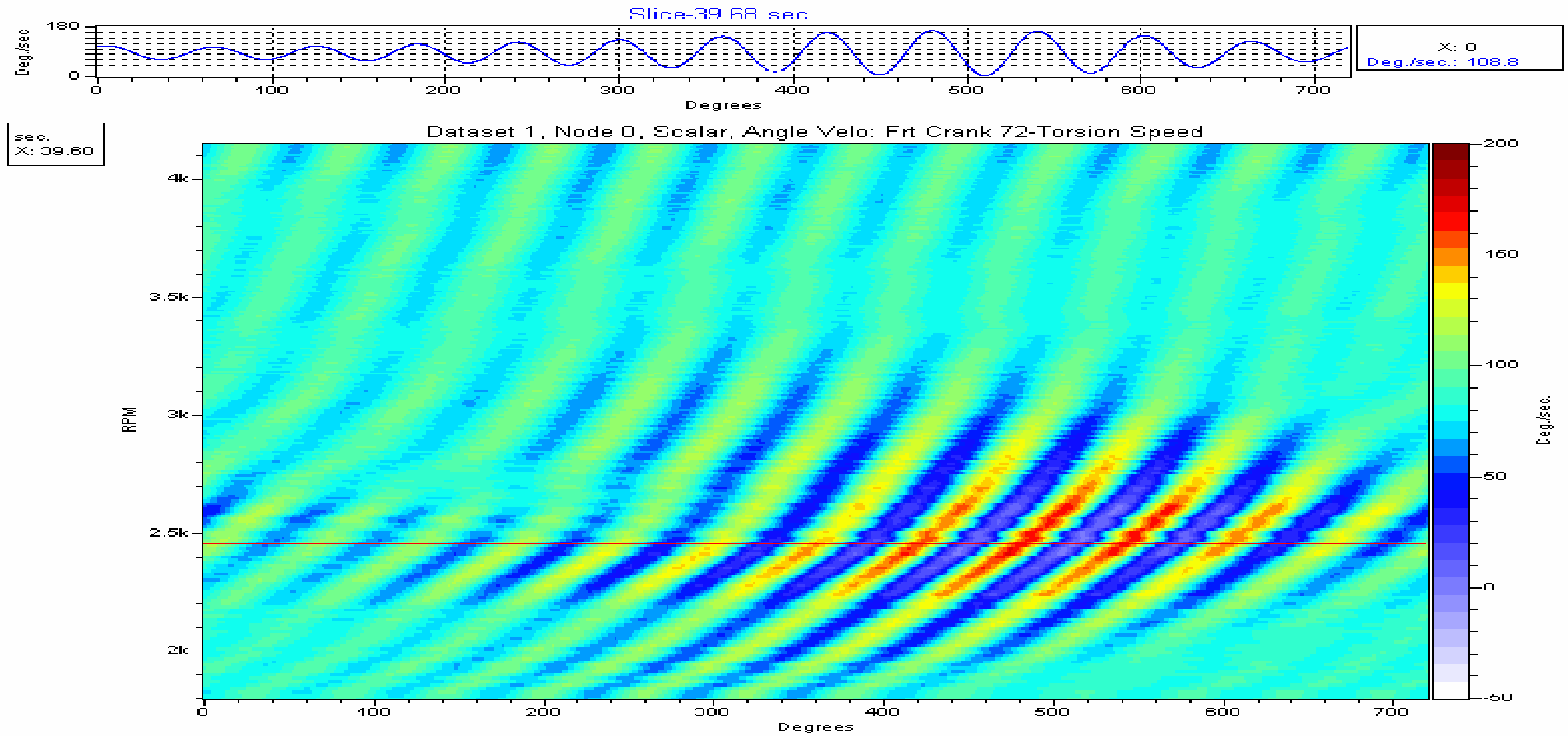


Crankshaft Angle Domain – Synchronous Averaging around sixth Order of three Cylinder Diesel Crankshaft Torsion passing through a Resonance



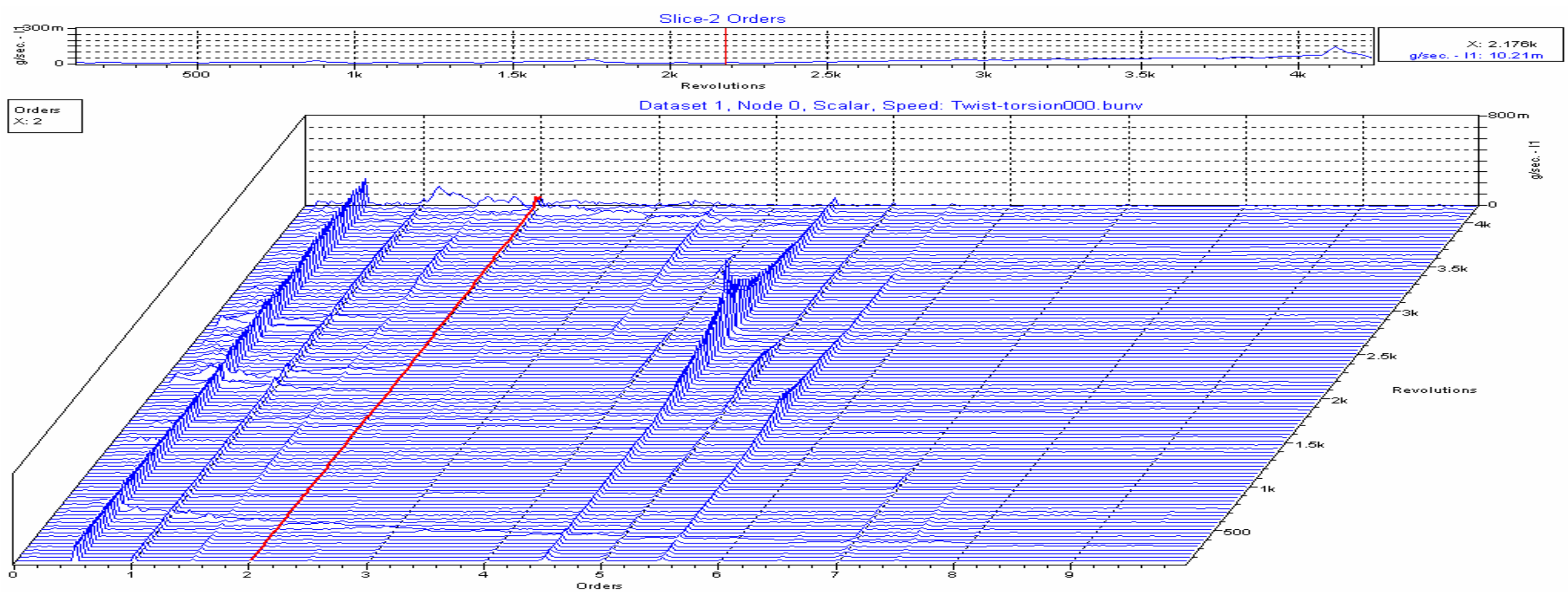
Crankshaft Angle Domain – Synchronous Averaging around sixth Order of three Cylinder Diesel Crankshaft Torsion passing through a Resonance

- Re-sampled to the angle domain, zoomed around the sixth order, plotted at two full cycles at each RPM value in a waterfall of crankshaft angle against RPM
- Phasing only meaningful relative to other points on the crankshaft



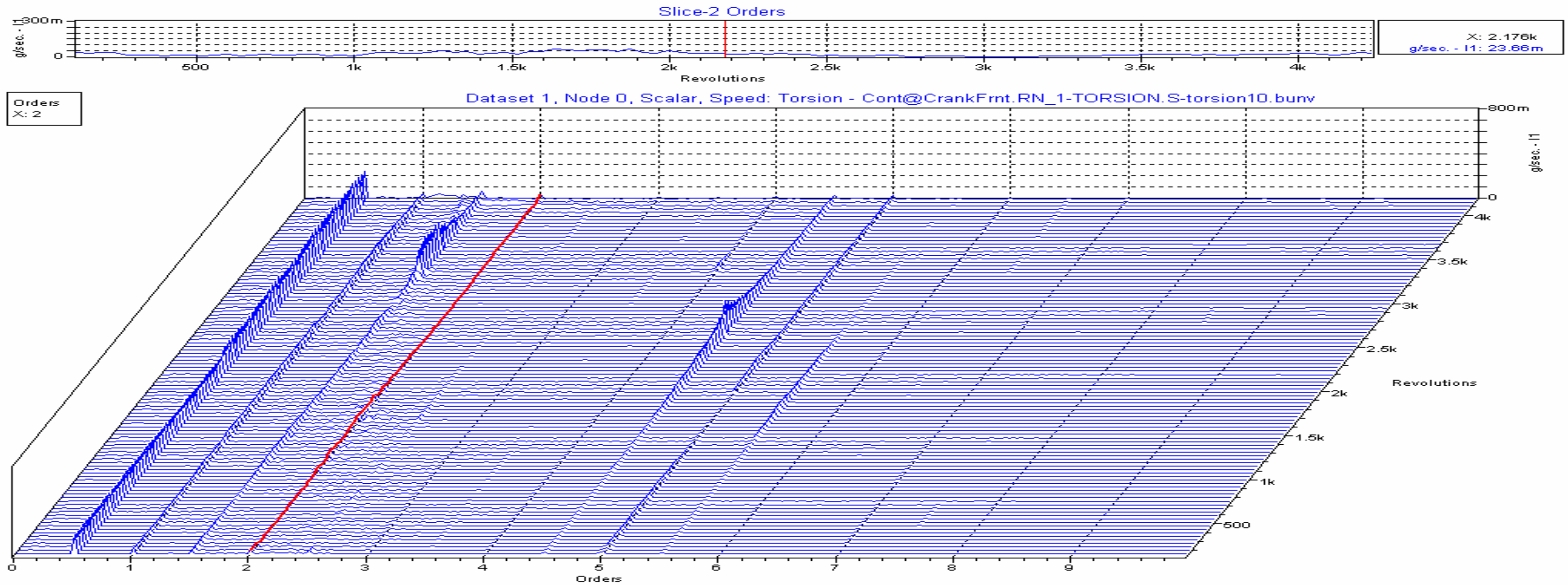
Crankshaft Twist in Formula 1 Engine

- Proximity Probes at Rear and Front Crank
- Analog Channels sampled at 100 KHz
- Torsional Resonance with Cranks out of Phase excited by 4.5/rev
- Trace of Torsional Resonance excited by 1.5/rev – very little twist, but quite visible in the kinematics of the Front and the Rear; see next two slides



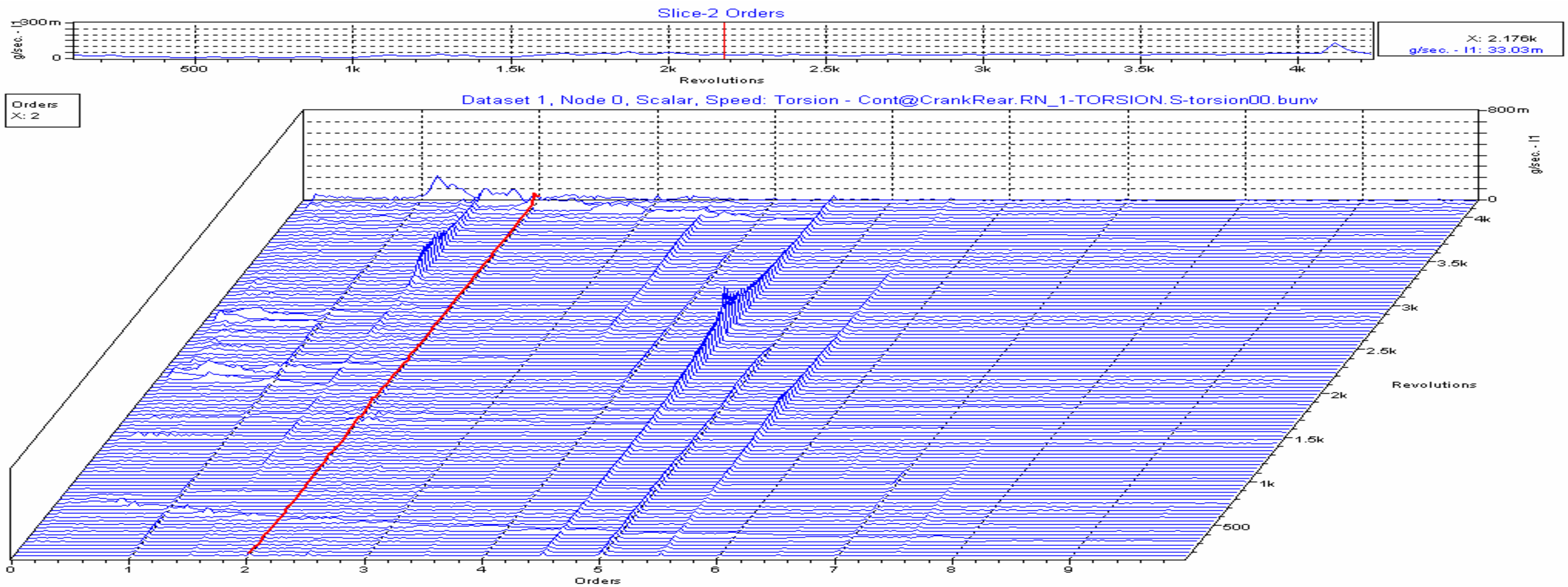
Crankshaft Torsionals in Formula 1 Engine

- Proximity Probes at Front Crank
- Analog Channels sampled at 100 KHz
- Torsional Resonances excited by 1.5/rev 4.5/rev



Crankshaft Torsionals in Formula 1 Engine

- Proximity Probes at Rear Crank
- Analog Channels sampled at 100 KHz
- Torsional Resonances excited by 1.5/rev and 4.5/rev



Sampling Facts in the Order Domain

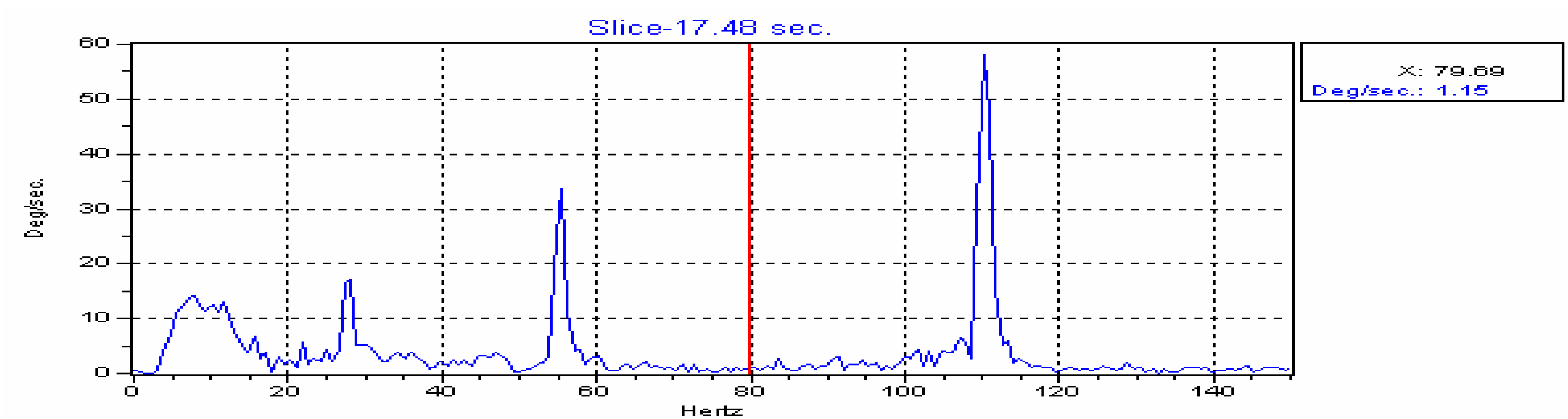
- To measure un-aliased orders up to N, the encoder must have at least 2N pulses per revolution
- The spacing of pulses need not be uniform as long as a geometric calibration is available
  - Geometric calibration – given that the encoder does not deform, its pattern will repeat, and by running the system at fairly slowly varying speeds, a variation of synchronous sampling will allow the estimation of angular spacing of pulses. At calibration time, the baseline for shaft twist can also be determined, so that also DC values of twist may be estimated under torque loads.
- The transformation of pulse event times to shaft speed and position requires that enough samples are taken to identify each pulse. In practice, this will entail about three to five time samples between pulses.
- The accuracy of pulse events is dictated by the temporal sampling rate. The higher the sampling rate, the better signal to noise ratio.
- The torsional signal processing of pulse signals is a time domain process. Antialiasing filters are seldom needed, and should as a rule be avoided.

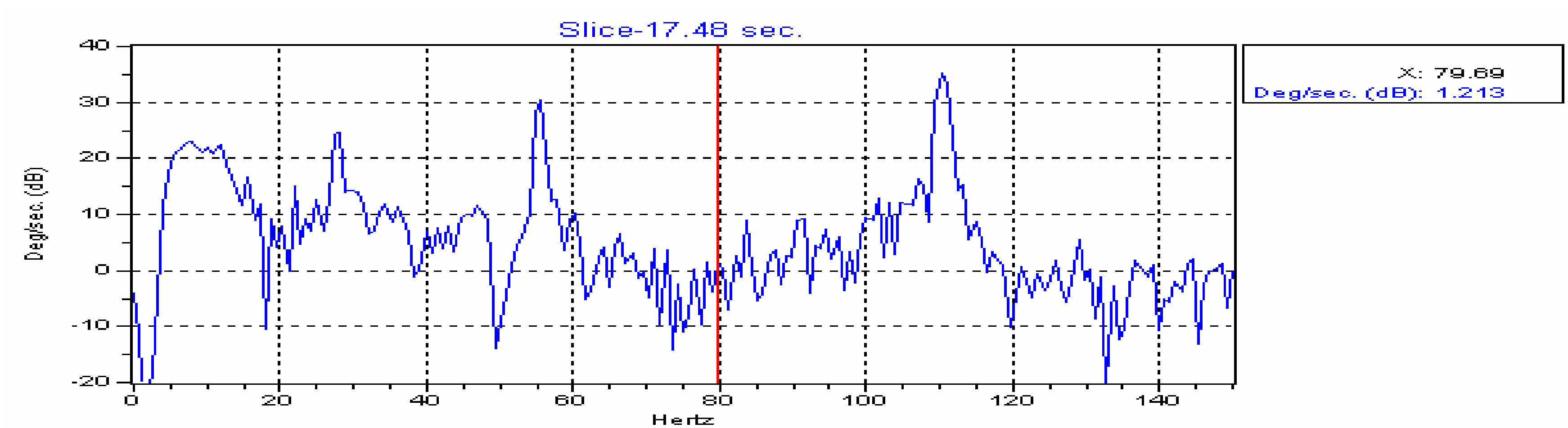
Signal to Noise in Encoder Measurements

- Having a geometrically calibrated encoder, the measurement of shaft position is given by the arrival time of pulses. Since normal measurements are done with a fixed sampling rate, the higher the sampling rate, the more accurate the position measurement.
- The raw signal to noise ratio on angular position is given by
  S/N = 20*Log10(Sampling Frequency/Pulse Frequency)
- This shows that doubling the sampling frequency gives an improvement of approximately six dB in signal to noise
- The calculation of order components entails an averaging done in the FFT; this makes for a remarkable improvement as seen in the next slide.
- Analog channels in NVH systems are typically designed for microphone and accelerometer speeds, e.g. maximum sampling rates of 50 to 100 KHz
- Real improvements in resolution is given by Counter/Timer channels which typically sample between 20 to 100 Megahertz. Some (more expensive) systems can go close to one Gigahertz. At these speeds the limiting factor is jitter in the encoder, which to some extent may be alleviated by geometric calibration.
- The good news is that Counter/Timers are most often less expensive per channel than high quality NVH analog channels.

Signal to Noise in Electric Motor Example

- Sampling at 200KHz
- 2000 Pulses per Revolution
- Nominal S/N at 1800 RPM is 11 dB; Averaging in the FFT improves Level





Cheap Roll Your Own Strap-On Encoders

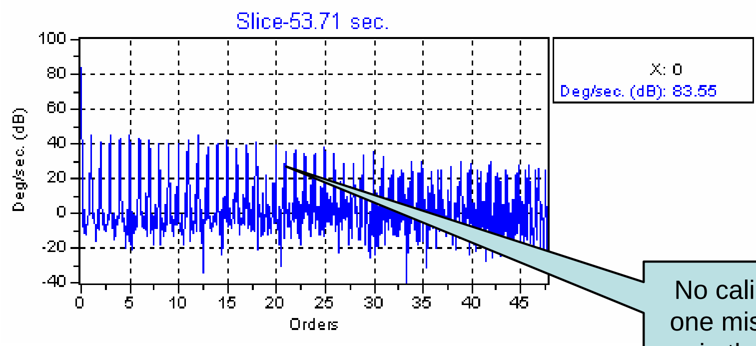
- High precision encoders tend to be expensive due to the uniform spacing between pulses that they guarantee.
- Since geometric calibration procedures are available, one can deploy cheaper encoders with uneven spacing as long as the spacing stays repeatable. Three roll your own encoders will be described here.
- Optic sensor encoders. Here we use a laser optic sensor that will record voltage fluctuations according to a black and white bar pattern.
  - Shaft encoder: Print a bar patterns on an adhesive sheet, strip off the backing and fasten around the shaft. Trim excess material. There will be a “welding seam”, but the calibration will compensate for that.
  - Pulley encoder: Print a radial (fan shape) bar pattern on an adhesive sheet. Proceed as above, but put on the pulley front. The calibration will take care of the off center issues.
- Proximity sensors. Here we use an eddy current probe that detects the presence of metal patterns.
  - Shaft encoder A: Machine a pattern in the shaft.
  - Pulley encoder A: Machine a pattern in the pulley.
  - Shaft encoder B: Prepare a suitable ribbon with a periodic pattern of metal in it; strap/fasten/weld on shaft. Calibration takes care of seams and imprecise fabrication.
  - Pulley encoder B: Choose a drive belt with a metal pattern.
- Laser optic and eddy current sensors can live in nasty environments in that the fragile electronics may be separated from the sensing location by rugged cabling.
- The encoder patterns may be implemented by materials that can handle the environmental conditions, such as heat, transmission fluid, salt water etc.

Things to look for in a Counter/Timer

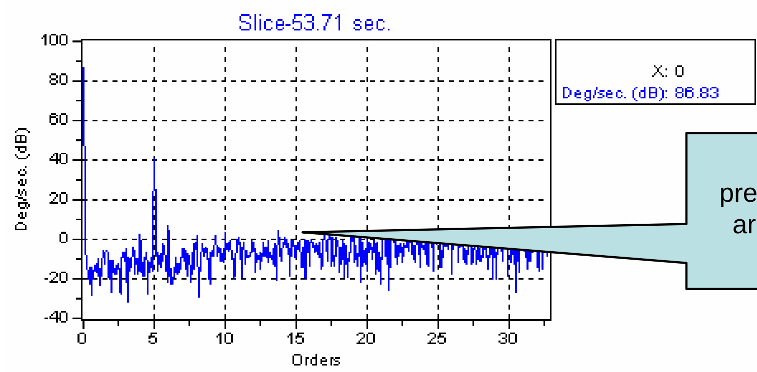
- Sampling rate: the higher the better, at least in the Megahertz range
- High Speed transfer to data acquisition device.
  - DMA (really the best)
  - Sampling the counter: at least 25 Kilohertz
- Synchronous triggering with other counter and analog channels for phase correctness
- Hysteresis and debounce filters

Encoder Calibration – Synthetic Example

- The data was generated in a program with a simulated counter resolution of 80 MHz.
- A numerical study on the effects of calibration, uneven spacing (jitter) of the pulses, and a missing tooth (gap), 100 pulses per rev, shaft speed 1500 to 2500 RPM
- The conclusion is that with the interpolation schemes that we are using, with the calibration, jitter and missing tooth play an insignificant role.
- The signal to noise seems to be around 85 dB on the sweep with 3% jitter and a missing tooth with a fifth order component in the data..



No calibration. Artifacts due to one missing tooth and 3% jitter in the spacing of the teeth

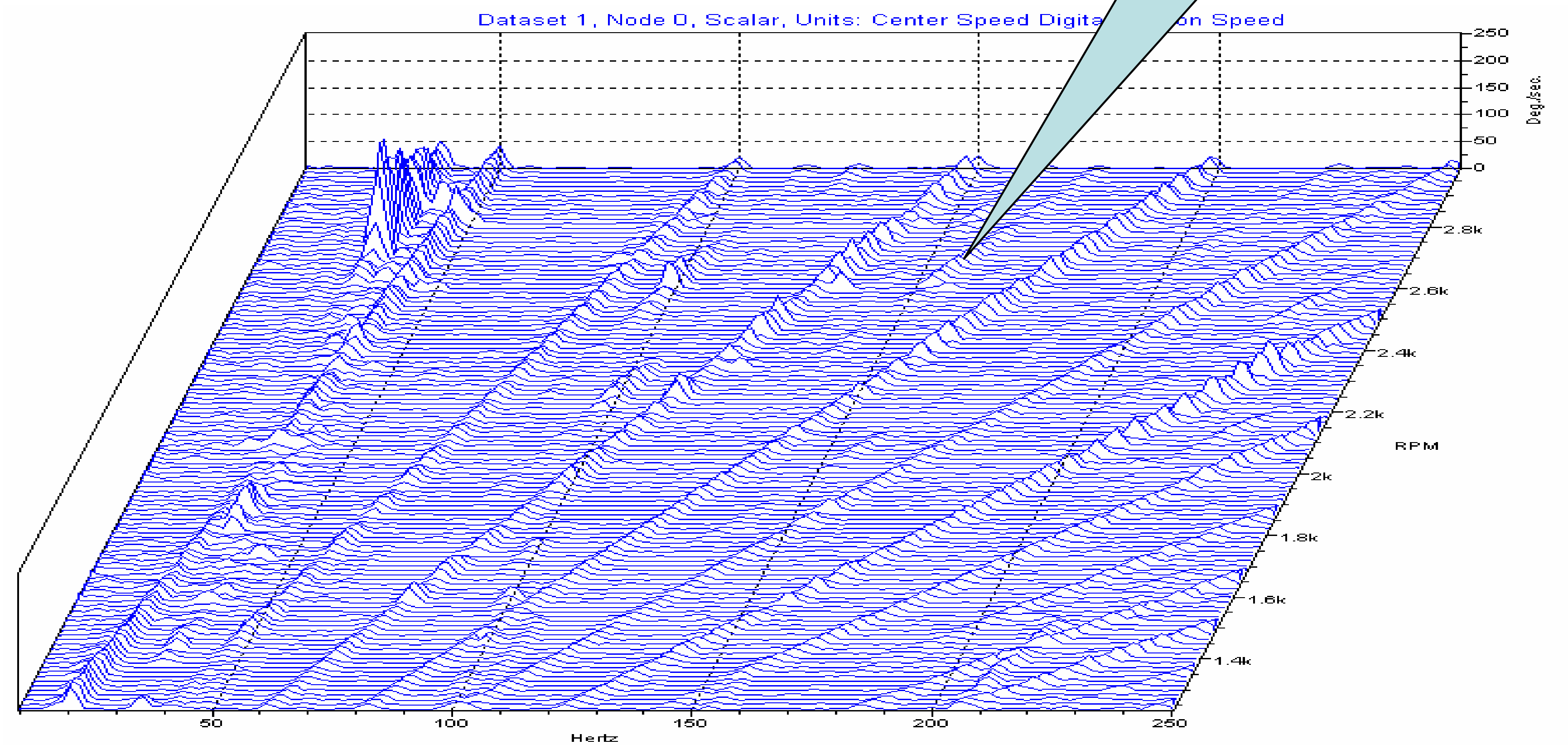


With calibration on the previous data. Small artifacts around the 5th order due to imperfect calibration.

Calibration Effect, Driveshaft with Adhesive Bar Pattern Encoder

- Sampling at 80 MHz with Counter Timer
- 60 Pulses per Revolution
- Shaft Speed from 1200 to 3000 RPM
- Calibration done by running system at constant speed

Notice energy in every integral order. This is contamination by uneven spacing



Calibration Effect, Driveshaft with Adhesive Bar Pattern Encoder

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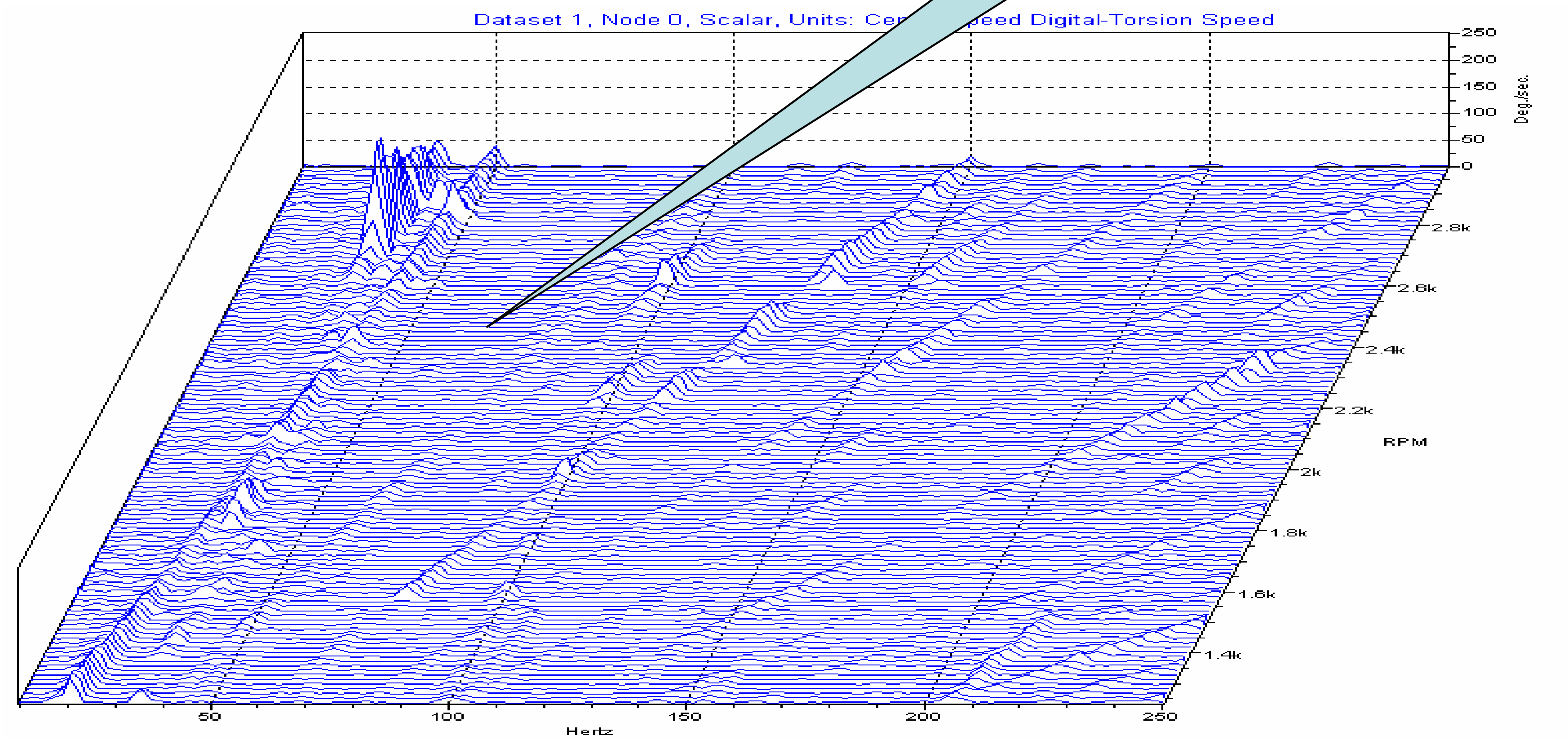
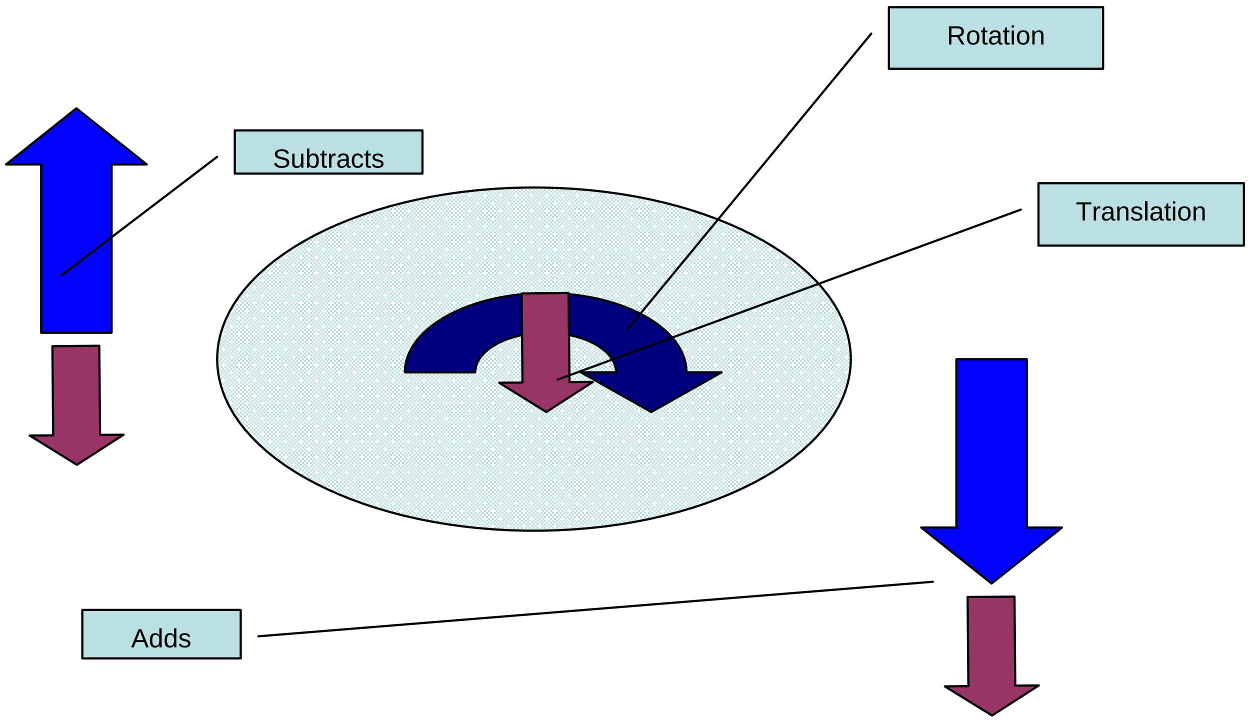
Same data analyzed with Calibration. Notice much more detail in waterfall.



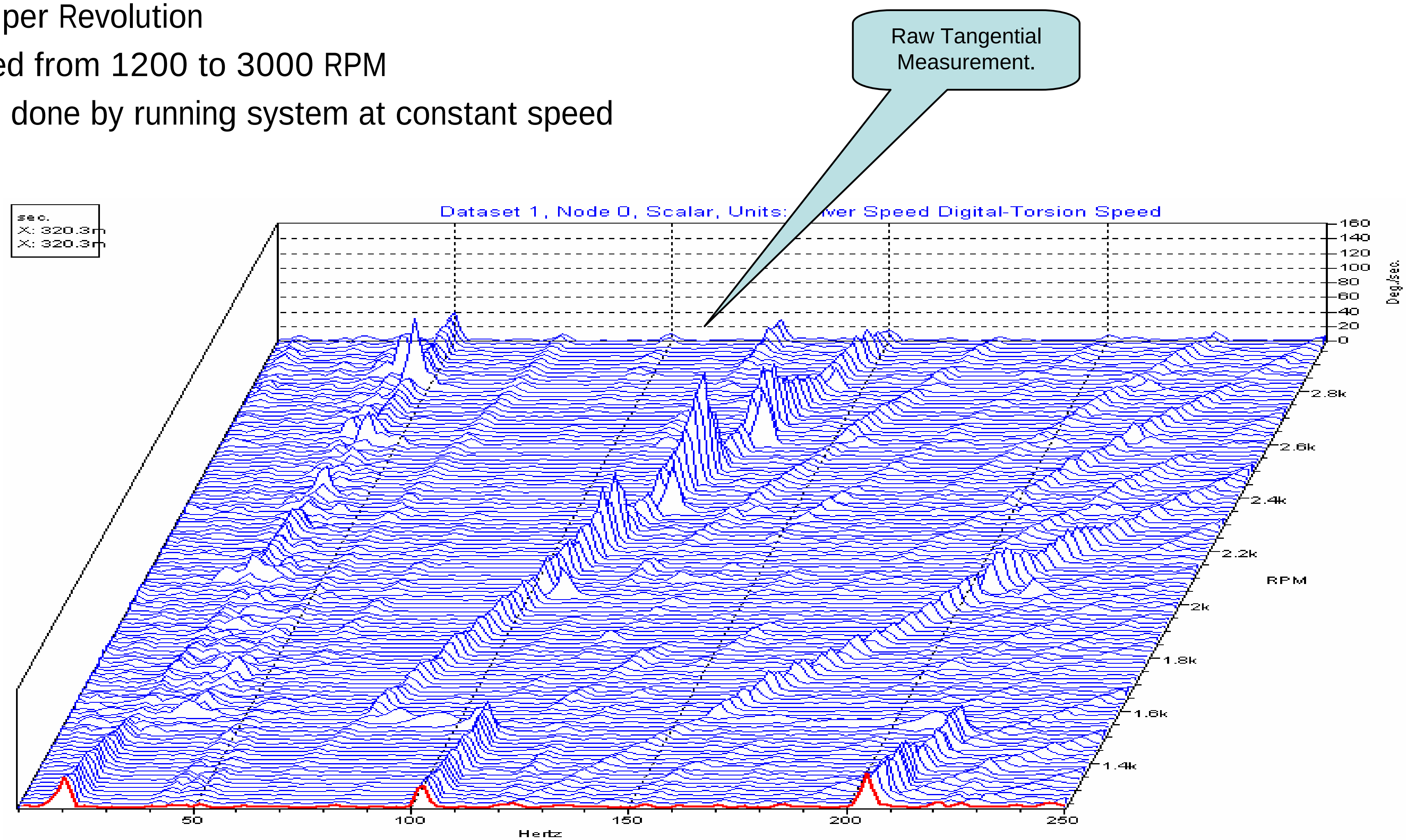
Decoupling translation from rotation, Driveshaft with Adhesive Bar Pattern Encoder

- Sampling at 80 MHz with Counter Timer
- 60 Pulses per Revolution
- Shaft Speed from 1200 to 3000 RPM
- Calibration done by running system at constant speed
- Two light sensitive probes, spaced 180 degrees apart
- Probes see the tangential speed
- Probes see the same rotational speed, but see translation speed with opposite polarity
- Hence, the sum of the speeds cancels the translation.
- Hence, the difference of the speed cancels rotation



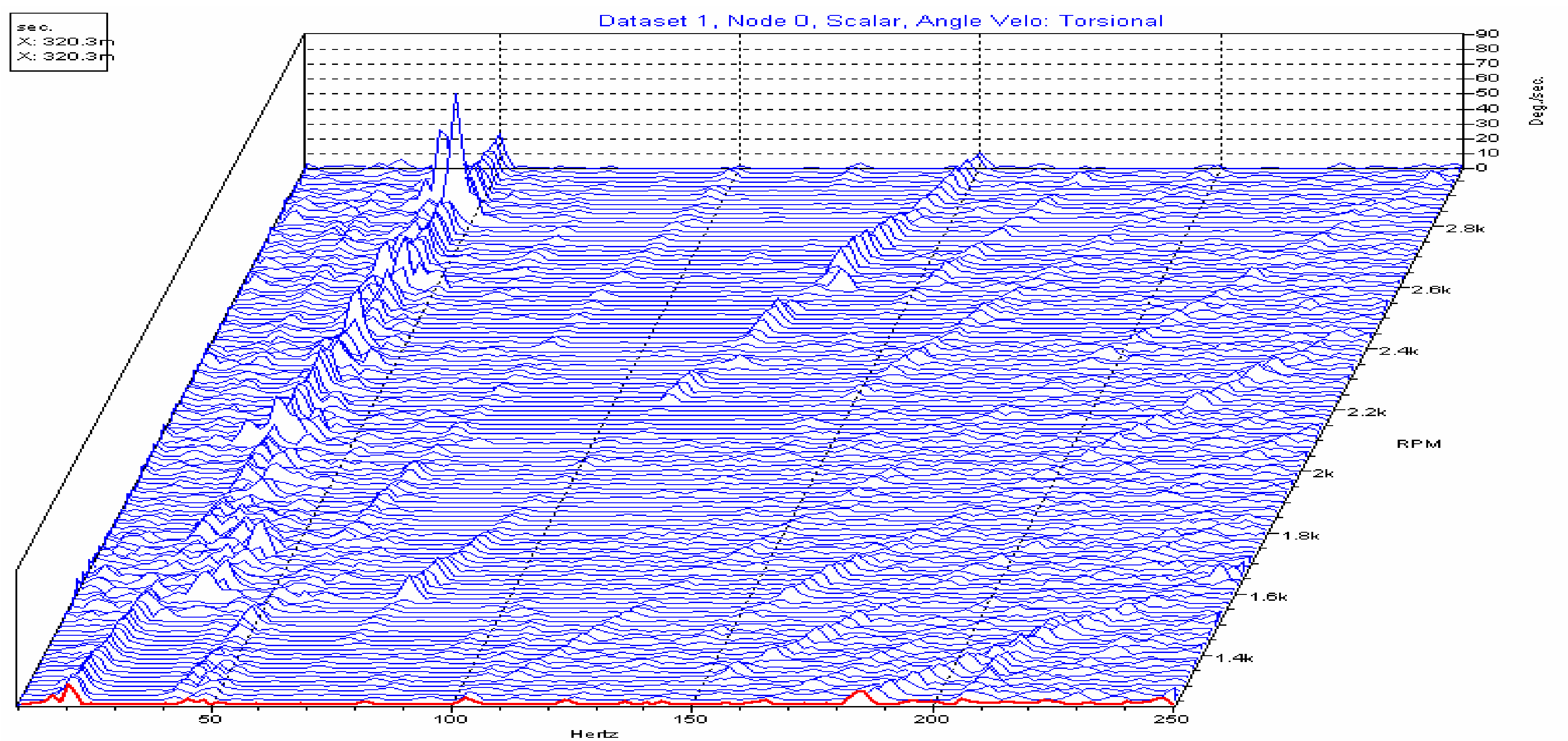
Decoupling translation from rotation, Driveshaft with Adhesive Bar Pattern Encoder, Raw Tangential Velocity

- Sampling at 80 MHz with Counter Timer
- 60 Pulses per Revolution
- Shaft Speed from 1200 to 3000 RPM
- Calibration done by running system at constant speed

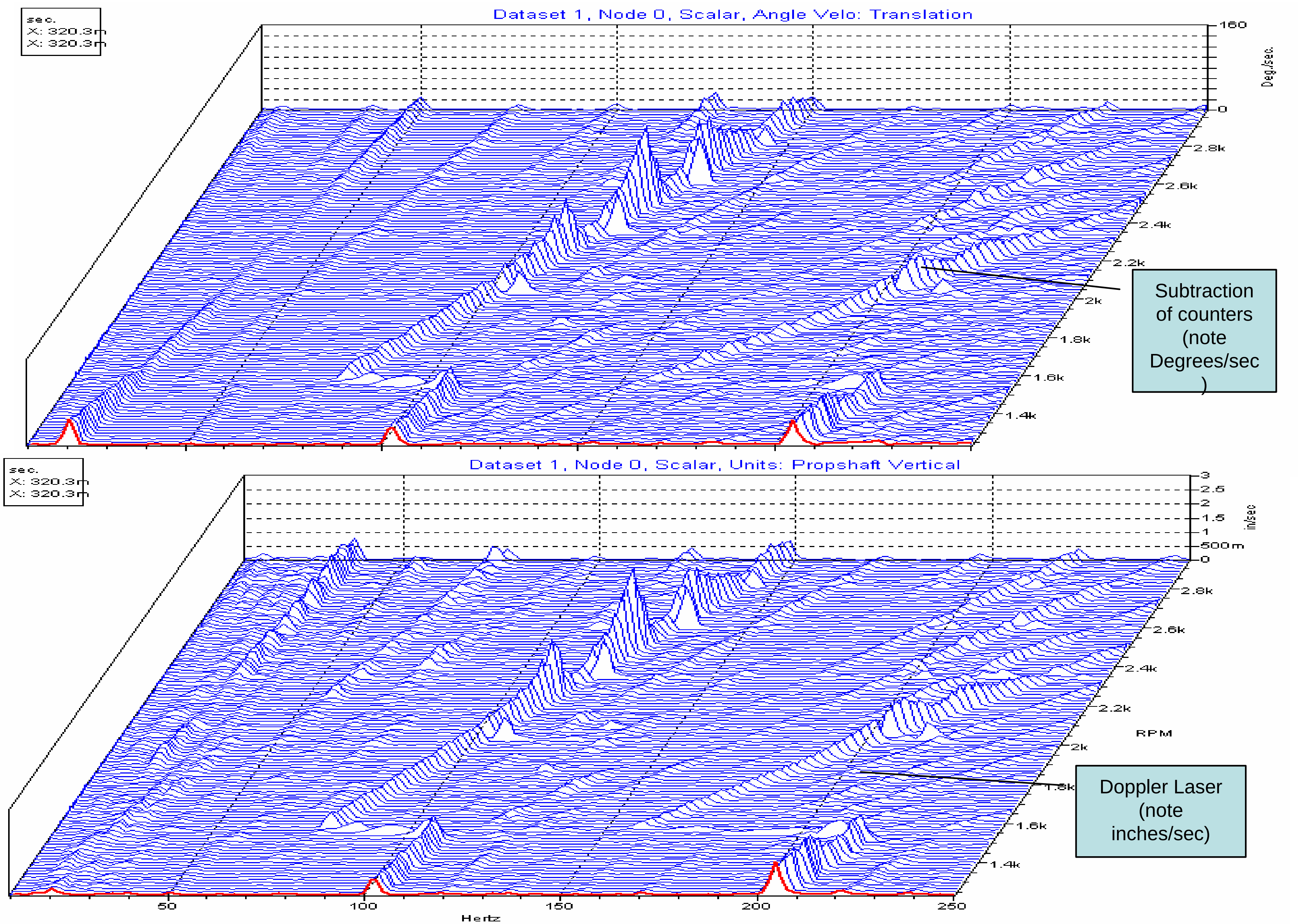


Decoupling translation from rotation, Driveshaft with Adhesive Bar Pattern Encoder, Torsional Velocity

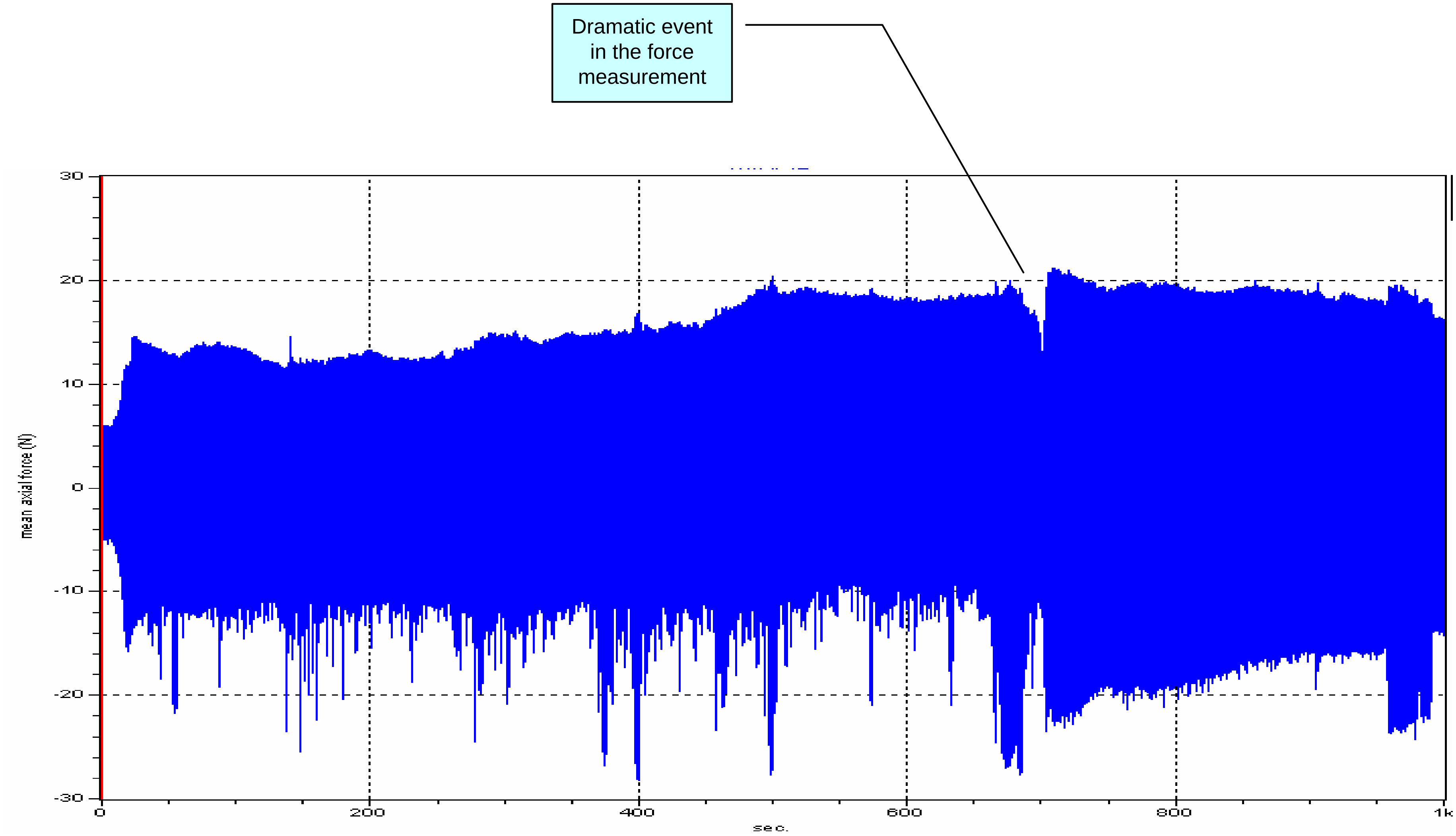
- Sampling at 80 MHz with Counter Timer
- 60 Pulses per Revolution
- Shaft Speed from 1200 to 3000 RPM
- Calibration done by running system at constant speed



Decoupling translation from rotation, Translation by subtraction and by Laser Doppler Velocimeter

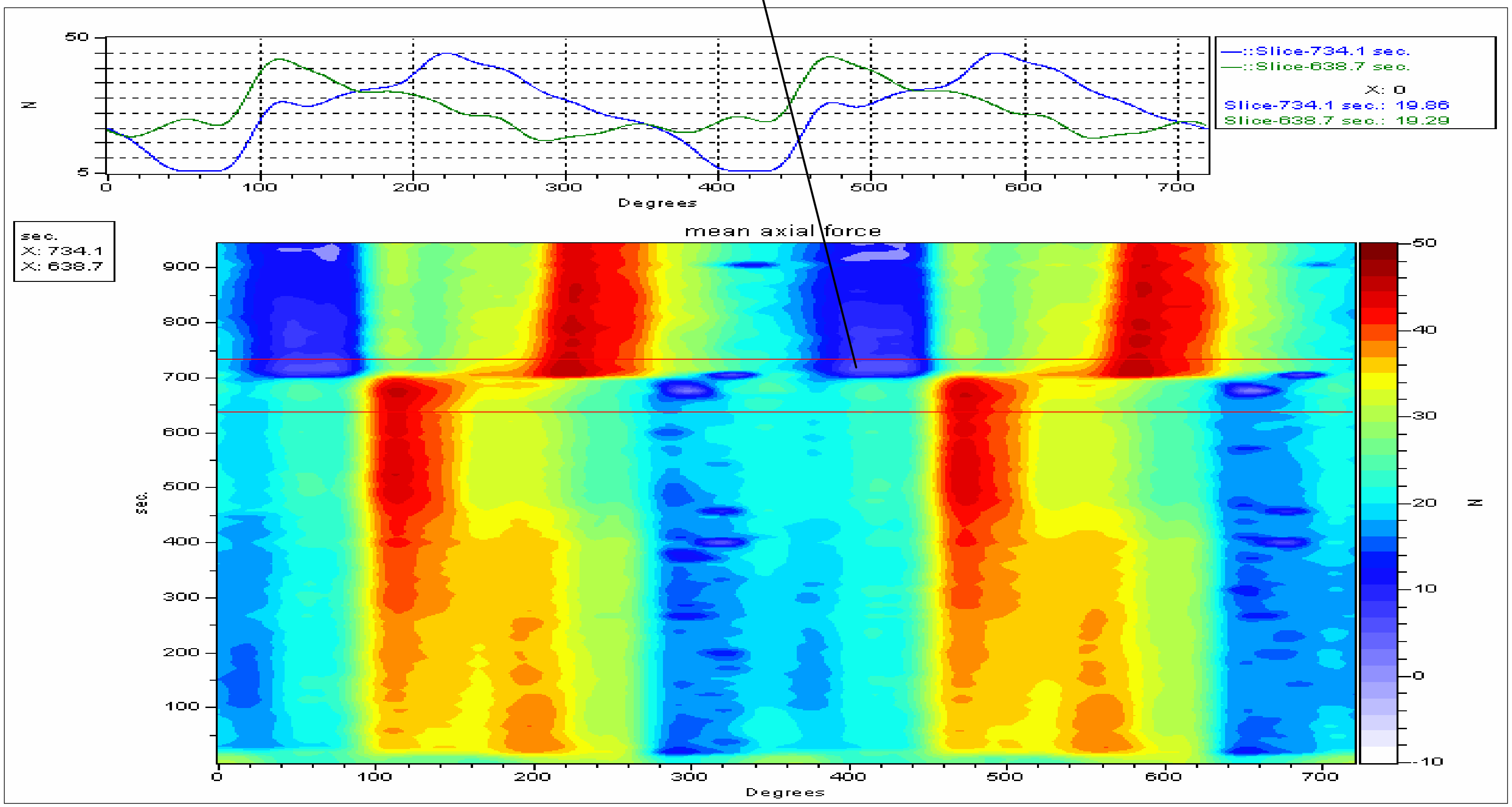


Angle Domain investigation of joint in propshaft



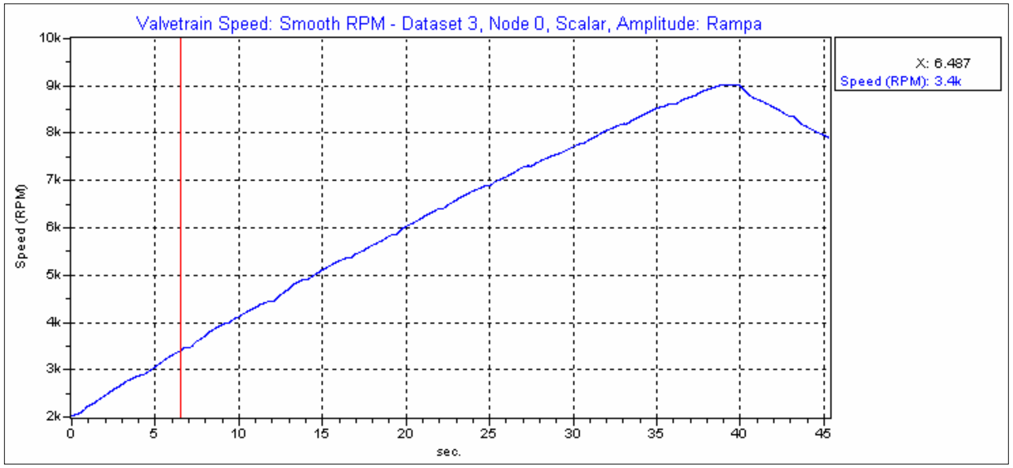
Angle Domain investigation of joint in propshaft – Resampled to Angle Domain

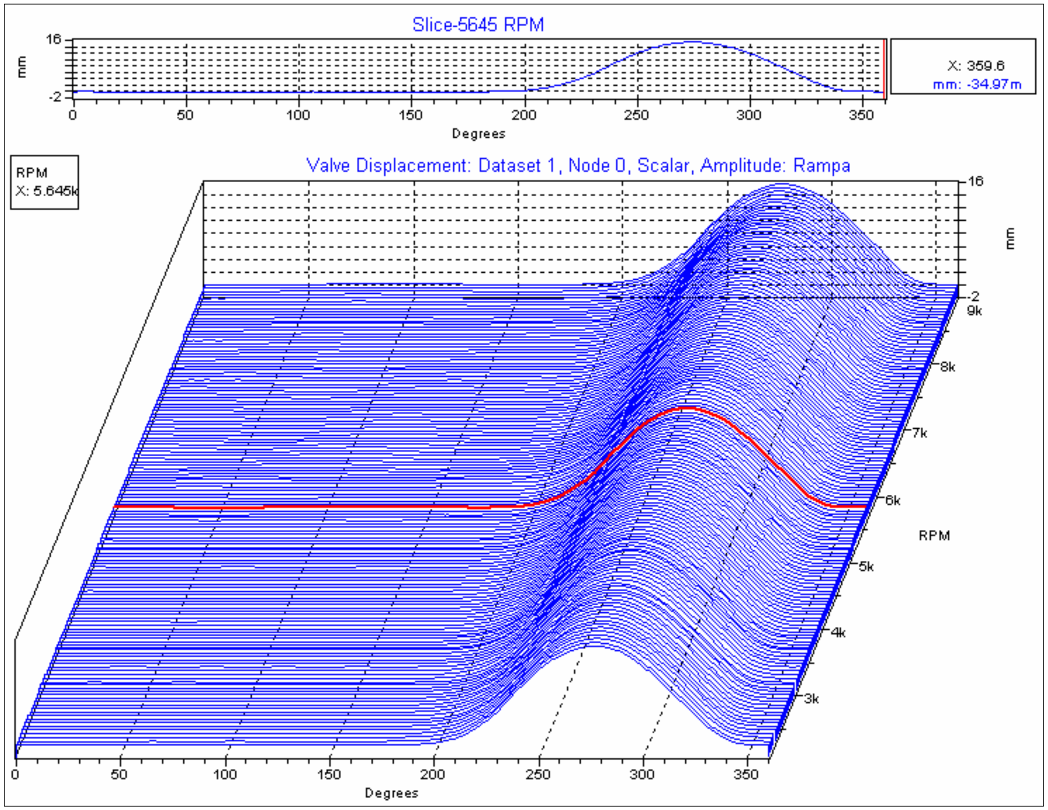
Phasing jumps by some 120 degrees at dramatic event at 700 seconds



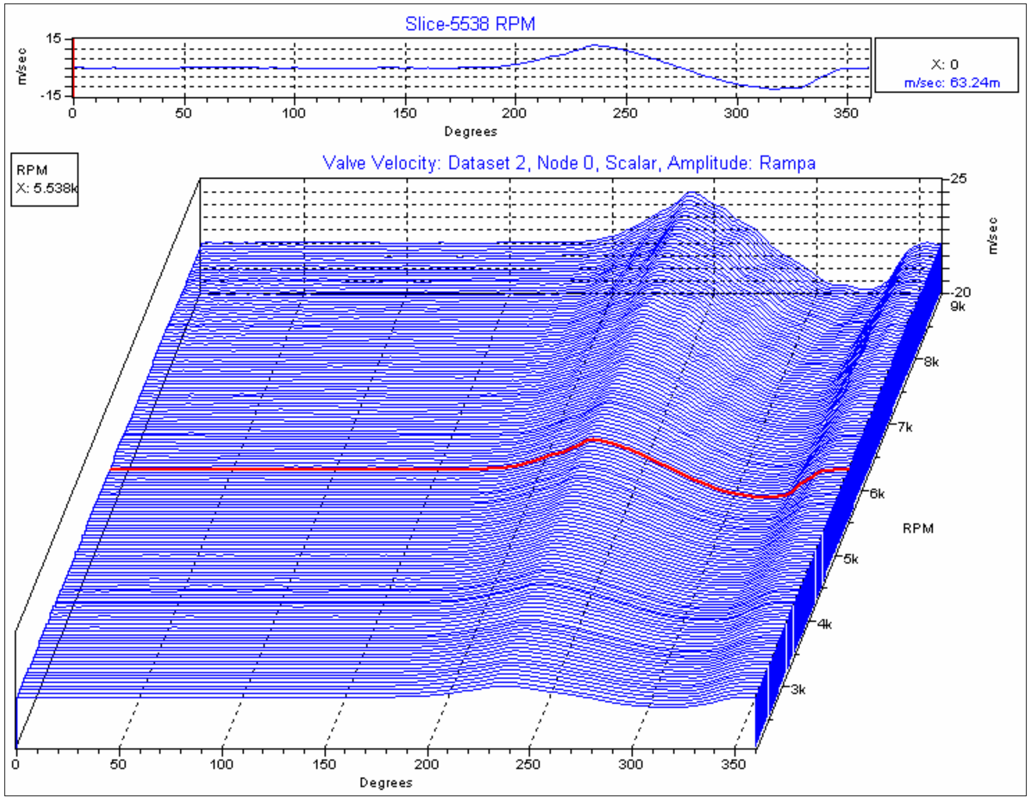
Angle Domain Investigation of Valvetrain Kinematics Speed and Displacement

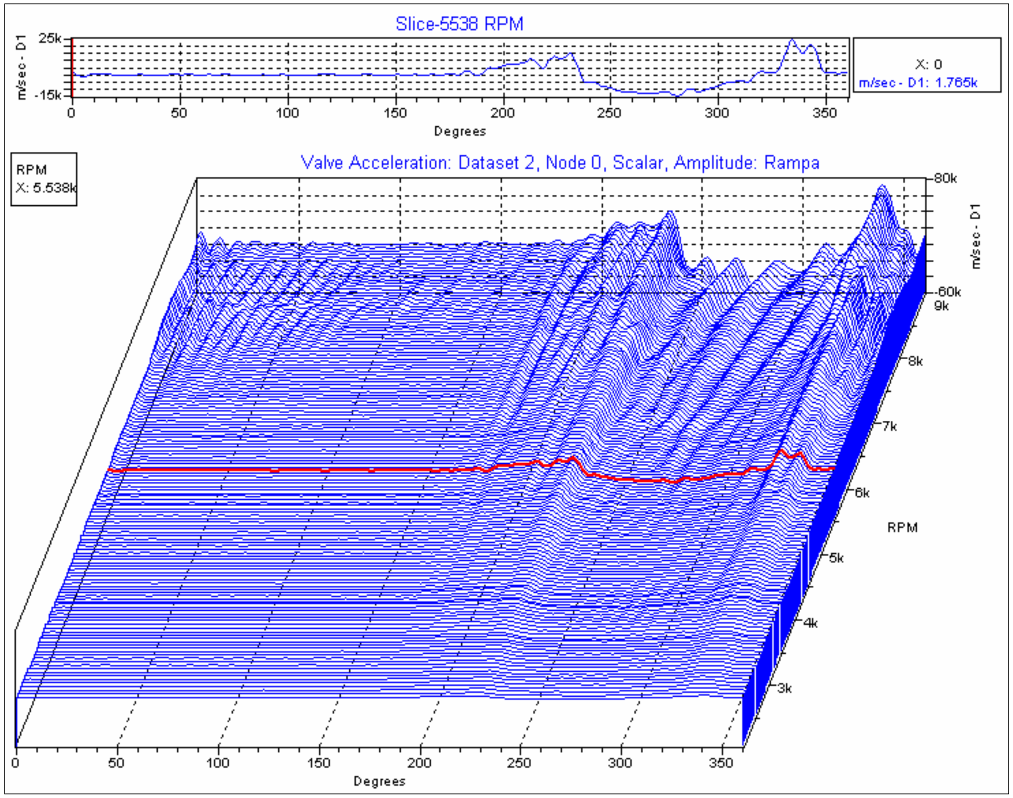
V10 Valvetrain driven in Dynamometer, Displacement and Velocity measured by Laser, Acceleration derived by differentiating Velocity



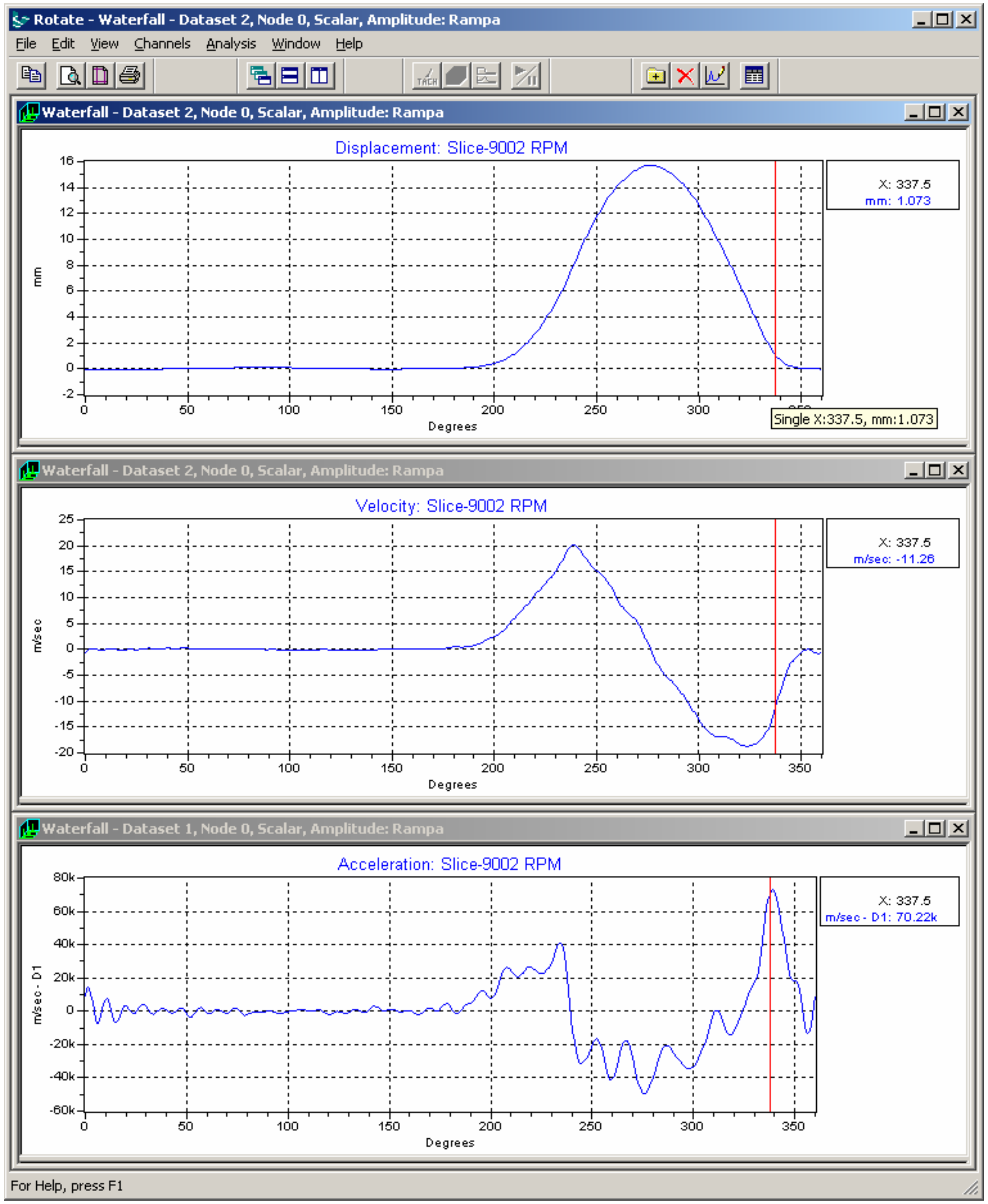


Angle Domain Investigation of Valvetrain Kinematics Velocity and Acceleration





Angle Domain Investigation of Valvetrain Kinematics



Equipment Used

- Software :
  - VSI Rotate Plus version 2.3
- Hardware
  - Electric Motor
    - Teac GX1 analog sampling at 200 KHz
  - Diesel Engine
    - Medallion Recorder analog sampling at 50 KHz
  - Formula 1 Engine
    - SoMat 2500 Recorder analog sampling at 100 KHz
  - Driveshaft
    - National Instruments 80 MHz counter/timer.
  - Valvetrain
    - STAC recorder analog sampling at 51.2 KHz
    - Polytec Laser Vibrometer

VSI Rotate Plus Hardware Support

- ASCII
- B&K Pulse
- B+S Multidata (also counter/timer at 40 MHz)
- Dactron
- Heim (also counter/timer at 800 KHz)
- Iotech
  - Medallion Recorder
  - Wavebook (also counter/timer at 50 MHz)
- LMS-Skalar Pimento/Roadrunner
- NI
  - 4472 (analog)
  - 660x (80 MHz counter/timer)
  - Multifunction (20 MHz counter/timer)
- Nicolet
- RPC III (MTS)
- SoMat SIF
- Sony DAT
- STAC
- Teac
  - GX1
  - DAT
- Universal File Format (SDRC), binary and ASCII
- VXI Agilent SDF Format
- Wave files (Microsoft, B&K, Oros)

More Information

- For more information about ROTATE and ROTATE PLUS software, please visit www.ata-rotate.com, or contact ATA Engineering, Inc. at (858) 480-2000.