Belt Analysis Using VALDYN

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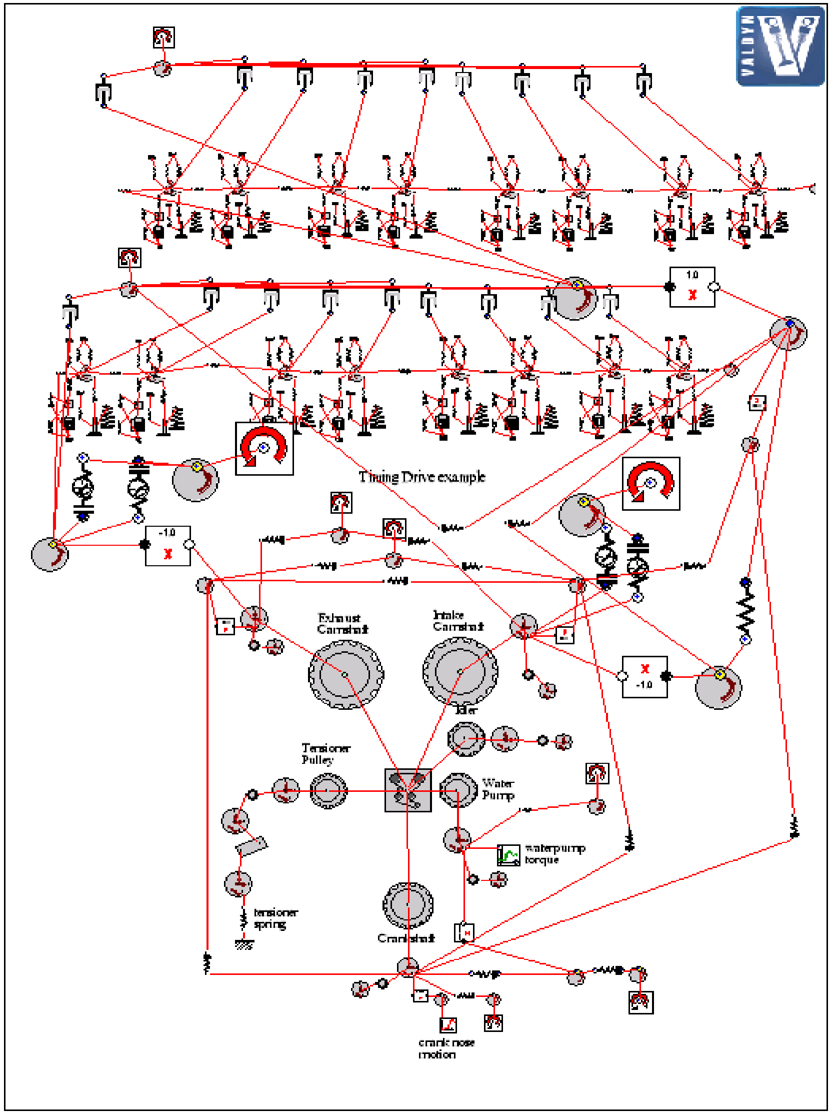
Contents

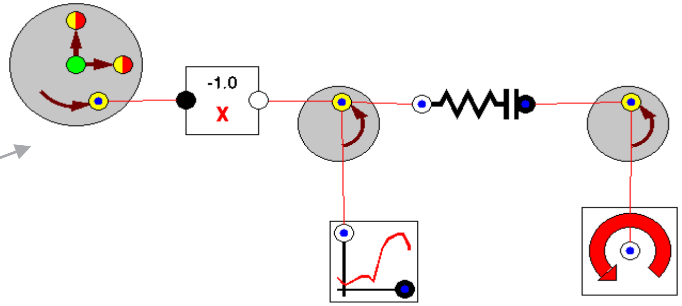
Overview of Model

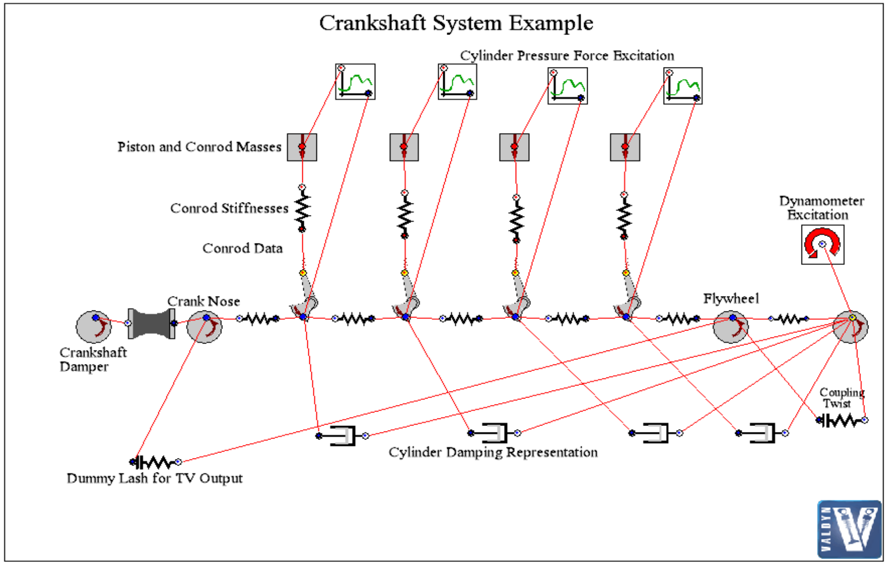
- The full timing drive model can be broken down into a number of sub-sections
  - Crankshaft
  - Idler
  - Water pump/other auxiliaries
  - Bearings
  - Belt
  - Tensioner
  - Valvetrain
  - Camshafts
  - Phaser if present
- It is often a good idea to model key sub-sections separately before assembling the full model – smaller models are easier to de-bug



Crankshaft Torsional Vibrations

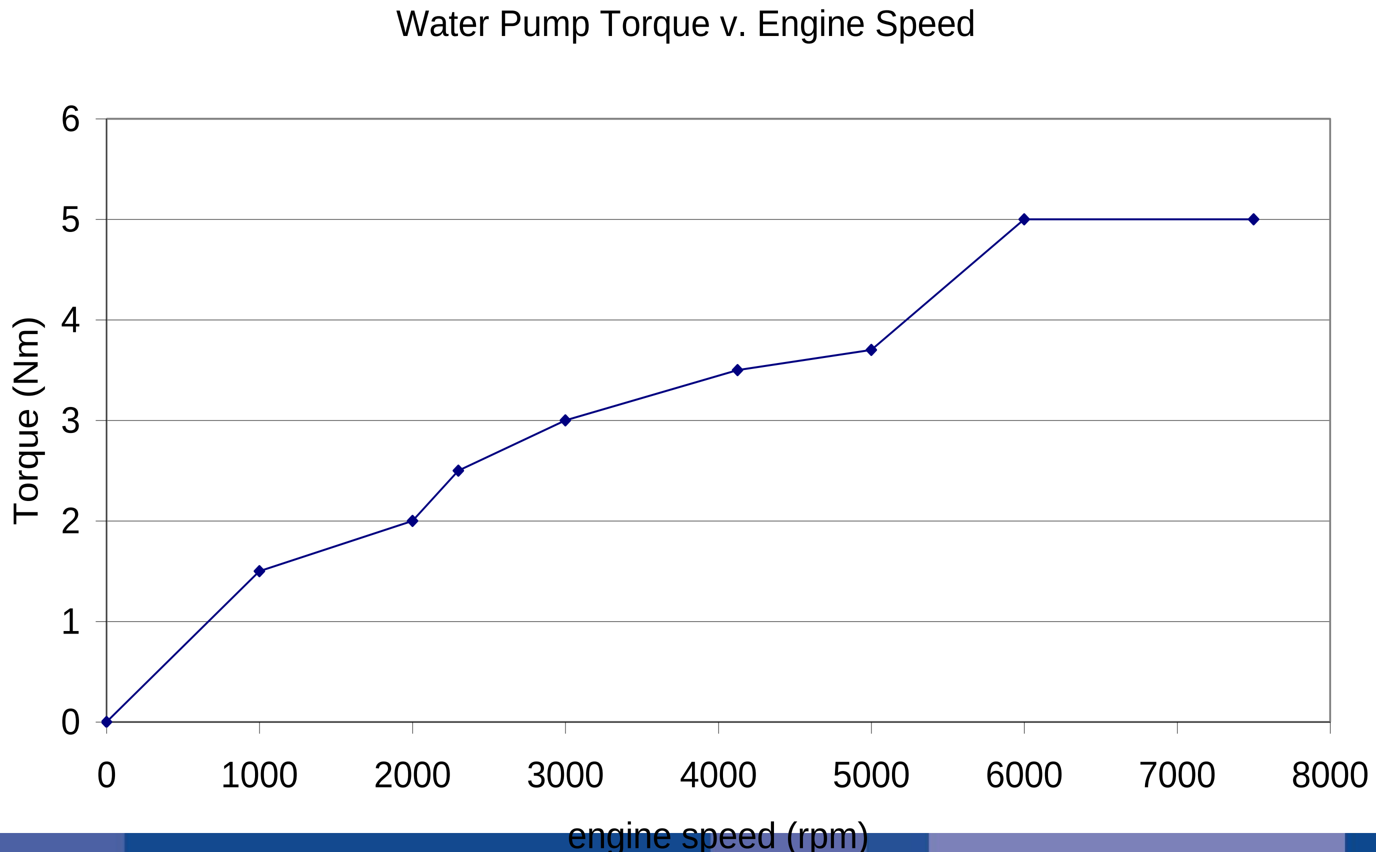
- Crankshaft torsional displacements can be applied using two methods:
  - An SMOTION element containing a text file definition of the displacements at different engine speeds
  - By modelling the full crankshaft and exciting it via cylinder pressure forces

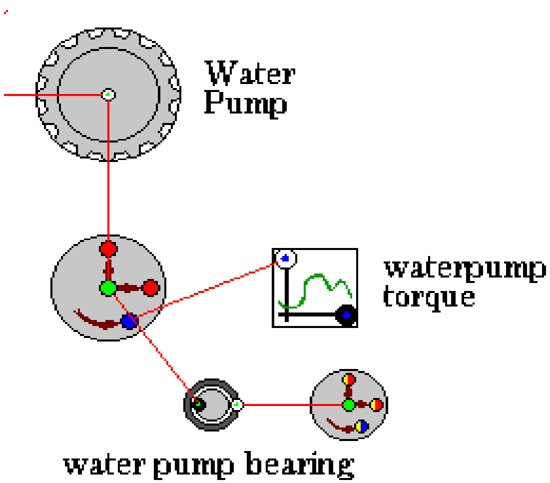




Ancillaries

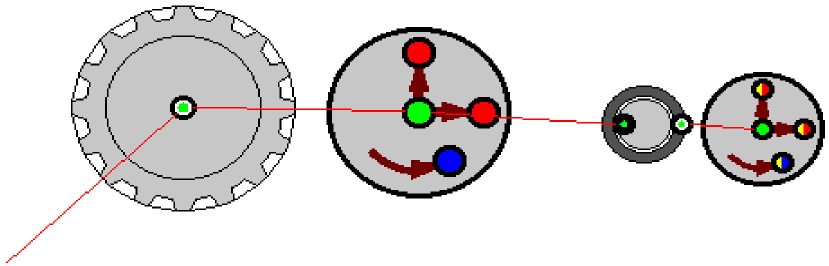
- Ancillary torques can be applied using SFORCE elements
  - The data required is torque v. engine speed data
- A water pump example is shown here

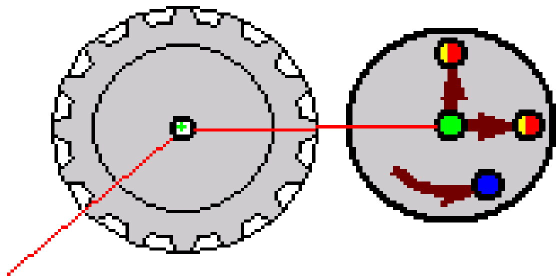




Timing drive bearing models

- **Each timing drive bearing is usually modeled using a BUSH element and a PIVOT element**
- **The BUSH element contains the**
  - x and y coordinates of the pulley centre
  - mass of the pulley
- **The PIVOT element allows the specification of**
  - bearing radius
  - radial bearing clearance
  - radial stiffness and damping
  - friction coefficient
- **Modelling in this way allows the bearing clearances to be taken up when tension is applied to the belt**
- Simpler models assume that the pulley mounting is rigid The data required is
  - Component inertia value
  - Torque v. engine speed data



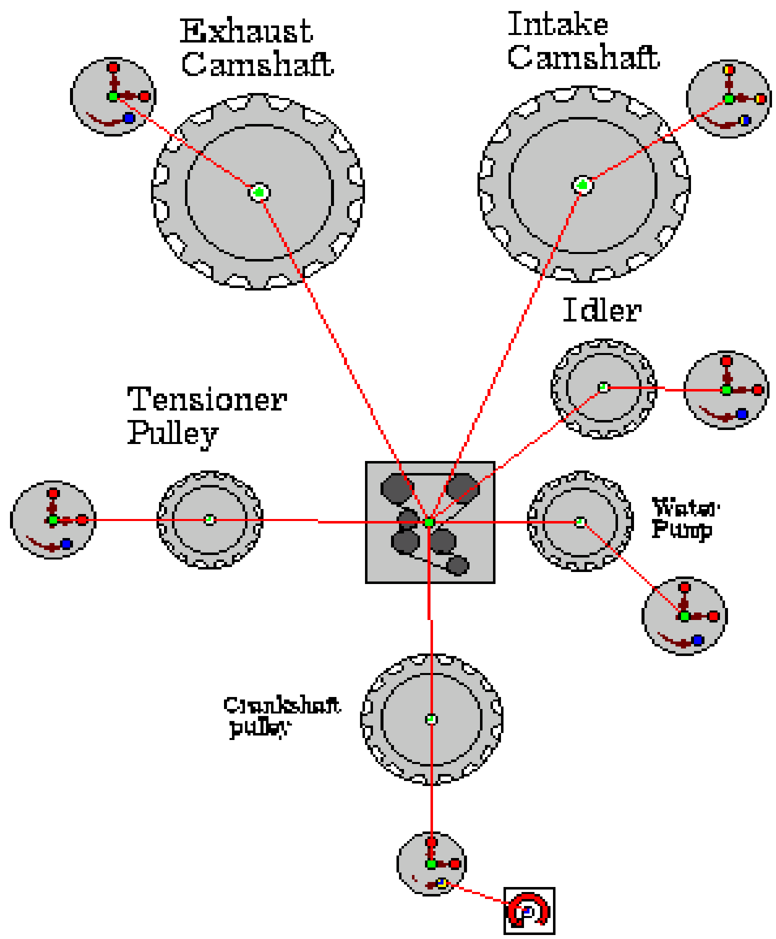


Timing drive bearing models

- **Front crankshaft and camshaft bearings are typically hydrodynamic bearings**
  - Bearing radius from drawing
  - Radial clearance assumed to be half the cold mean diametral value
  - Radial stiffness estimated by hand calculation accounting for the oil film stiffness and the local structural stiffness
  - Damping calculated based on 10% of critical damping
  - Friction coefficient typically assumed to be 0.05
  - Typical value of friction damping assumed
- **Tensioner bearing is typically rolling element bearing**
  - Bearing radius from drawings
  - Radial clearance was assumed to be typical value of 0.01 mm
  - Radial stiffness was assumed to be typical value of 100000 N/mm
  - Damping calculated based on 5% of critical damping
  - Friction coefficient assumed to be 0.001
  - Typical value of friction damping assumed

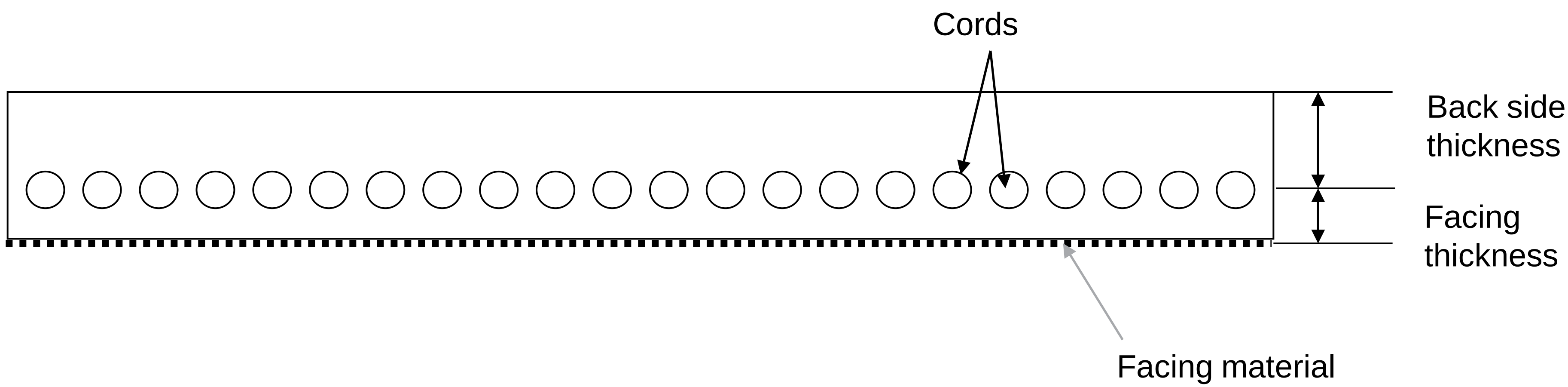
Belt Model

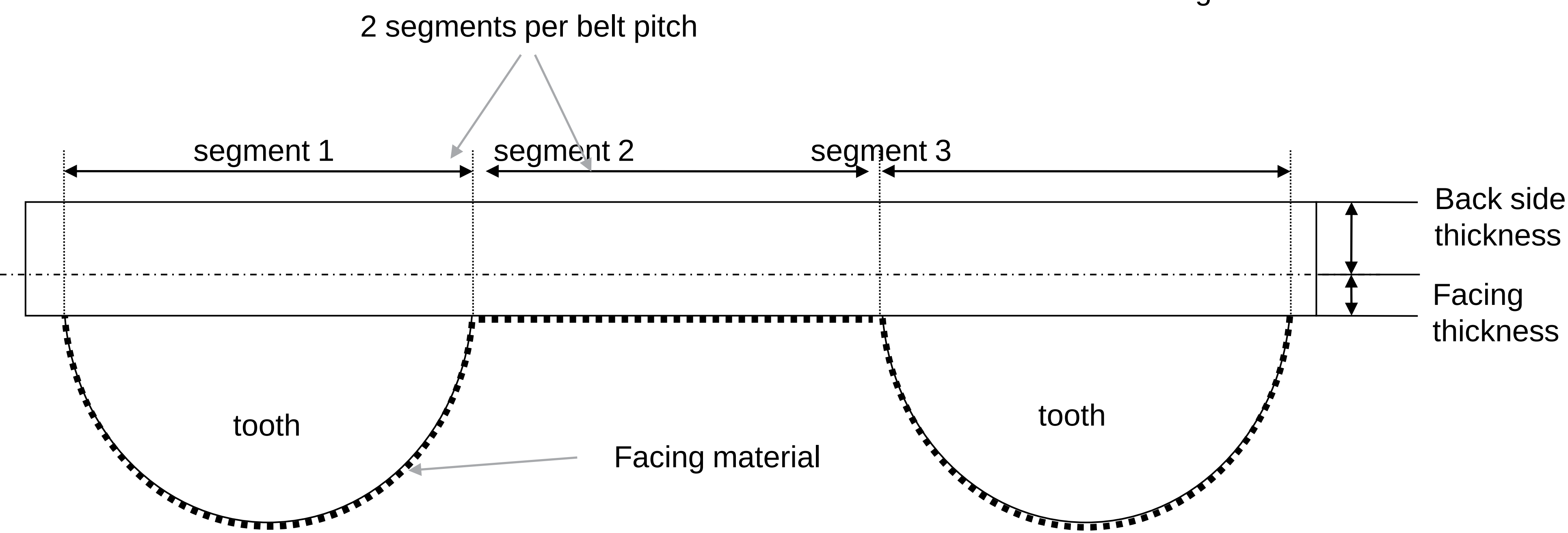
- **For the pulleys at the crankshaft, camshafts and pumps the VALDYN model requires**
  - Pulley radius
  - Number of teeth
  - Profile of a single tooth defined by a series of arcs and included angles
  - Tooth contact stiffness, damping and friction
- **Pulleys acting on the back of the belt have no teeth so the model requires only pulley radius and friction coefficient**



Belt Model

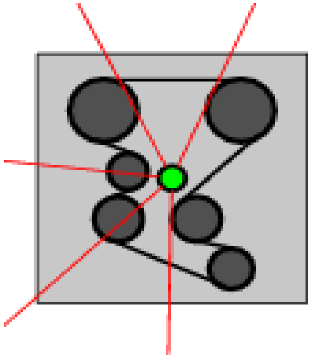
- Terminology used to describe toothed belts in VALDYN





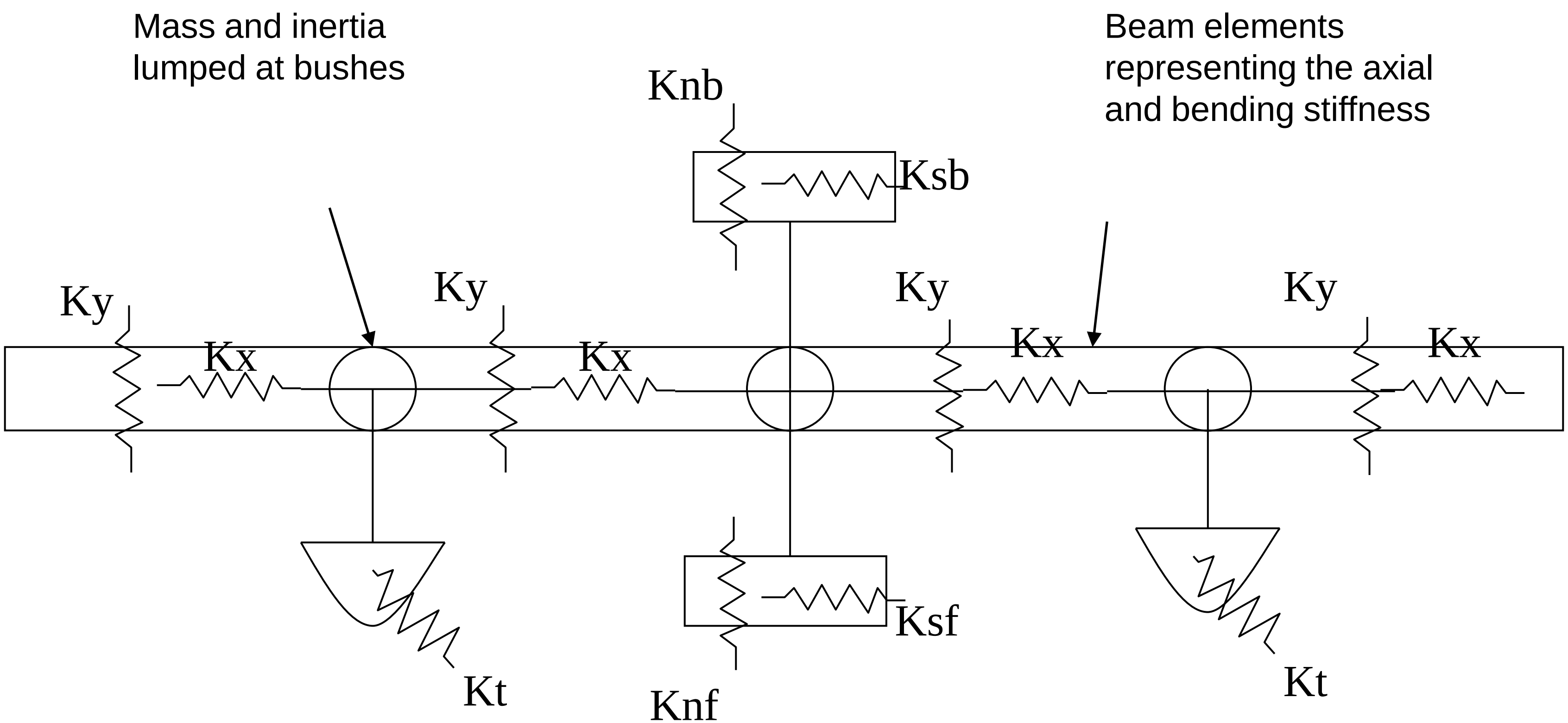
Belt Model

- The timing belt is typically modelled in VALDYN using the BELT_V2 element with the TL_nonlinear beam formulation
  - This is a geometrically non-linear representation
    - Axial belt stiffness changes with preload
    - Bending belt stiffness is dependent on the axial tension and the bending angle – i.e. the bending stiffness will change around a sprocket
- The BELT_V2 element models the belt as a series of beam elements to represent belt axial and bending stiffness connected by nodes representing belt mass
- Also attached to the nodes are stiffness elements to represent the facing and back side of the belt and belt teeth
  - From these stiffness elements the normal forces between the belt and the pulleys are computed
  - From the friction coefficients tangential forces are computed
- The geometry of the belt teeth and the pulley teeth are specified and the 'meshing' is modelled
- Each belt pitch consists of 2 'segments'
  - The tooth is attached to one of these segments



Belt Model

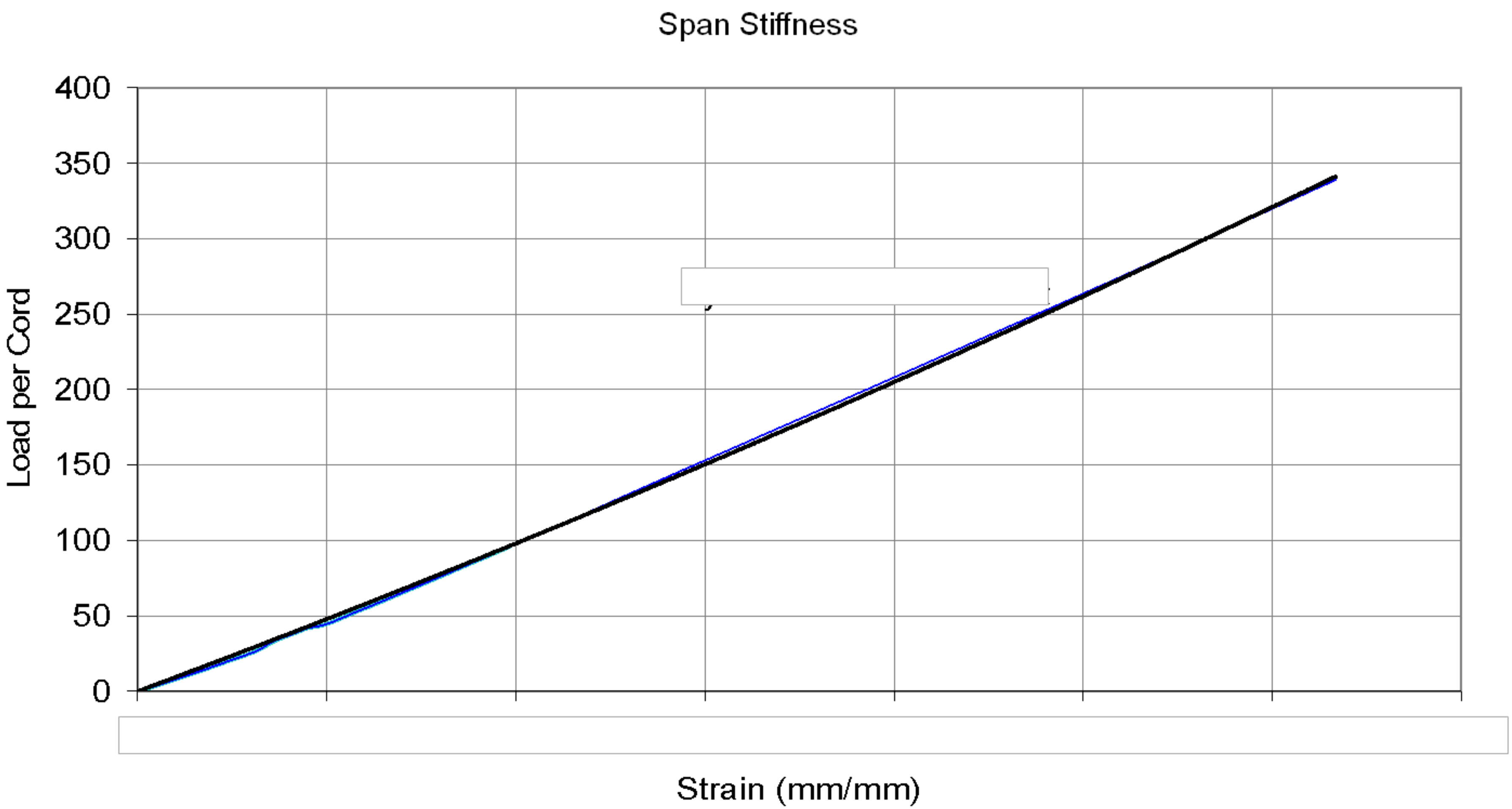
- A representation of the VALDYN BELT_V2 model



Kx	Beam axial stiffness
Ky	Beam shear stiffness
Knb	Backing normal stiffness
Ksb	Backing shear stiffness
Knf	Land normal stiffness
Ksf	Land shear stiffness
Kt	Tooth normal stiffness

Belt Model – Axial Stiffness

- The belt axial stiffness is typically obtained from measured data



Belt Model – Axial Stiffness Calculations

- Belt Axial Stiffness
  - TL_nonlinear model has stiffness dependent on load
  - Axial stiffness is defined by the belt effective Young's Modulus and effective area:

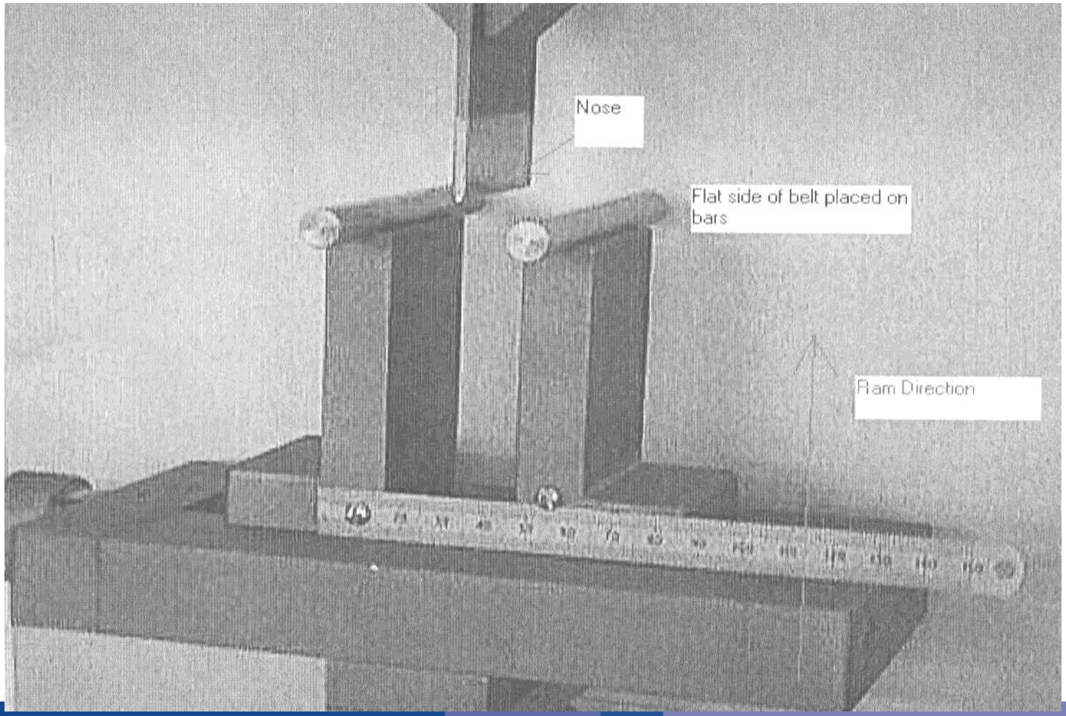
$$K_x = \frac{E * A_s}{l}$$

  - Kx is known from the belt stiffness measurements
  - As is usually taken as the area of the cords as most of the belt axial stiffness is due to the cords
  - The effective Young's Modulus can then be calculated:

$$E = \frac{K_{cord} * l}{A_{cord}} = \frac{23522 \frac{N}{mm} * 1mm}{0.785mm^2} = 29949MPa$$

Belt Model - Shear Stiffness

- Belt Shear Stiffness (or bending stiffness)
  - This can be estimated from measurements of belt bending stiffness
  - An example test rig is shown below
  - For the example case:
    - The belt sample was 19mm wide and 5 pitches in length
    - The belt was simply supported with a load is applied to the centre of the sample
    - Force v. displacement measurements were recorded at the centre point
- The measured shear stiffness for the sample was [redacted] N/mm



Belt Model – Shear Stiffness

- VALDYN requires shear stiffness input data for a 1mm cantilevered length of belt
- Therefore, factors to allow for the difference in sample support method, width and length are required to convert the measured stiffness to a VALDYN input values
- Factor 1 - the measured belt stiffness is for a simply supported sample but the VALDYN considers a cantilevered sample:
  - Displacement at the middle of a simply supported span:

$$\delta_c = \frac{FL^3}{48EI} \longrightarrow K = \frac{48EI}{L^3}$$

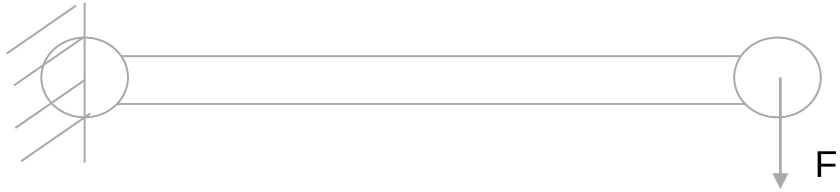
  - Displacement at the end of a cantilevered span:

$$\delta_e = \frac{FL^3}{3EI} \longrightarrow K = \frac{3EI}{L^3}$$

  - Giving:

$$\text{factor} = \frac{3}{48} = 0.063$$

Belt Model – Shear Stiffness



- Factor 2 - the sample length was 5 pitches = 5 x 9.525mm but VALDYN considers a 1mm length
  - Giving:

$$\text{factor} = \left(\frac{5 * 9.525\text{mm}}{1\text{mm}}\right)^3 = 108076$$

- Factor 3 - the sample width was 19mm but the belt is 27.4mm wide
  - Giving:

$$\text{factor} = \frac{27.4\text{mm}}{19\text{mm}} = 1.442$$

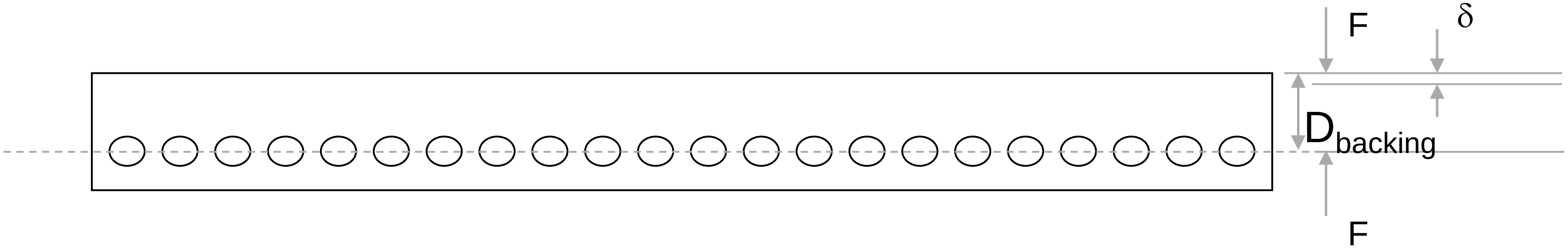
- VALDYN required shear stiffness

$$K_y = 1.13 * 0.063 * 1.442 * 108076 = 110002\left(\frac{\text{N}}{\text{mm}}\right)$$

- The shear stiffness is defined by the Young's Modulus and belt section 2nd moment of area:

$$K_y = \frac{3EI_z}{l^3} \longrightarrow I_z = \frac{K_y l^3}{3E} = 0.12\text{mm}^4$$

Belt Model – Facing and Backing Normal Stiffness



- The belt facing and backing normal stiffness are defined as the compression stiffness of these sections of belt
- Values can be measured or estimated using the following assumptions
- Standard equations for calculating the normal stiffness of an infinitely long rubber block, with negligible strain along its length;
  - fully constrained in the other two directions:

$$K_{n\_constrained} = \frac{4}{3} * \frac{E * beltwidth}{belt\_thickness} * \left(1 + kS^{2}\right)$$

  - unconstrained in the other two directions:

$$K_{n\_unconstrained} = \frac{4}{3} * \frac{E * beltwidth}{belt\_thickness}$$

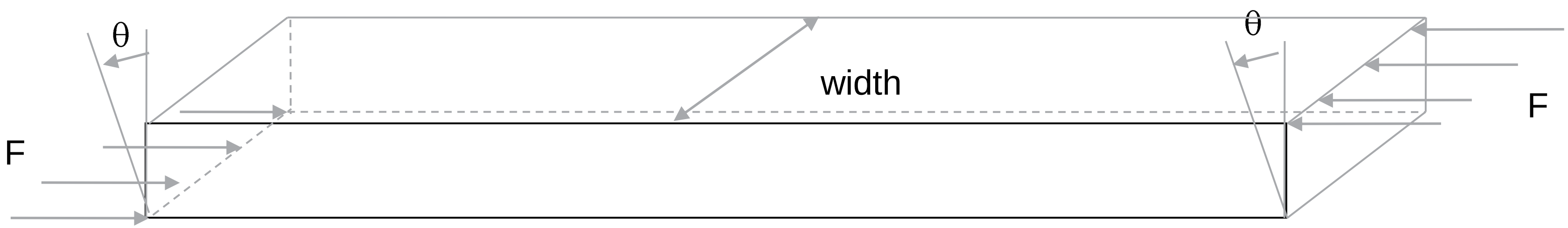
    - k is a factor depending on the rubber hardness
    - S is a shape factor based on the rubber geometry and can be estimated as

$$S = \frac{beltwidth}{2 * belt\_thickness}$$

Belt Model – Facing and Backing Normal Stiffness

- The belt construction falls between these two cases, with a partial constraint across one side due to bonding with the cords
- Typically the following might be assumed :
  - The rubber hardness was 30 IRHD
  - Young's modulus for a rubber of this hardness is 0.92MPa
  - Facing material was assumed to increase the effective Young's modulus by a factor of 2
  - k value for a rubber of 30 IRHD hardness is 0.93
  - An estimated shape factor of 2.4 to allow for the partial constraint provided by the cords
    - This value was derived from an analysis sensitivity study
    - The shape factor for a constrained piece of rubber is 5.5
- The calculated normal stiffness value for the facing was [redacted] N/mm per mm length and for the backing was [redacted] N/mm per mm length
- Damping values associated with each of the normal stiffness values were calculated as 12.5% of critical based on the local belt mass and stiffness

Belt Model – Facing and Backing Shear Stiffness



- The VALDYN shear stiffness is defined as the force required per angle of shear produced
- For a belt with a rubber stiffness of 30 IHRD
  - A shear modulus of 0.3MPa is typical
  - Shear stiffness is calculated as the product of shear modulus and belt projected area:

$$K_{shear\_backing} = GA = G * width * 1mm$$

G = Shear modulus

  - It can be assumed that the facing material can increase the effective shear modulus by a factor of 1.8
  - The calculated shear stiffness therefore for the facing is [redacted] N/rad and for the backing is [redacted] N/rad
  - Damping values associated with each of the normal stiffness values were calculated as 25% of critical based on the drive natural frequency and shear stiffness

Belt Model – Other Input Parameters

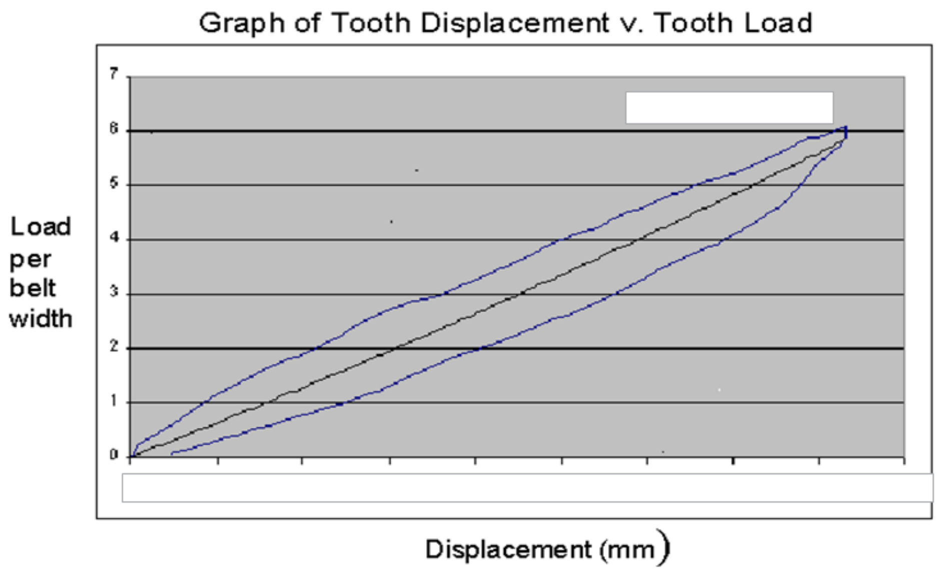
- VALDYN internally calculates the mass and inertia of the belt body (I.e. without the teeth) from the effective area (cord area) and an effective density:

$$M = effective\_density * l * As$$

  - The effective density is entered into VALDYN
  - This can be calculated from the mass and geometry on the belt drawing
- The tooth mass and inertia are entered separately and can be calculated from the belt geometry
- The friction coefficients for each contact face of the belt are usually provided by the belt supplier
  - Facing and teeth = 0.2-0.3
  - Backing = 0.3-0.5
- A modal damping value of 1 is typically chosen

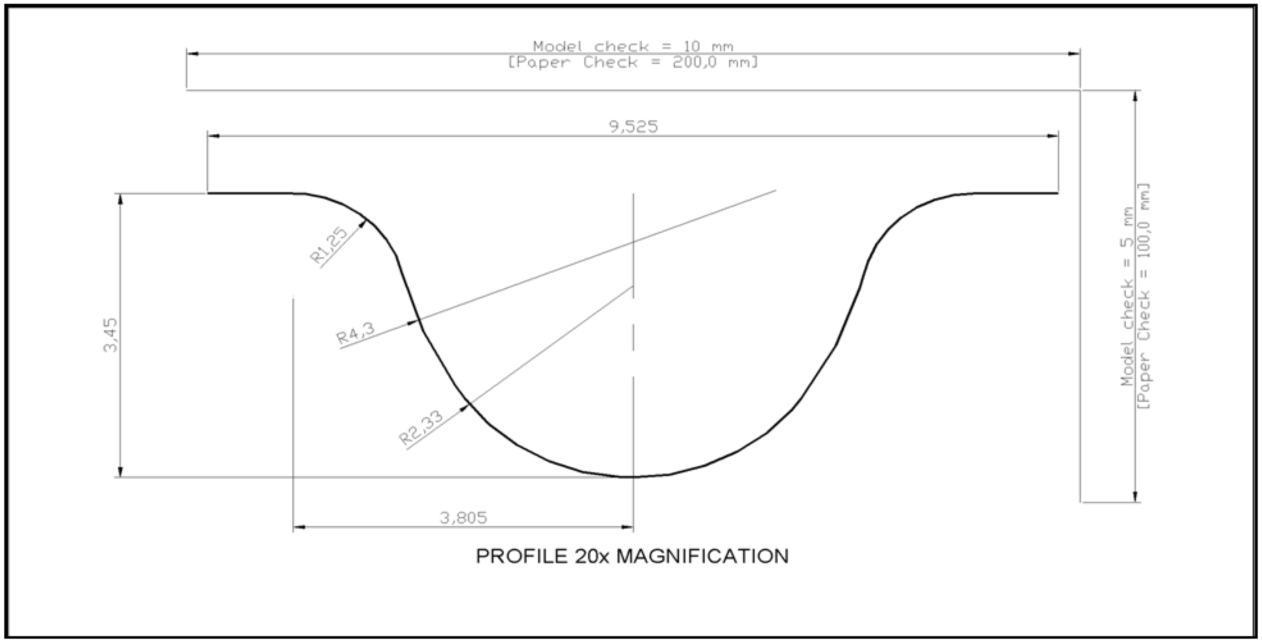
Belt Model – Tooth Stiffness

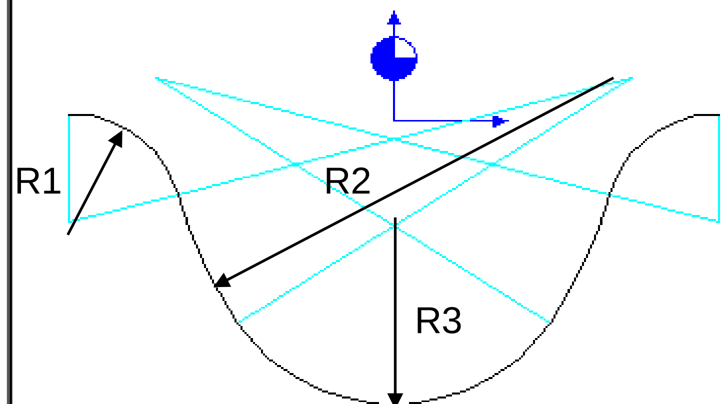
- For example the measured stiffness data for a 19mm wide belt sample
  - Two pieces of belt are held back to back
  - Tooth shaped dies are pushed over a single tooth on each belt sample
  - The belt is held and a force is applied to the dies, parallel to the belt cords
  - Measurements of applied force v. displacement are recorded
- The VALDYN belt tooth normal stiffness is defined as the compression stiffness of the belt tooth in the direction normal to the tooth face
  - The tooth stiffness values are entered into the VALDYN Pulley elements
- Correcting for the width of the belt, the VALDYN tooth stiffness input is [redacted] N/mm



Belt Model – Tooth Profile Definition

- The belt supplier should be able to provide the geometry of the belt tooth profile
  - This is entered into VALDYN as a series of radii and included angles





Belt Model – Tooth Profile Definition

- The profile is entered using a LAMINA element within the VALDYN BELT_V2 element as shown below

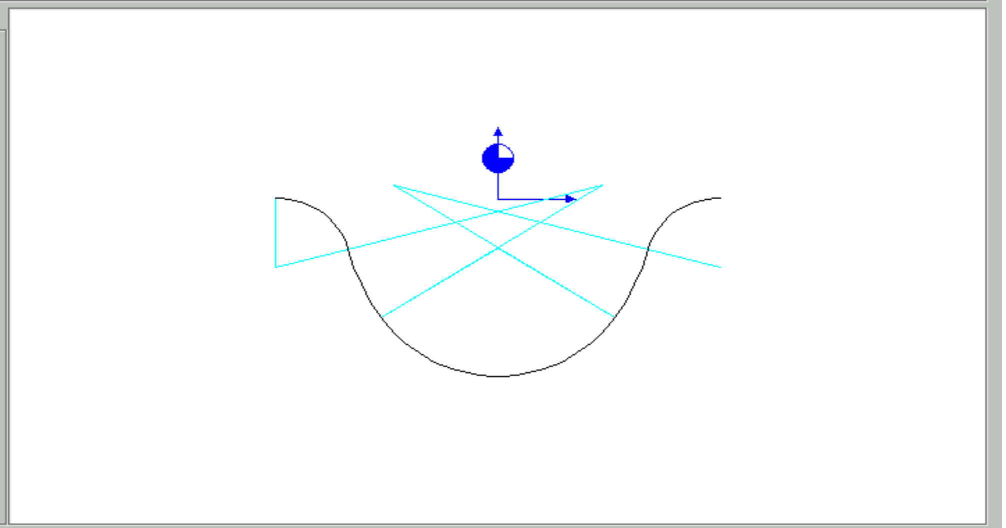
LAMINAGEOM_4

Name: Tooth profile

Data

Cyclic Symmetry No	0
Length Units	mm
Angle Units	deg
X Coordinate	0
Y Coordinate	0.745

☐ Scale To Construction Lines

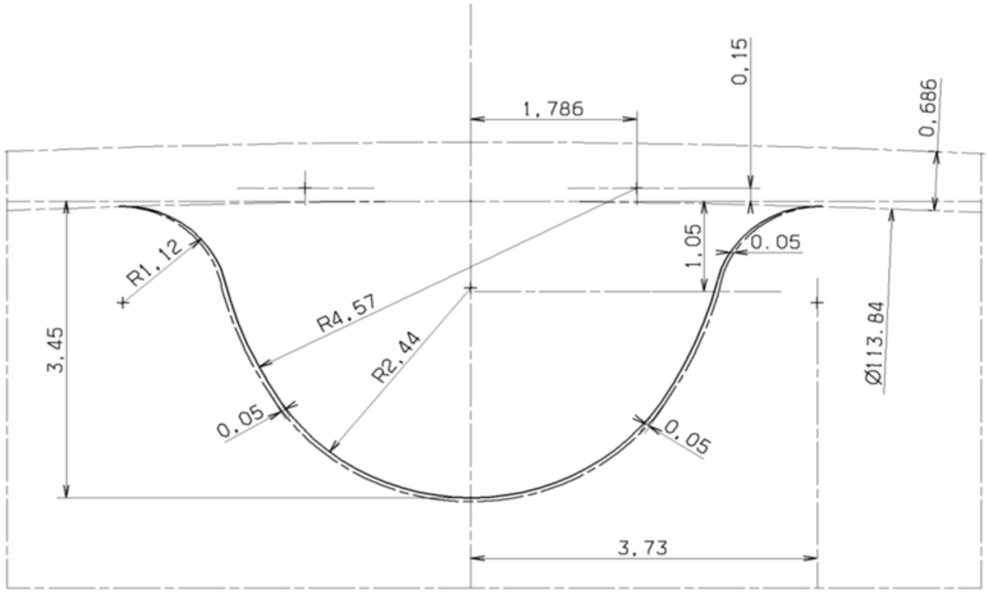


Shape Data

	Type	Status	Radius/ Length	Included/ Start Angle	End Angle	x	y	Angle
1	ARC	A	0.0	360	N/A			
2	ARC	A	1.286	-74.846	N/A			
3	ARC	A	4.52	17.864	N/A			
4	ARC	A	2.39	113.964	N/A	0	-0.91	-146.982
5	ARC	A	4.52	17.864	N/A			
6	ARC	A	1.286	-74.846	N/A			
7	ARC	A	0.0	360	N/A			

Pulley Tooth Profile

- The details of the tooth profiles for each of the pulleys are defined in a similar way to the belt tooth profile
- The profile details are entered into VALDYN using LAMINA elements within the PULLEY Macro element
  - The profile for a single tooth is defined as a series of arcs
  - VALDYN then repeats this by the appropriate number to produce the full pulley profile



Pulley Tooth Profile

- The VALDYN definition of a camshaft pulley tooth profile

LAMINAGEOM_2

Name: 38-tooth pulley

Data

Number of Teeth: 38

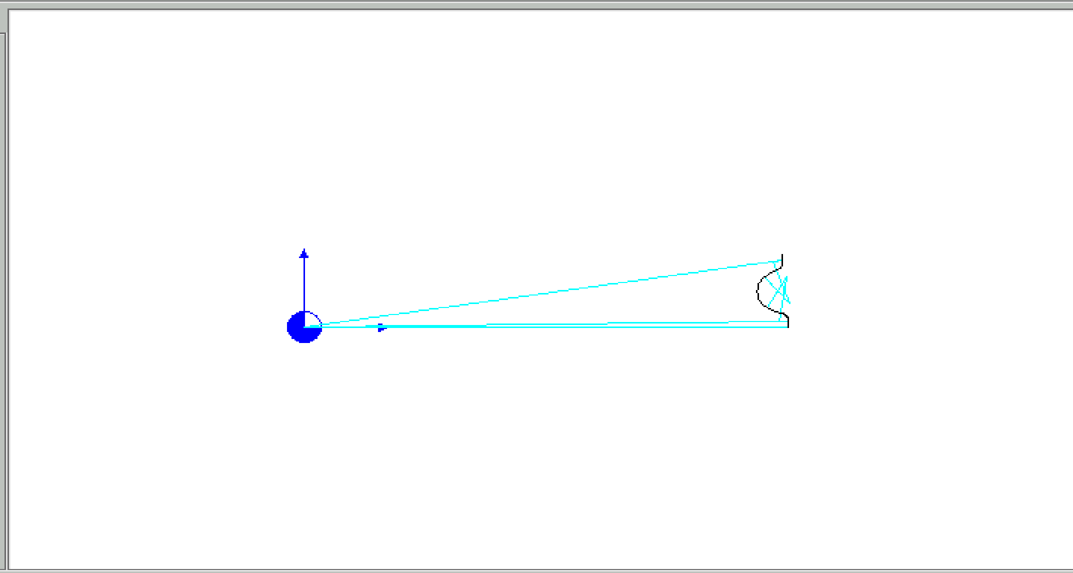
Length Units: mm

Angle Units: deg

X Coordinate: 0

Y Coordinate: 0

☐ Scale To Construction Lines

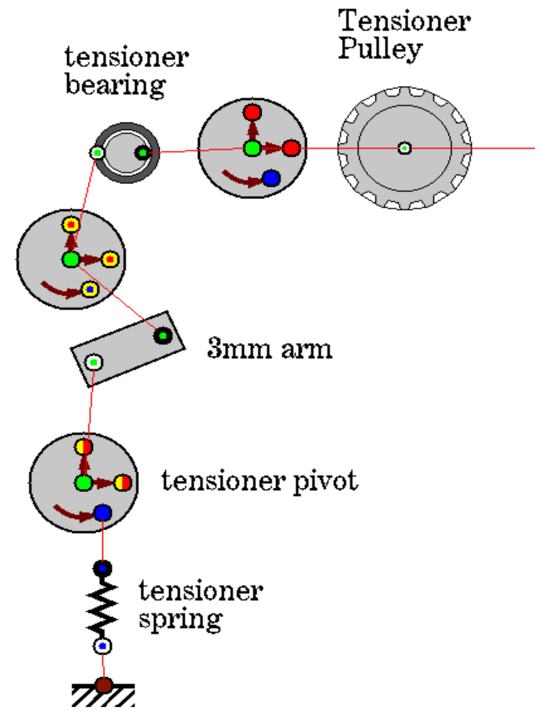


Shape Data

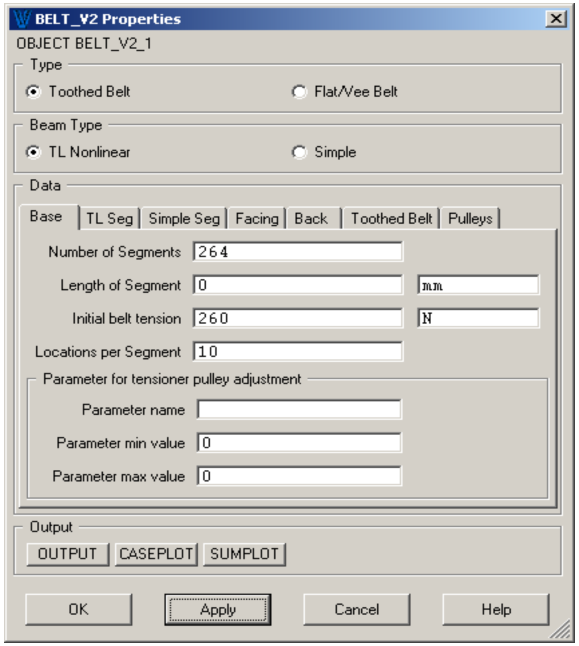
	Type	Status	Radius/ Length	Included/ Start Angle	End Angle	x	y	Angle
1	ARC	A	56.92	0.8464	N/A			
2	ARC	A	1.12	78.716	N/A			
3	ARC	A	4.57	-21.623	N/A			
4	ARC	A	2.44	-106.404	N/A			
5	ARC	A	4.57	-21.623	N/A			
6	ARC	A	1.12	78.716	N/A			
7	ARC	A	56.92	0.8464	N/A			

Belt Tensioner

- The tensioner may either be fixed in place or be actively spring loaded
- The tensioner supplier can usually provide preload and stiffness values for an active tensioner



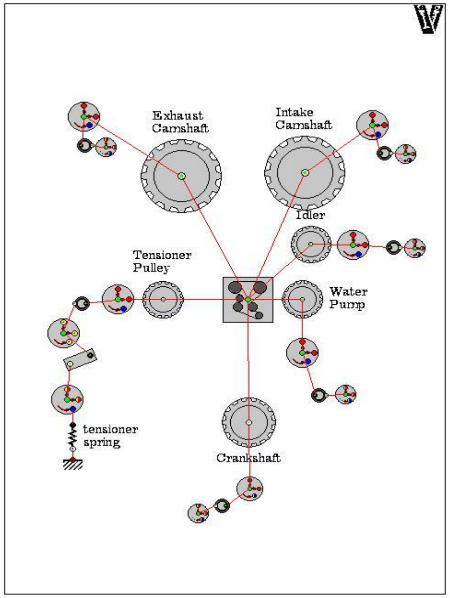
Belt Model – Initialising the Belt Tension



- VALDYN BELT_V2 models can be initialised using a number of different methods depending on the available data
- The simplest methods are the 3 built in ‘Auto Tensioning’ methods
- TYPE_A method
  - VALDYN adjusts a specified parameter (e.g. tensioner position) to achieve a given belt preload with a specified belt segment length, layout and number of belt segments
- TYPE_B method
  - VALDYN calculates an unloaded belt segment length that will result in the required belt preload with the specified layout and number of belt segments
- TYPE_C_method
  - VALDYN calculates a belt preload from a given belt segment length with the specified layout and number of belt segments

Belt Model – Initialising the Belt Tension

- The disadvantage with this method is that the pulleys are assumed to be in the centre of their bearings during initialisation – I.e. the bearing clearances are not taken up
  - The result is a slightly reduced tensioner nominal preload (with in tensioner tolerances)
- To account for this, a separate static analysis can be run to set the initial conditions
  - For the static analysis a simplified model of the belt drive is used, without any applied torques or displacements
  - An estimate is made for the initial belt segment length
  - The model is run until the tension is settled and the resulting tension is plotted
  - The process is iterated until the resulting tension is equal to the required value



Running the Analysis

- A speed sweep analysis can be performed across the engine running range
- The total run time for a speed sweep using the example timing drive model was ~4 hrs (Year 2007)
  - 1000rpm to 6000rpm in 250rpm steps
  - Computer specification: AMD 64bit FX53, 2.4GHz, 2G RAM
- The model should be run for a number of cycles before output results are recorded to allow the model to converge
  - A typical model might be run for 6 engine cycles and then have the output recorded over a following two engine cycles
  - This will depend on the model complexity and excitations
- Many results plots can be generated to assess the bet drive behaviour
- These results can be viewed using the RPLOT program
- Plot types include :
  - Time history plots look at the behaviour of a specified variable v. crank angle
  - Speed sweep plots look at the value of a specified variable v. engine speed
  - Location plots look at the value of a specified variable v. location number for a particular engine speed - I.e. the value at different positions around the drive
    - An explanation of the location numbering system is shown on the next slide

Output Elements

- It is useful to include a number of extra LSTIFF elements to generate 'relative displacement' output results
- These elements have no stiffness or damping input and have no physical function
- The highlighted LSTIFF element can be used to output the relative displacement between the crankshaft pulley and the exhaust camshaft pulley
  - The cam pulley displacements are first multiplied by a RATIO of 2 for this output to give the same constant speed as the crankshaft

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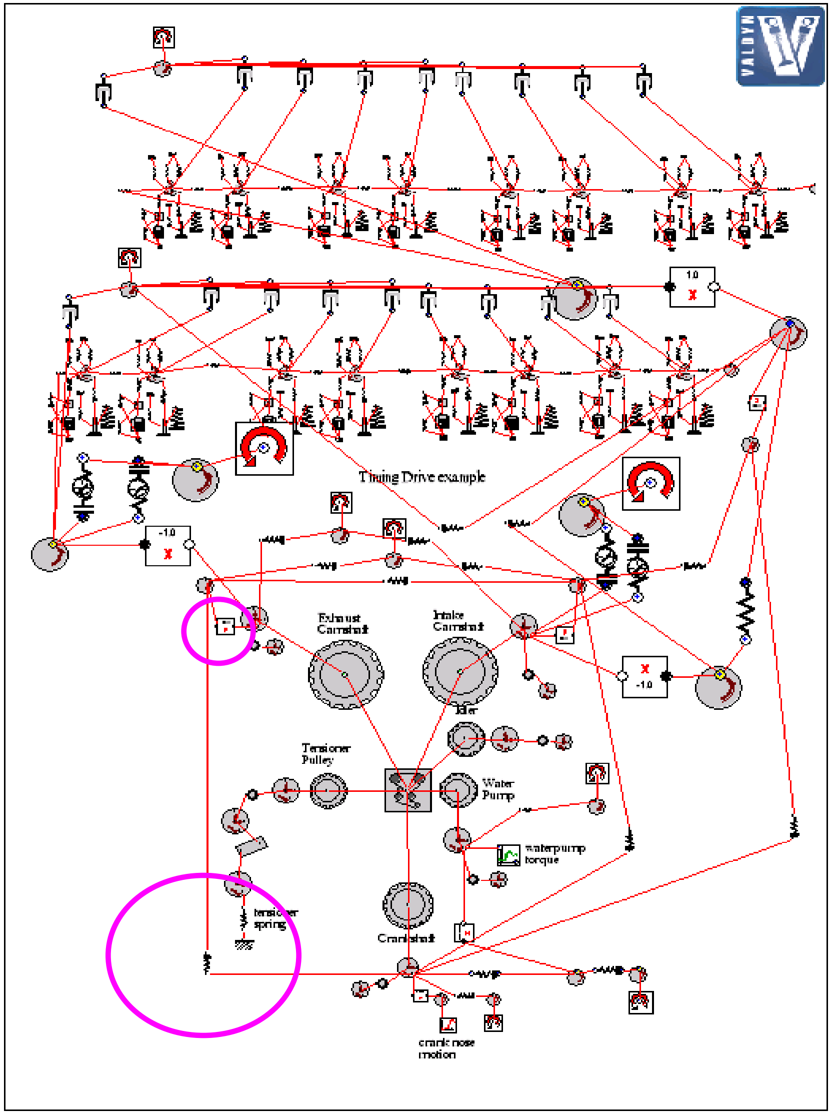
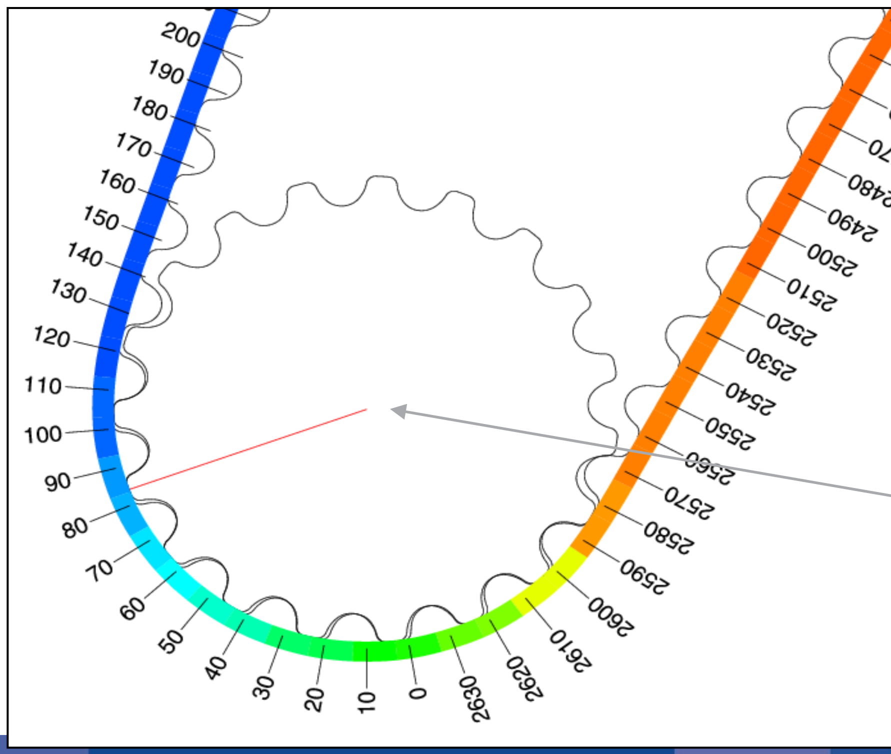
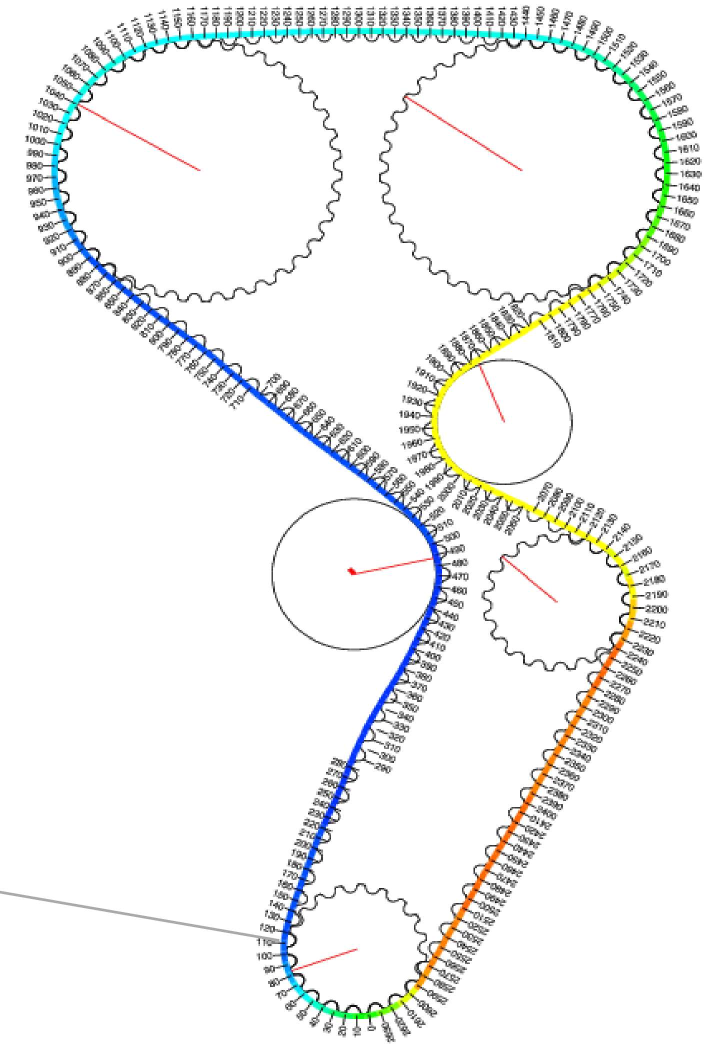


Belt Location Numbering System

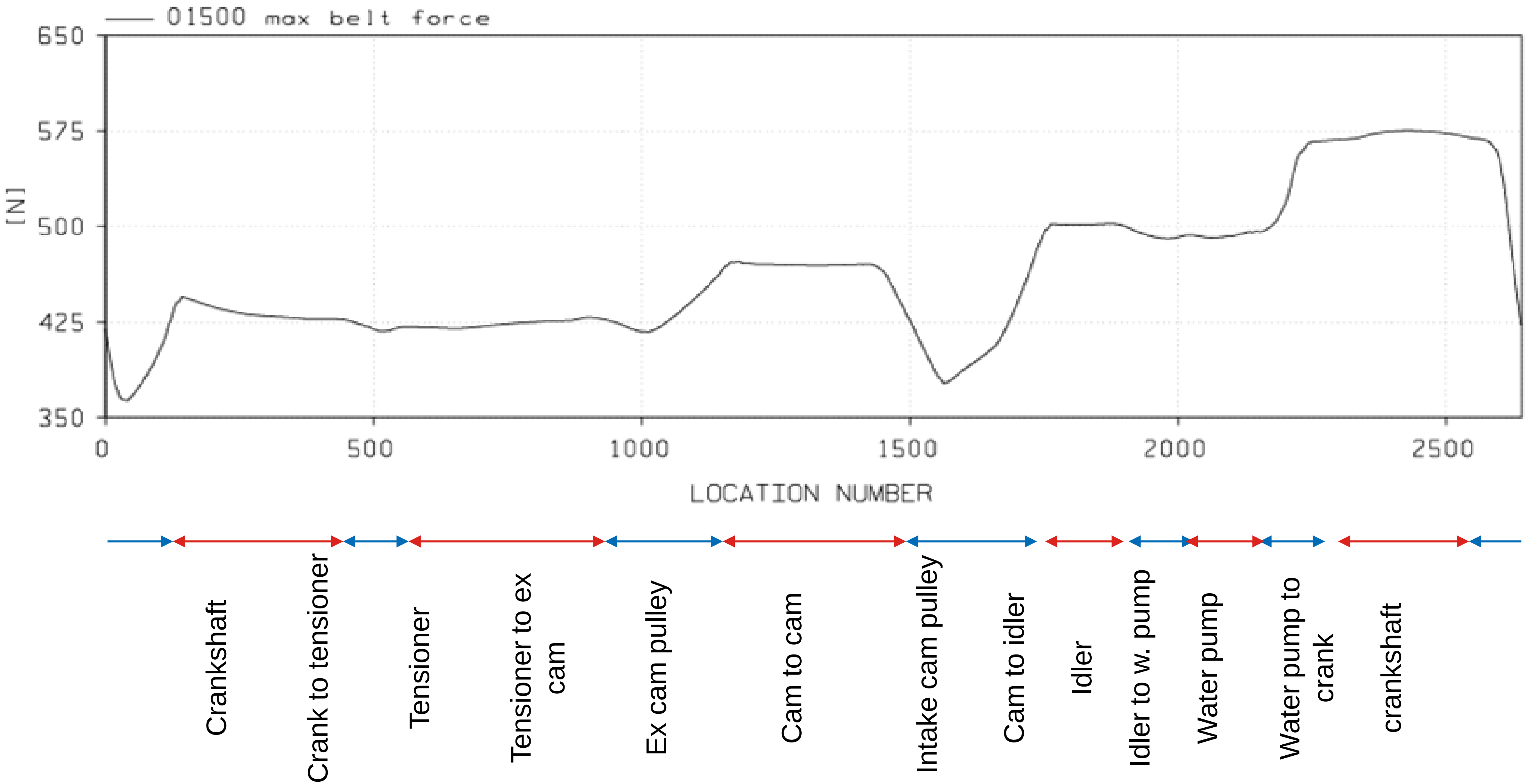
- A location numbering system is defined in VALDYN to enable outputs at a particular position in the drive to be identified
- The zero location was positioned at the rear of the crankshaft sprocket
- 10 locations per segment or 20 per belt pitch
- This numbering system is fixed in space





Belt Results Plotting v. Location

- The example plot shown is maximum belt force v. location at 1500rpm
- The different components in the drive layout can be identified from the location plots



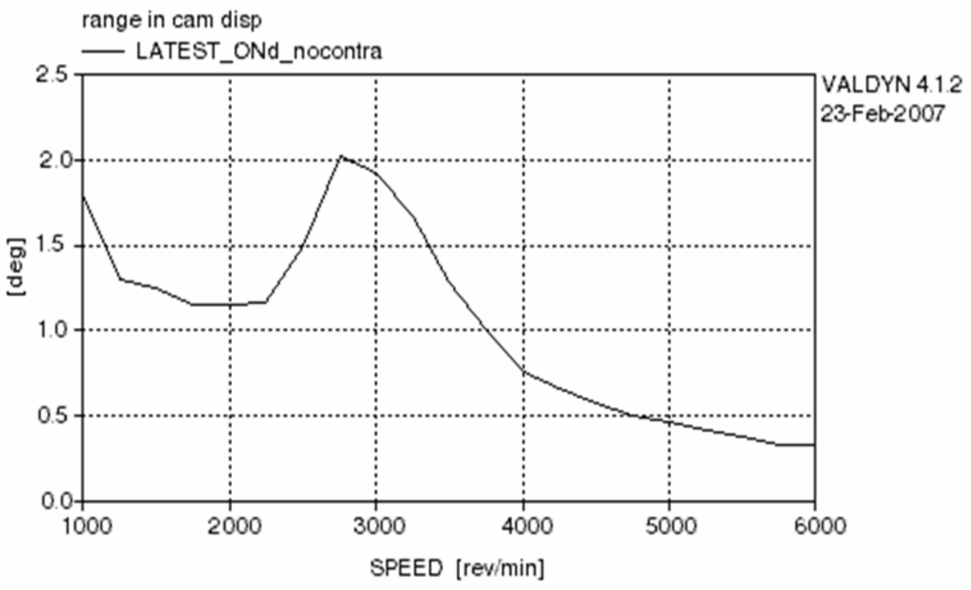
Typical Analysis Results
Phaser Stiffness

- The phaser stiffness depends on oil supply pressure
- Oil supply pressure generally increases across the speed range
- The simple stiffness representation can be modelled with a stiffness that increases with engine speed using PARAMETERS
- Typical values of stiffness v. engine speed are shown below

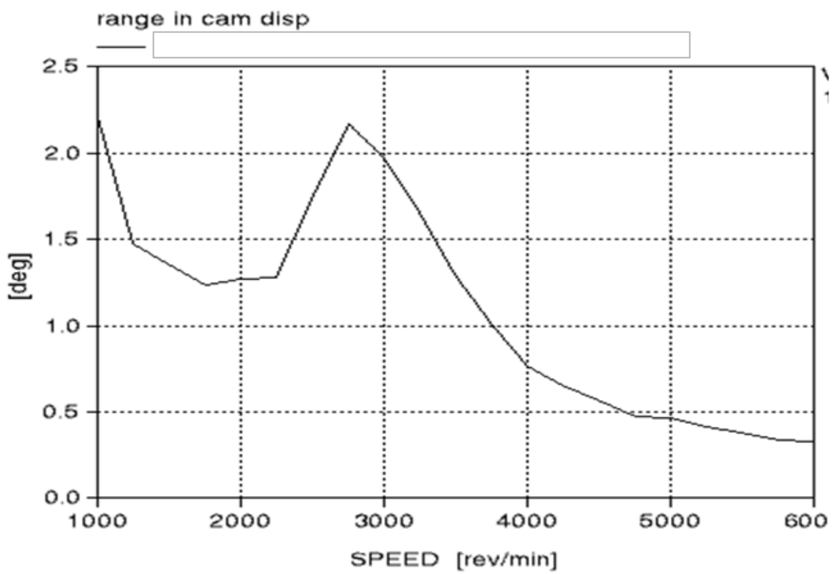
Engine speed (rpm)	Simple phaser stiffness (Nm/rad)
1000	1000
1500	1500
1750	2000
2000	2500
2250	2750
2500	3000
6000	3000

Typical Analysis Results
Intake camshaft displacement

- Intake camshaft torsional displacement results for VANE_PHASER model and simple model
  - Results are very similar



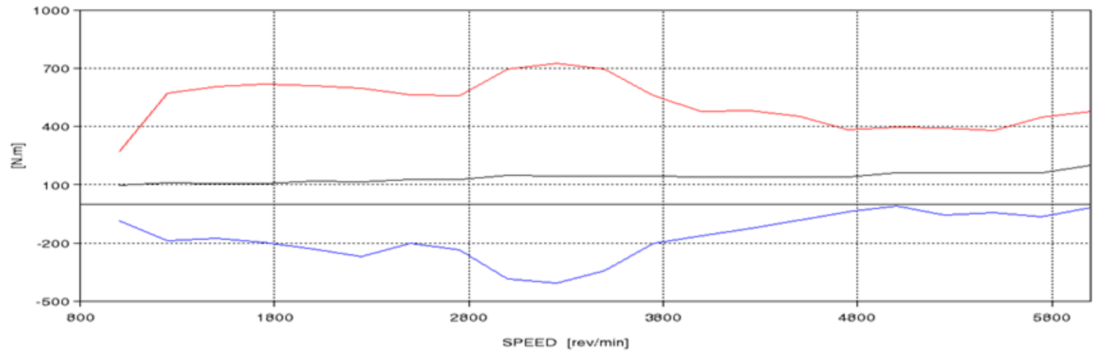
VANE_PHASER analysis model



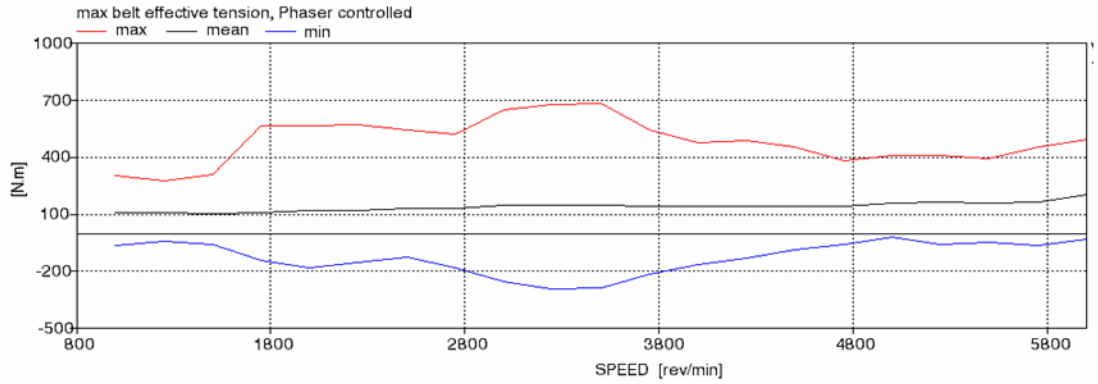
Simple analysis model, phaser K varying

Typical Analysis Results
Effective Belt Tension

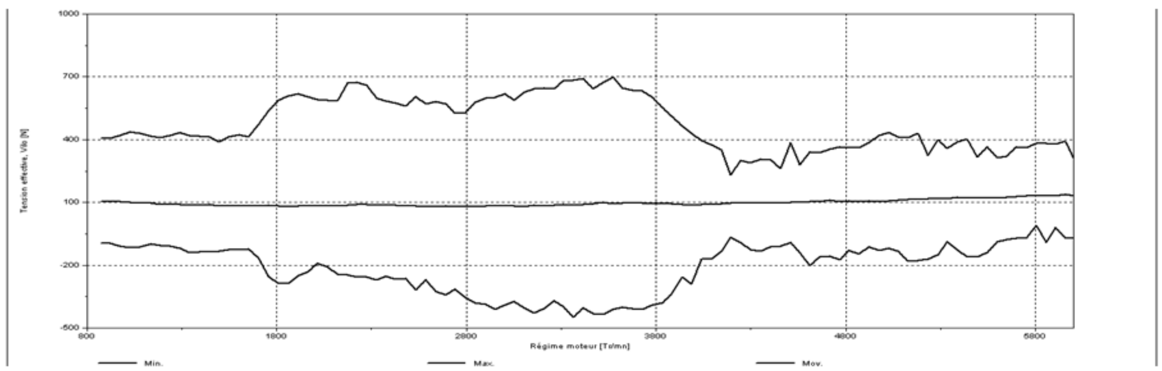
Simple model



VANE PHASER model



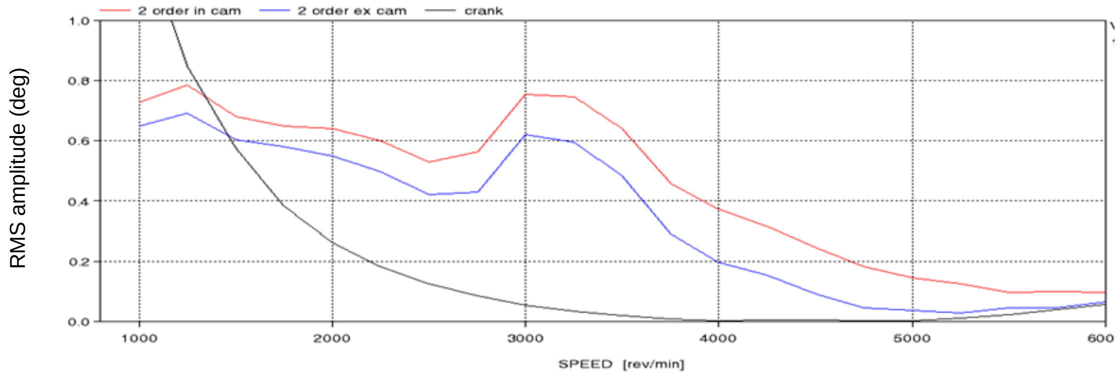
Measured data



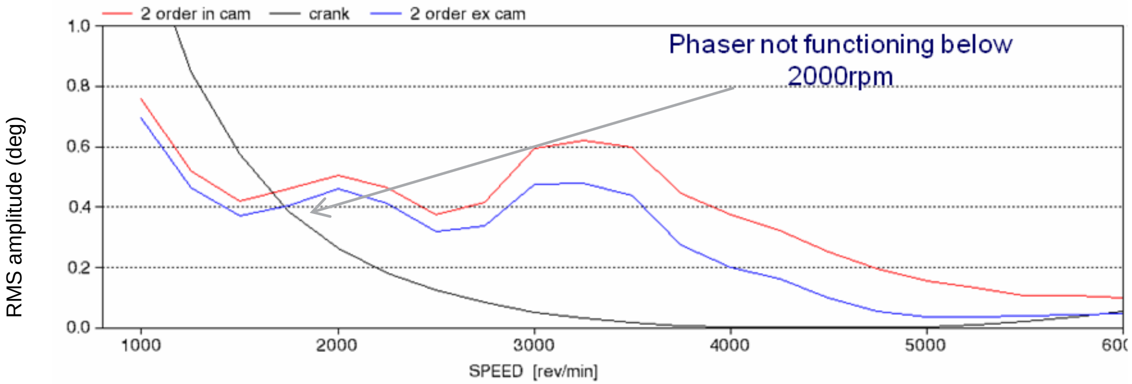
- Effective belt tension results for VANE_PHASER model and simple model
- Both analysis models show similar trends to the measured data
- The low speed results for the simple model match less well
  - The simple model follows the desired phasing map
  - The VANE_PHASER model and measured engine, do not have sufficient oil pressure to function until 1800rpm

Typical Analysis Results
Camshaft Pulley Displacement

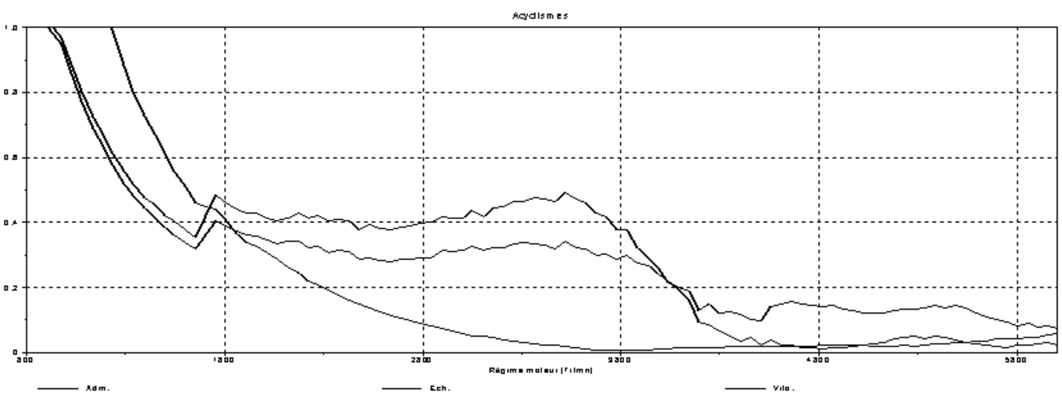
Simple model



VANE PHASER model



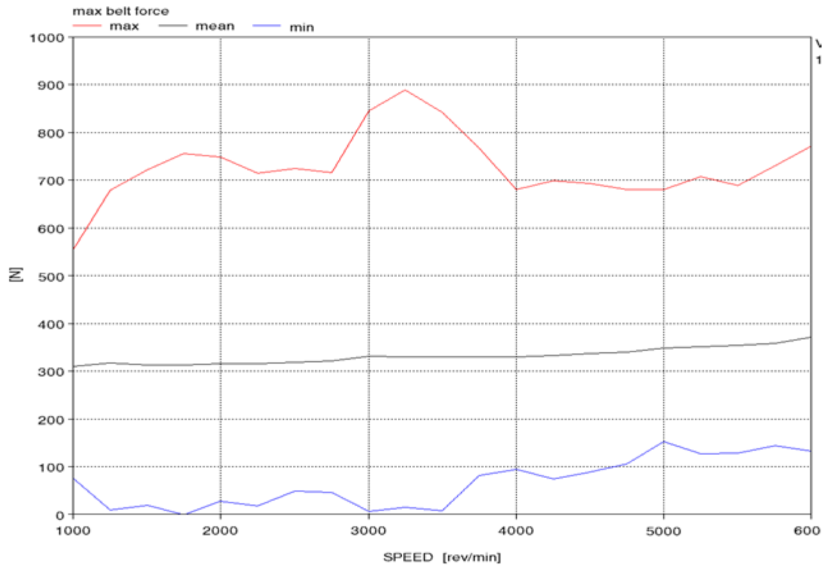
Measured data



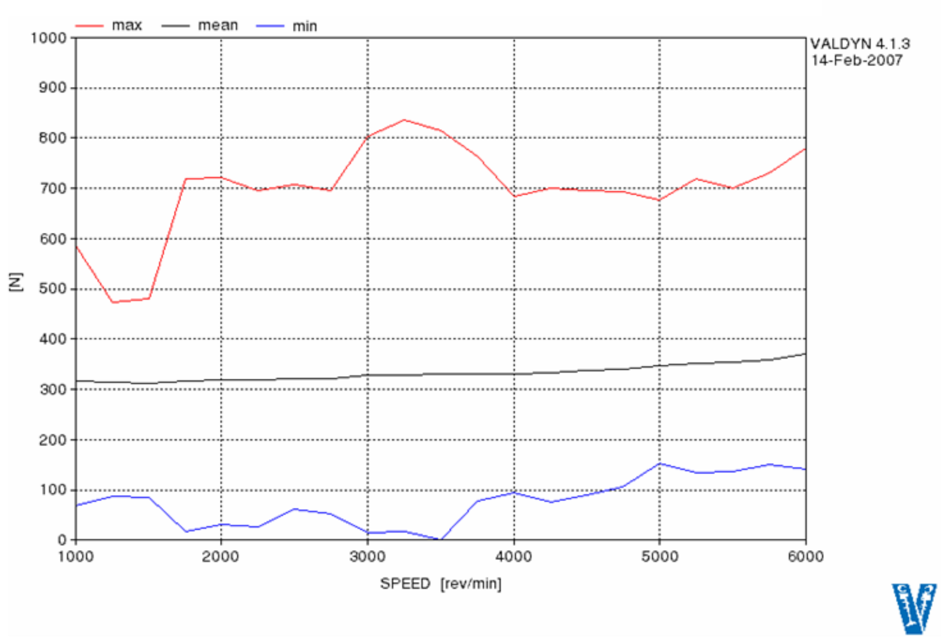
- Camshaft pulley displacement results for VANE_PHASER model and simple model
- Both analysis models show similar trends to the measured data
- As before, the low speed results for the simple model match less well

Typical Analysis Results
Maximum Belt Force

Simple phaser model



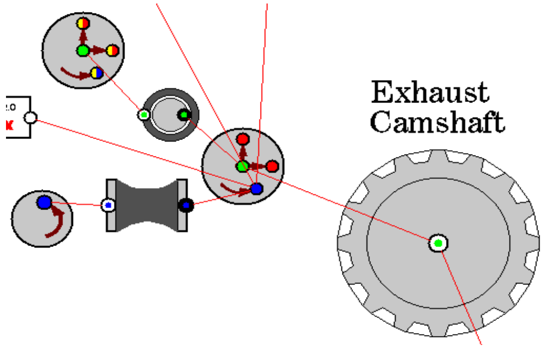
VANE_PHASER model



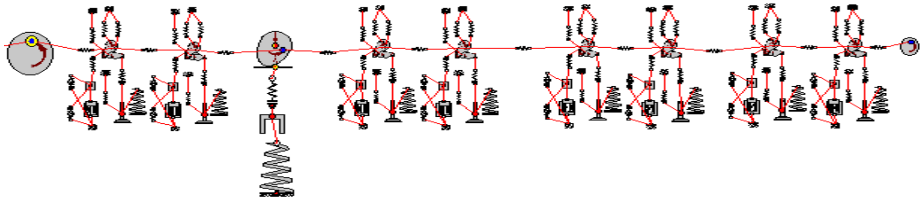
- Belt force results for VANE_PHASER model and simple model
  - Results are very similar

Countermeasures

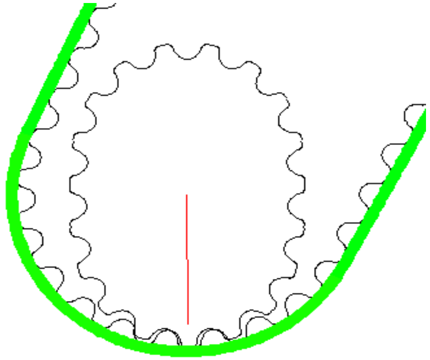
- A number of different countermeasures can be employed to reduced the belt drive dynamics due to the camshaft torque loading
  - Camshaft damper



  - Contra-cam unit



  - Oval pulley



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- All these counter measures can be modelled within VALDYN