VALDYN 1-D Crankshaft modelling

Tutorial

11th May 2011

Contents

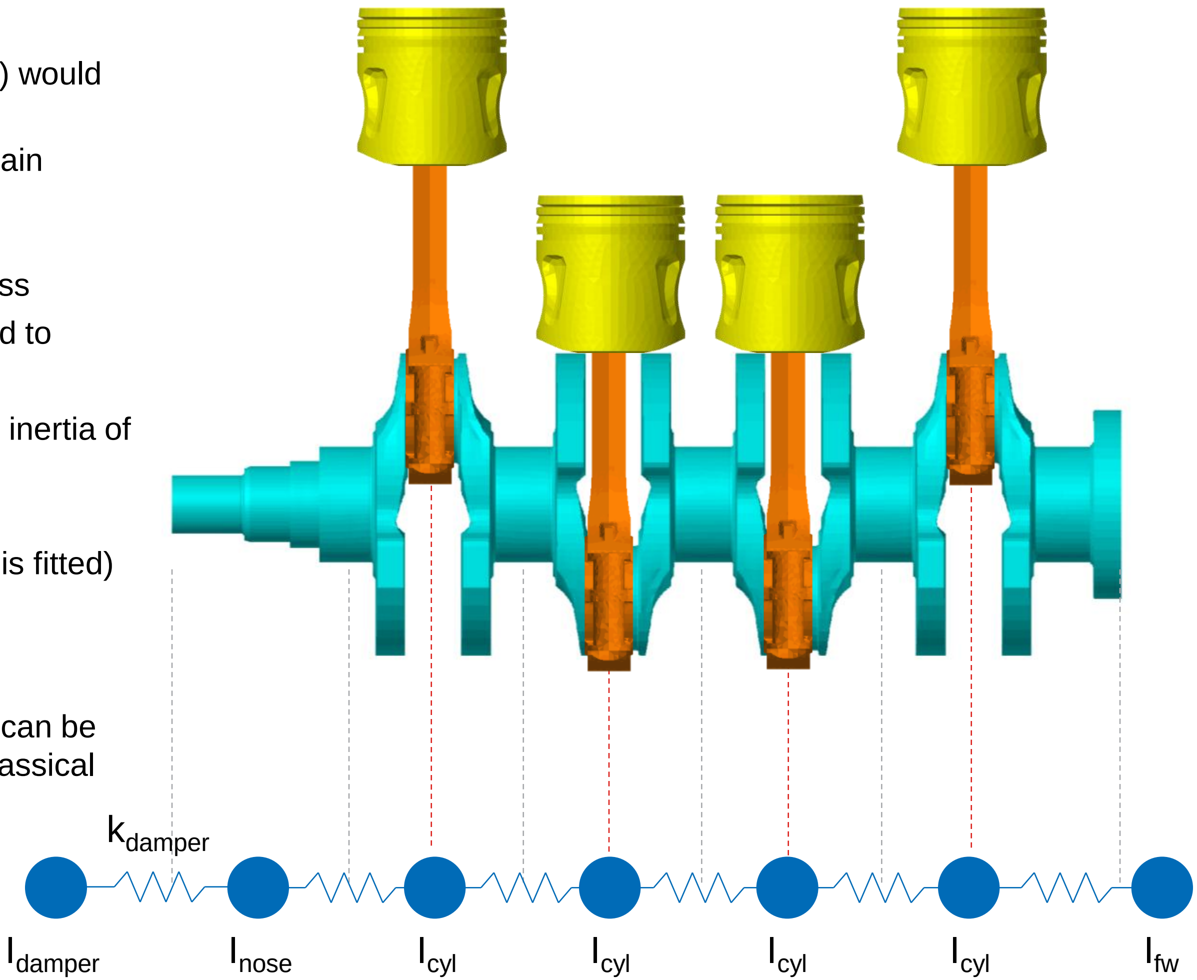
Introduction

- This tutorial will
  - Introduce the concept of crankshaft torsional (1 dimensional) modelling
  - Describe how to generate a VALDYN crankshaft model
  - Show how to run the model in the frequency and time domains
  - Introduce the concept of tuning a tuned rubber damper
  - Describe how to export results to ENGDYN for subsequent stress analyses
- Data files needed
  - Cylinder pressure diagrams: `<VALDYN installation folder>\4.5\examples\dynamic\LFD\crank\cylpress.*`
- A basic knowledge of using the VALDYN GUUI is expected before commencing with this tutorial]
  - This can be gained from sections 1 & 2 of the VALDYN standard tutorials

Contents

Crankshaft torsional (1-D) modelling

- The crankshaft is broken in to lumped parameters of stiffness and inertia
- For an inline engine, the inertia at each cylinder (I_{cyl}) would typically include
  - Inertia of the crank between the centre of the main bearings – about the crankshaft rotational axis
  - The rotating mass of the connecting rod and a proportion (usually half) of the reciprocating mass
    - This is multiplied by the crank throw squared to convert to an equivalent inertia
- The inertia of the nose (I_{nose}) would also include the inertia of anything assembled to it
  - Timing sprocket/pulley
  - FEAD pulley (or damper hub if a tuned damper is fitted)
  - Viscous damper casing (if fitted)
- The inertia of the flywheel is included at I_{fw}
- The torsional stiffness between the lumped inertias can be calculated either by Finite Element analysis or by classical methods
- Gas loads applied at I_{bay}
- Cylinder damping applied at I_{bay}



Contents

Crankshaft torsional analysis

- The model is excited by the piston forces from cylinder pressure traces
- There are typically two dynamic analysis methods used
  - Frequency domain
    - Overview
      - Inertia and stiffness data used to calculate system Eigenvalues and Eigenvectors
      - Harmonic content of gas loads used to excite each torsional mode to calculate the total forced-damped response
    - Advantages
      - Very fast analysis times
      - Zero mean torque means model can be free-free (no need to restrain model)
      - No cycle-to-cycle variation because of no restraint (using a soft spring or P.I.D. controller)
    - Disadvantages
      - Zero mean torque
      - Non-linear effects of slider-crank ignored
      - Transient responses (e.g., misfire) can not be modelled
  - Time domain
    - Overview
      - Time stepping
      - Force balance at each time step is calculated (by a re-iterative process until force balance is within set convergence criteria)
    - Advantages and disadvantages are generally the opposite to those of the frequency domain method

  - Ricardo would usually recommend running in the frequency domain

Contents

Crankshaft data

- The table shows the parameters that need to be entered in to the crankshaft model
- Engine configuration: Inline 4
- Firing order: 1-3-4-2
- Damper data not shown because this will be determined as part of the tutorial

Cranktrain parameters

Parameter	Reference	Unit	Value	Comment
Inertia of crank nose assembly	Inose	$kg.mm^2$	1200	Includes FEAD pulley/damper hub
Inertia at cylinder 1	Icyl1	$kg.mm^2$	4000	Includes rotating mass of connecting rod (typically 2/3 of rod mass)
Inertia at cylinder 2	Icyl2	$kg.mm^2$	4000	
Inertia at cylinder 3	Icyl3	$kg.mm^2$	4000	
Inertia at cylinder 4	Icyl4	$kg.mm^2$	4000	
Inertia at flywheel	Ifw	$kg.mm^2$	150000	Should include clutch
Stiffness between FEAD pulley hub and centre of crank pin 1	K0	N.m/rad	150000	Pulleys will stiffen the nose
Stiffness between centre of crank pin 1 & crank pin 2	K1	N.m/rad	350000	
Stiffness between centre of crank pin 2 & crank pin 3	K2	N.m/rad	350000	
Stiffness between centre of crank pin 3 & crank pin 4	K3	N.m/rad	350000	
Stiffness between centre of crank pin 4 and flywheel attachment	K4	N.m/rad	600000	
Cylinder damping	Ccyl	N.m.s/rad	1.5	Typical for a small gasoline engine
Mass of piston assembly and connecting rod reciprocating mass (usually 1/3 rod mass)	Mrec	kg	0.4	
Connecting rod axial stiffness	Krod	N/mm	250000	Used in time domain analysis only
Cylinder bore	BORE	mm	80	
Crank throw radius	THROW	mm	40	
Connecting rod length	LROD	mm	130	
Cylinder offset	CO	mm	0	
Pin offset	PO	mm	0	

Contents

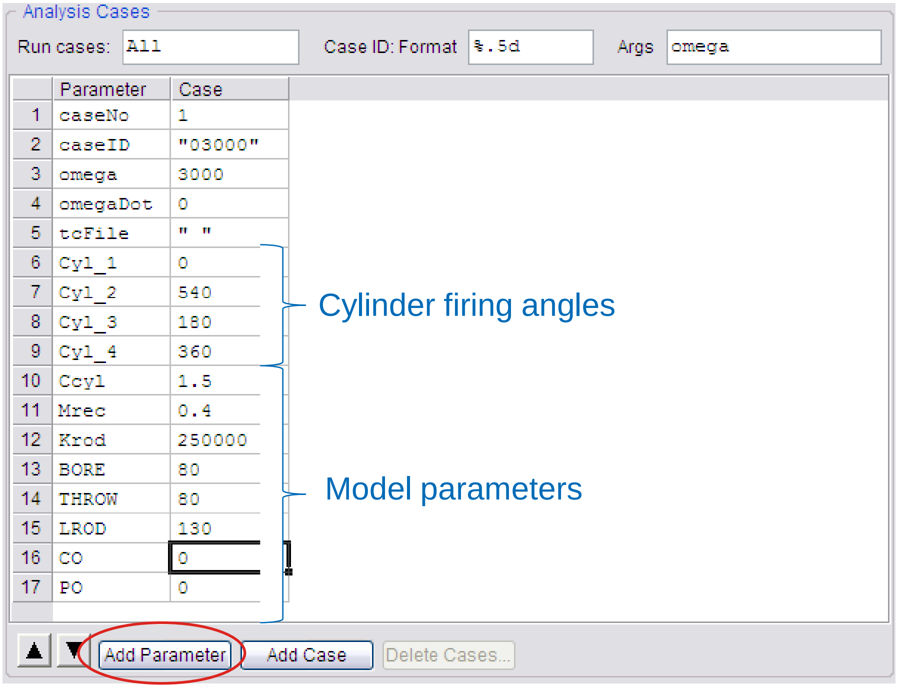
Build model

1

- Copy the required cylinder pressure files to the working directory
- Start the VALDYN GUI

2

- Define the parameters shown in the table
  - Defined in the “Model” > “Analyse…” panel
  - Parameters can be added by pressing ‘Add Parameter’ button



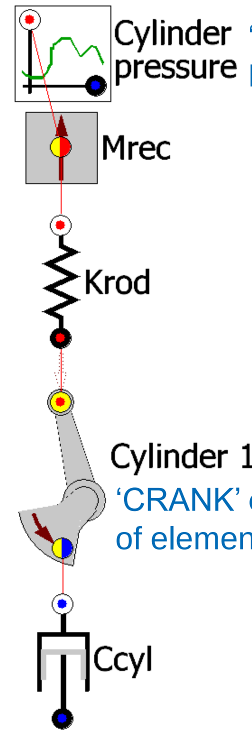
3

- Save the model in the working directory
  - It is recommended that you regularly save the model

Build model

4

- Construct 1 cylinder of the model as shown in the figure
  – Click the right mouse button over each element and select ‘Edit Appearance…’ from the context menu to add the description

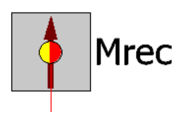


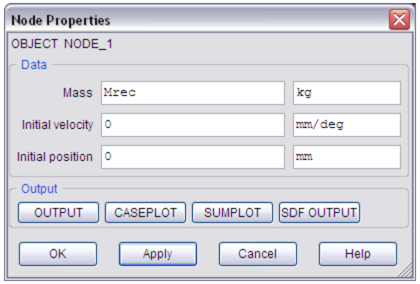
‘SFORCE’ element (found in MISC tab of element palette

‘CRANK’ element (found in MISC tab of element palette

5

- Set reciprocating mass (Mrec, NODE_1)
  – Mass = Mrec [kg]
  – Initial velocity = 0 [mm/deg]
  – Initial position = 0 [mm]
    - 0 mm equates to top dead centre
    - (80 mm would equate to bottom dead centre)

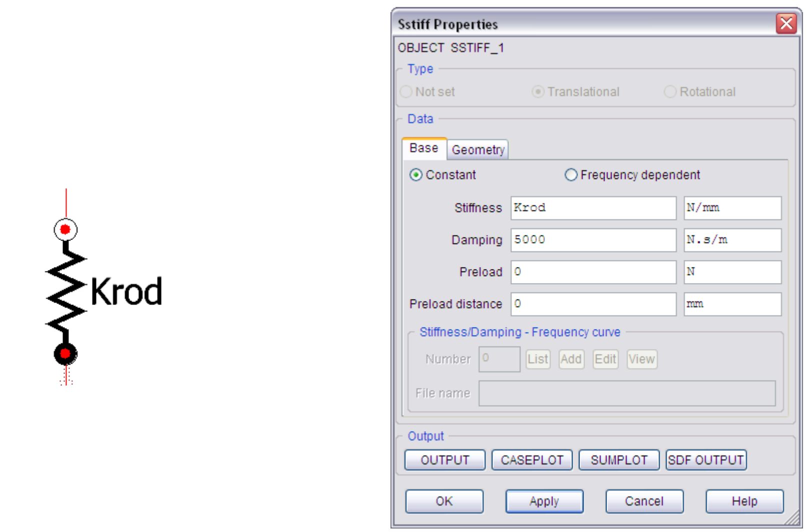




Build model

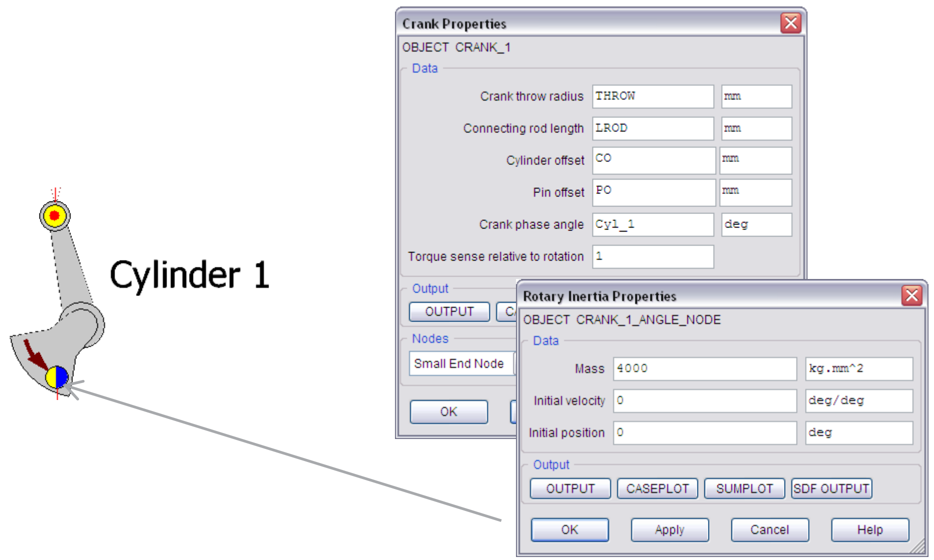
6

- Set connecting rod (Krod, SSTIFF_1)
  - Stiffness = Krod [N/mm]
  - Damping = 5000 [Ns/m]
  - It is not essential to complete the connecting rod properties for the frequency domain solution (frequency domain assumes a rigid connecting rod), but it is useful to enter to protect for any future time domain solutions



7

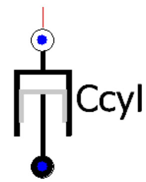
- Set crank mechanism (Cylinder 1, CRANK_1)
  - Crank throw = THROW [mm]
  - Connecting rod length = LROD [mm]
  - Cylinder offset = CO [mm]
  - Pin offset = PO [mm]
  - Crank phase angle = Cyl_1 [deg]
    - Defines the TDC angle
  - Torque sense relative to rotation = 1 (default)
    - Can be left as default for most applications, refer to manual for more information
  - Mass (CRANK_1_ANGLE_NODE) = 4000 [$kg.mm^2$]

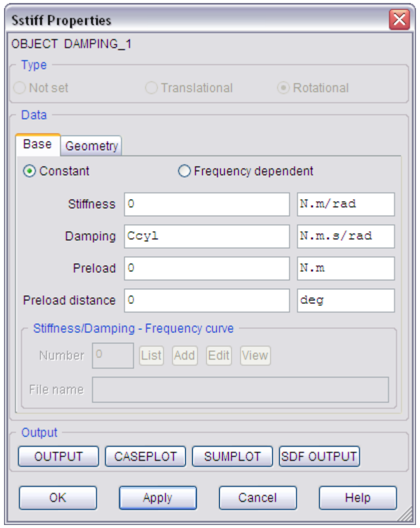


Build model

8

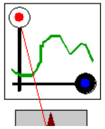
- Set cylinder damping (Ccyl, DAMPING_1)
  - Damping = Ccyl [Ns/m]

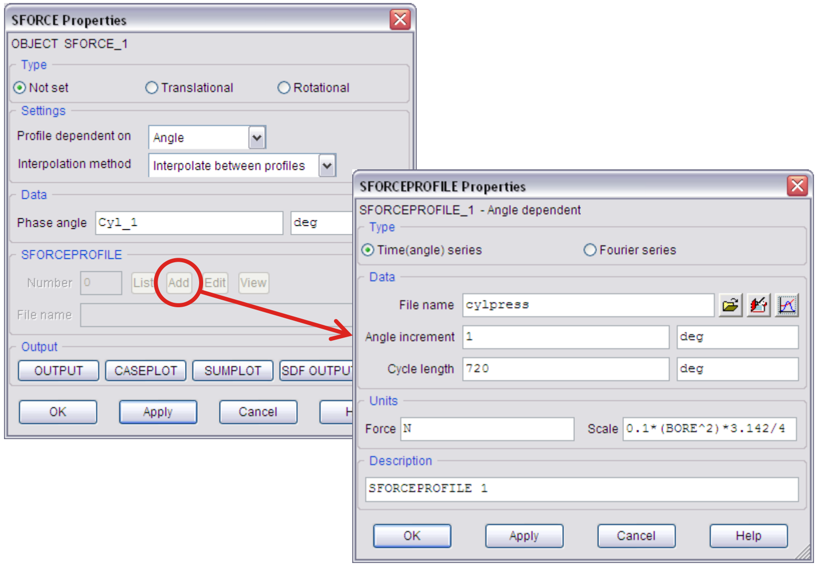




9

- Set cylinder pressure (SFORCE_1)
  - Profile dependent on = Angle
  - Interpolation = ‘Interpolate between profiles’
    - If the simulation is run at a speed not defined by one of the cylinder pressure diagrams, then VALDYN will interpolate from diagrams at the nearest speeds above and below the required speed
  - Phase angle = Cyl_1 [deg]
    - Defines the TDC angle – assumes that cylinder pressure table has TDC at either 0° or 360°
  - ‘Add’ an SFORCE profile (continued on next slide)

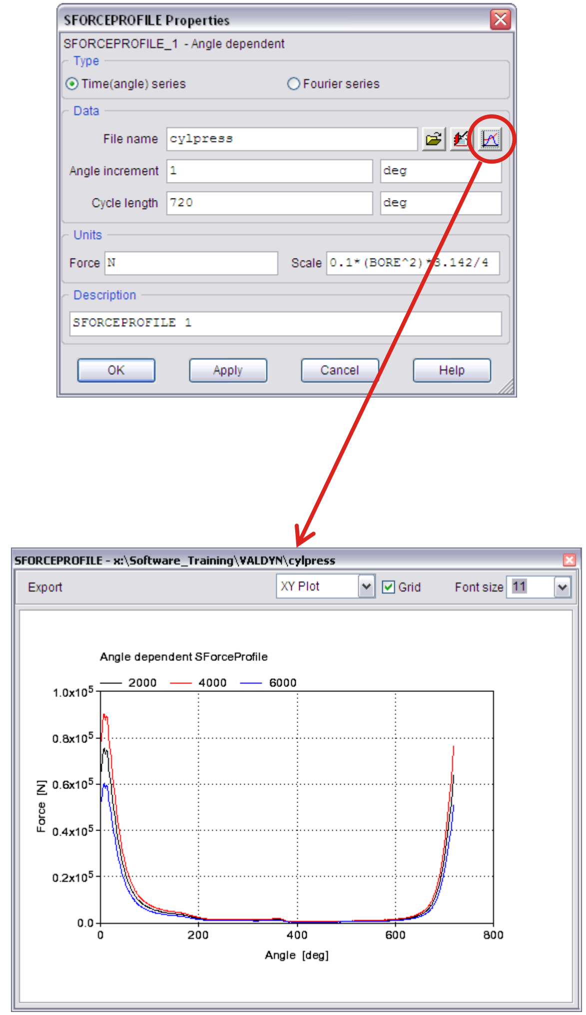




Build model

10

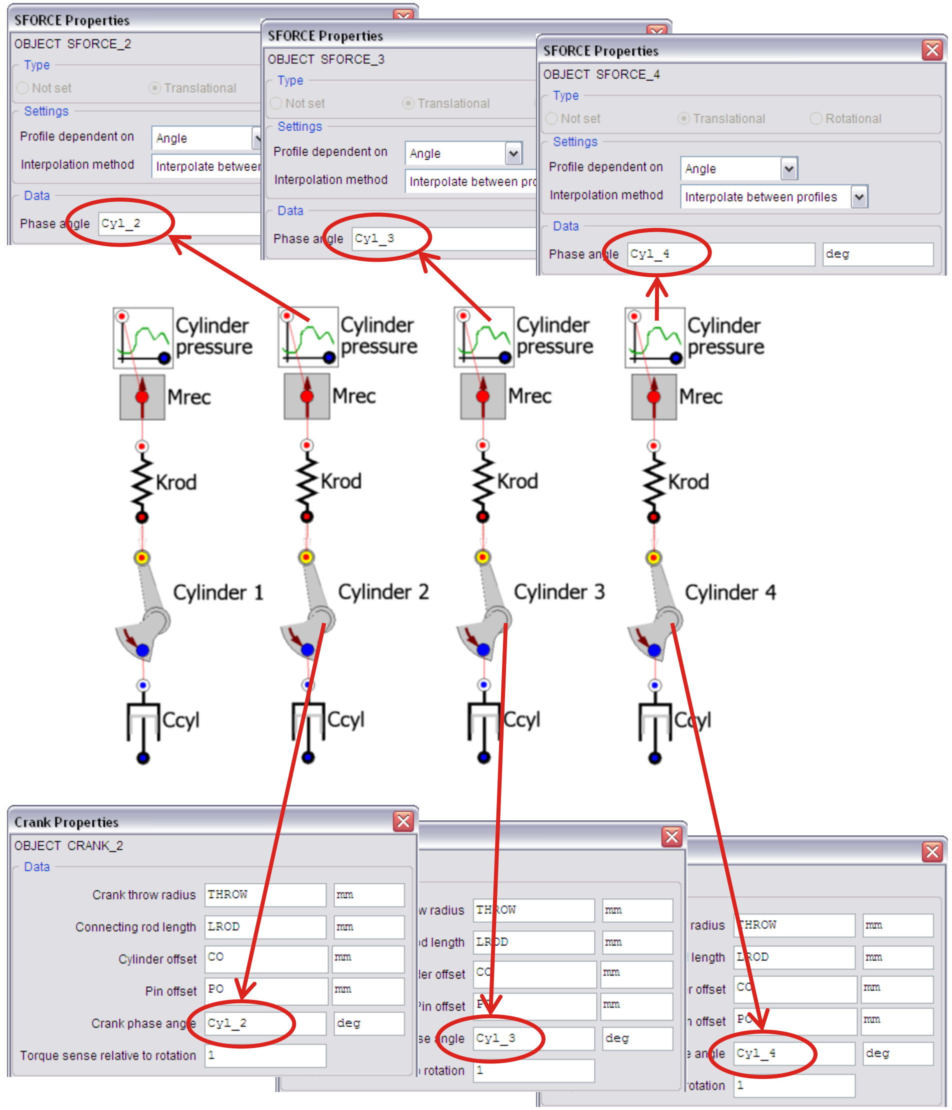
- Set cylinder pressure continued
  - File name = cylpress
    - Enter the prefix of the file name only. VALDYN will automatically add the suffix based on the simulation speed
    - E.g., At 2000 revs/min, VALDYN will load file ‘cylpress.2000’
  - Angle increment is ignored because the cylinder pressure diagram already contains angle data in the first column
  - Cycle length = 720 [deg]
  - Units
    - Force = N
    - Scale = 0.1 * BORE^2 * pi/4
      - This is a scaling factor to convert cylinder pressure to force based on the surface area of the piston
  - The gas forces may be viewed within VALDYN by pressing the button highlighted in the diagram



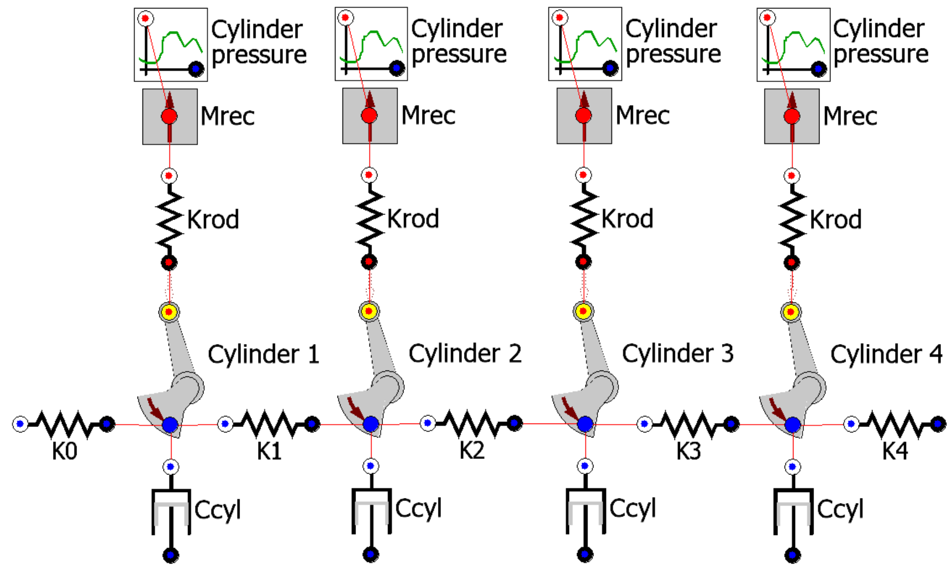
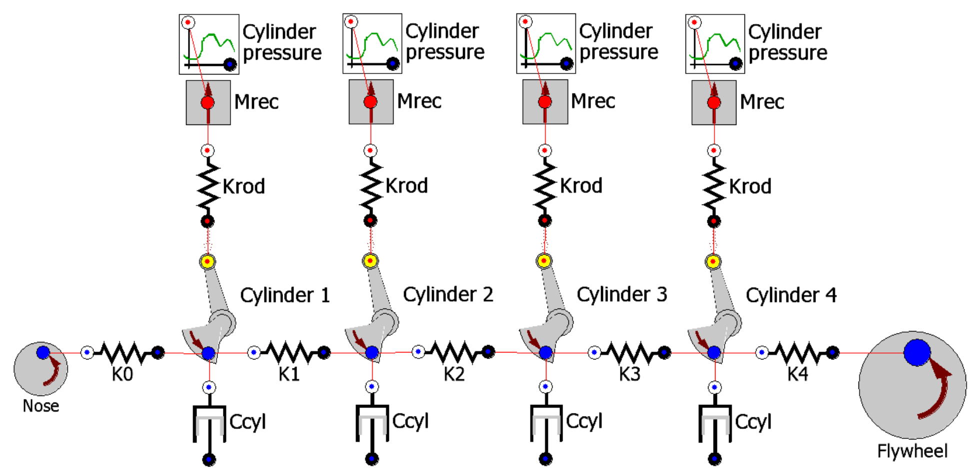
Build model

11

- Select all the elements and copy & paste 3x across the canvas to generate a 4 cylinder model as shown in the figure
  - Multiple elements may be selected by
    - Drawing a box around the required elements (whilst holding down left mouse button)
    - Holding the SHIFT button down while selecting each element (with the left mouse button)
  - Copy/paste functions can be found in the context menus (right mouse button) or using keyboard Ctrl+c & Ctrl+v
- Update cylinder numbers in the model annotation
- Update the phase angles in each CRANK & SFORCE element according to it's cylinder number
  - CRANK_2, SFORCE_2 = Cyl_2
  - CRANK_3, SFORCE_3 = Cyl_3
  - CRANK_4, SFORCE_4 = Cyl_4
  - As shown in the figure



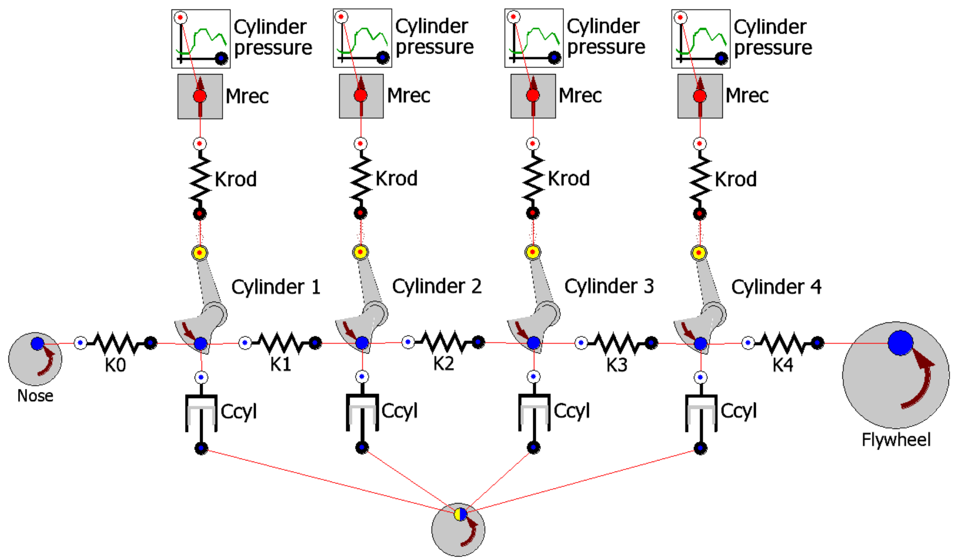
Build model

12	• Add crankshaft stiffness SSTIFF elements as shown in the figure – Rotate the SSTIFF elements so that the i (white) node points to the crank nose (front) – this is necessary only to ensure the correct sign convention if the results are to be exported to ENGDYN • Set stiffness values in each element as shown – K0 = 150000 [Nm/rad] – K1 = 350000 [Nm/rad] – K2 = 350000 [Nm/rad] – K3 = 350000 [Nm/rad] – K4 = 600000 [Nm/rad]	
13	• Add crankshaft nose and flywheel NODE elements as shown in the figure – The size of the elements can easily be changed by selecting the element (right mouse button) and rolling the middle/roller mouse button • Set inertia values as shown – Nose = 1200 [kg.m^2] – Flywheel = 150000 [kg.m^2]	

Build model

14

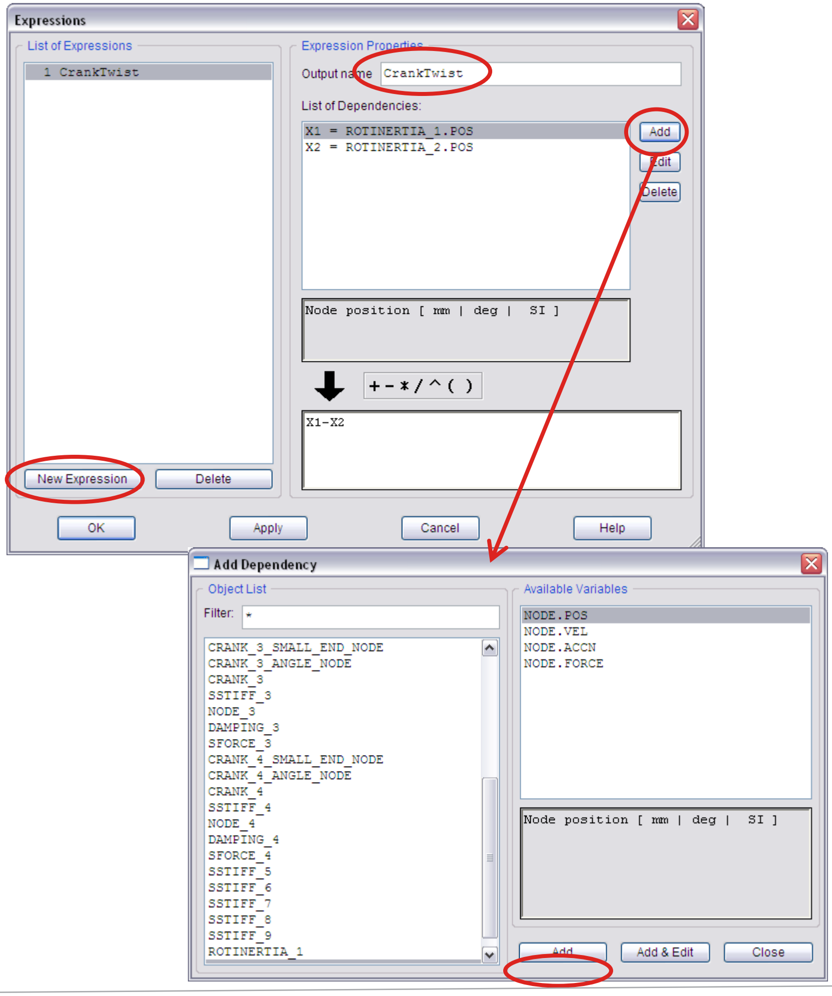
- Add a NODE element below the DAMPER elements and connect to all the DAMPER elements
  - As shown in the figure
- The NODE properties can be left as default
  - Inertia is kept at zero so that it behaves like a GROUND
    - Cylinder damping is often known as 'mass' damping. It is based on the relative velocity between the crank node and a constant velocity node whose velocity is equal to the mean velocity of the crank node
    - In the frequency domain the mean velocity of the nodes in the model are zero. Therefore the DAMPER elements can be connected to a GROUND element or a NODE with zero velocity
    - The advantage of using a NODE is that it allows for easier conversion to a time domain model because the constant velocity node would need to be set to rotate at the simulation speed



Build model

15

- Create a new expression to measure crankshaft twist
  - Open ‘Expressions’ panel (menu ‘Model’ > ‘Expression…’
  - Press ‘New Expression’ button
  - Set ‘Output name’ = CrankTwist
  - Press ‘Add’ button from List of Dependencies
  - Select nose NODE position (ROTINERTIA_1.POS)
    - ‘Add’ as X1
  - Select Flywheel NODE position (ROTINERTIA_2.POS)
    - ‘Add’ as X2
  - Close ‘Add Dependency’ panel
  - Enter equation to calculate crankshaft twist
    - X1-X2



16

- The model is now complete. Output plots and analysis settings now need to be defined

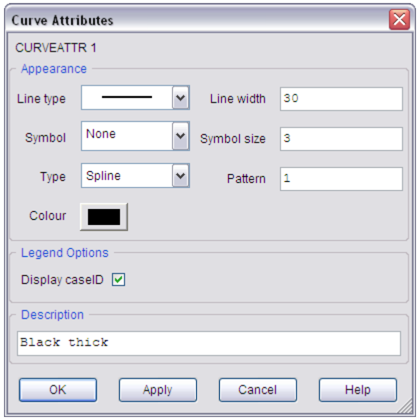
Contents

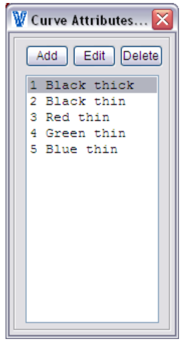
- Introduction
- Crankshaft torsional (1-D) modelling
- Crankshaft torsional analysis
- Crankshaft data
- Build model
- **Define output plots**
- Define analysis settings and run analysis
- Results
- Add a tuned rubber damper
- Re-run the analysis
- Create outputs for ENGDYN to import

Define output plots

- Before creating the plots it is useful to define the curve attributes that are to be used in the plots
- Define the curve attributes shown in the table on the right
  - Curve attributes should remain default except for the changes listed in the table
  - Curve attributes can be defined from the menu ‘Model’ > ‘CurveAttributes…’, and then using the ‘Add’ button to create a new definition.
  - The figure on the right shows the curve attribute definition for the first curve

Description	Line width	Type	Colour
Black thick	30	Spline	Black
Black thin	15	Spline	Black
Red thin	15	Spline	Red
Green thin	15	Spline	Green
Blue thin	15	Spline	Blue





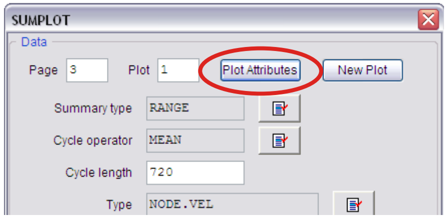
Define output plots

- Create the SUMPLOTs shown in the table below
  - Plot definitions should remain default except for the changes listed in the table
  - Plots of 'Expressions' are created from the 'Add' button of the SUMPLOTs panel (menu 'Model' > 'Sumplot…')

Plot #	Page	Plot	Curve Attribute	Summary type	Cycle operator	Element	Type	Other	Legend
1	1	1	1	Range	Mean	Crank nose (ROTINERTIA_1)	NODE.POS	-	Total
2	1	1	2	Order	Mean	Crank nose (ROTINERTIA_1)	NODE.POS	Order = 2	2.0
3	1	1	3	Order	Mean	Crank nose (ROTINERTIA_1)	NODE.POS	Order = 4	4.0
4	1	1	4	Order	Mean	Crank nose (ROTINERTIA_1)	NODE.POS	Order = 6	6.0
5	1	1	5	Order	Mean	Crank nose (ROTINERTIA_1)	NODE.POS	Order = 8	8.0
6	1	2	-	Spectrum	Order	Crank nose (ROTINERTIA_1)	NODE.POS	Output orders = 24	-
7	2	1	1	Range	Mean	Expression: CrankTwist	Expression	-	Total
8	2	1	2	Order	Mean	Expression: CrankTwist	Expression	Order = 2	2.0
9	2	1	3	Order	Mean	Expression: CrankTwist	Expression	Order = 4	4.0
10	2	1	4	Order	Mean	Expression: CrankTwist	Expression	Order = 6	6.0
11	2	1	5	Order	Mean	Expression: CrankTwist	Expression	Order = 8	8.0
12	2	2	-	Spectrum	Order	Expression: CrankTwist	Expression	Output orders = 24	-
13	3	1	1	Range	Mean	Flywheel (ROTINERTIA_2)	NODE.VEL	-	-

- The plot attributes are shown in the table below
  - Plot definitions should remain default except for the changes listed in the table
  - Plot attributes can be edited by opening up a define SUMPLOT and selecting 'Plot Attributes' at the top of the panel

Page number	Plot number	Title 1	Y axis unit
1	1	Crank nose motion	Default
1	2	Crank nose motion	Default
2	1	Crankshaft twist	deg
2	2	Crankshaft twist	Default
3	1	Flywheel velocity variation	rpm

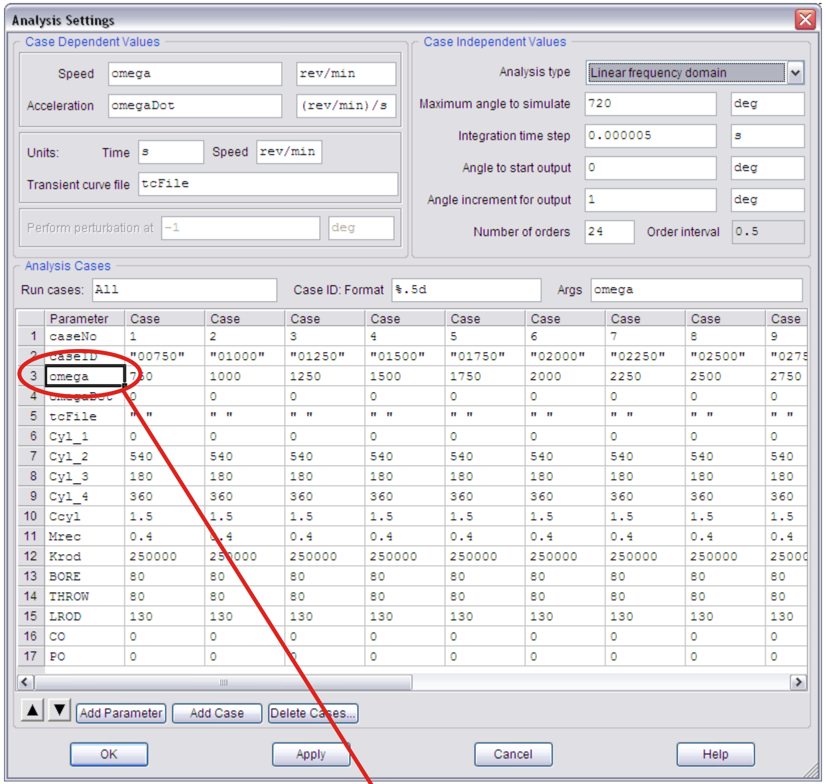


Contents

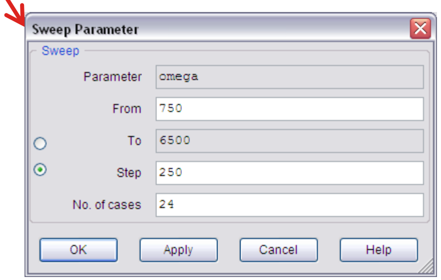
Define analysis settings and run analysis

- Open ‘Analysis Settings’ panel (menu ‘Model’ > ‘Analyse…’)
- Set analysis type = Linear Frequency Domain
- Define a speed sweep from 750 rev/min to 6500 rev/min in 250 rev/min steps
  - Number of cases = 24
  - Shown in the figures on the right

- Start the analysis
  - This should take a few seconds to run



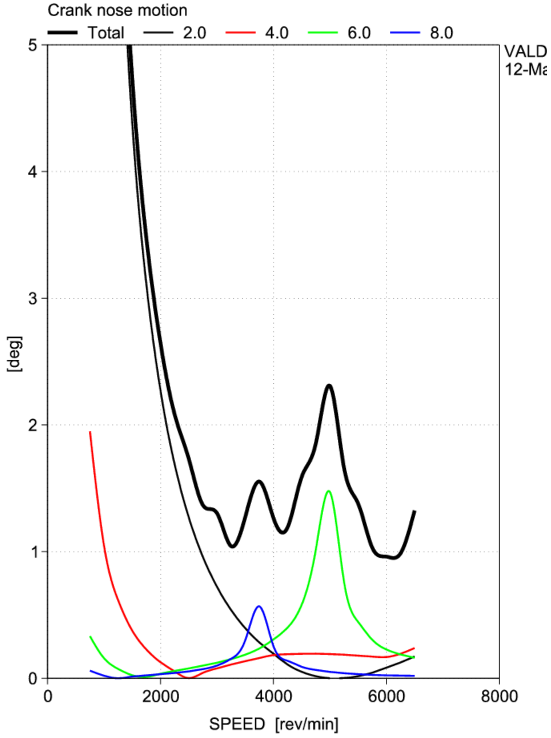
Right mouse button > ‘Sweep parameter…’

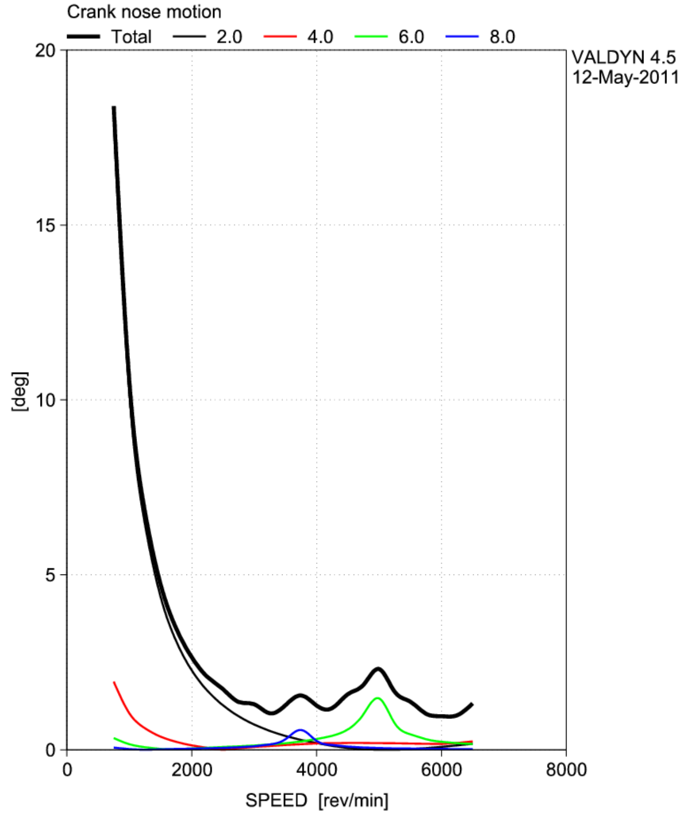


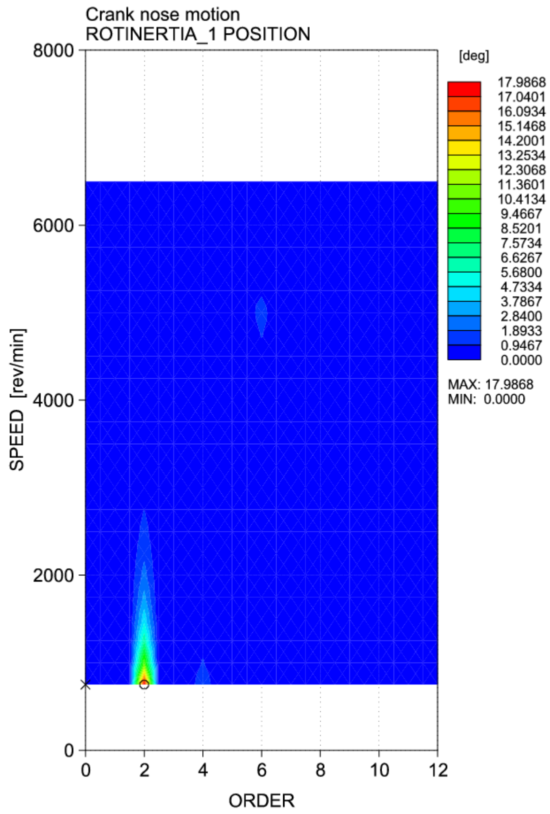
Contents

Results

- Crankshaft nose motion dominated by 2nd order in a 4 cylinder engine
- Influenced by flywheel inertia and cylinder pressure
- Nose motion of 4, 6, 8 orders significantly above any limits (typically 0.15 deg)

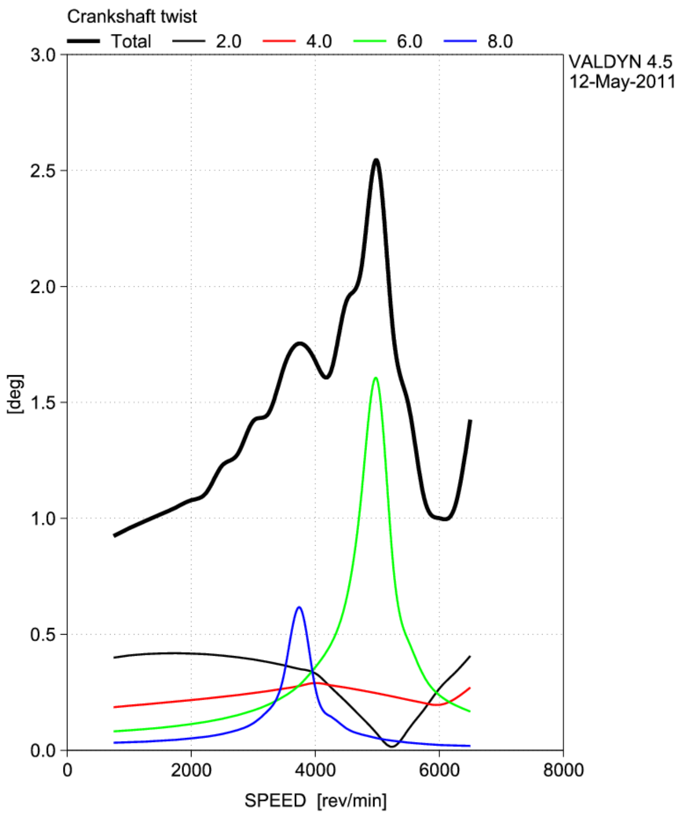


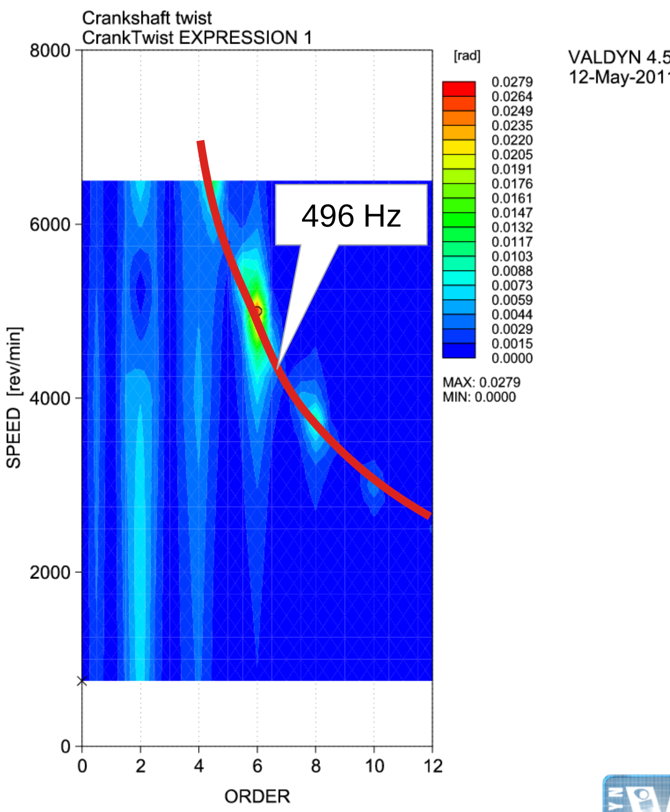




Results

- The crankshaft's 1st torsional mode can be seen to be 496 Hz
  - This is greatly excited by the 6th and 8th order excitations
- A tuned rubber damper should be added to reduce the vibration amplitudes

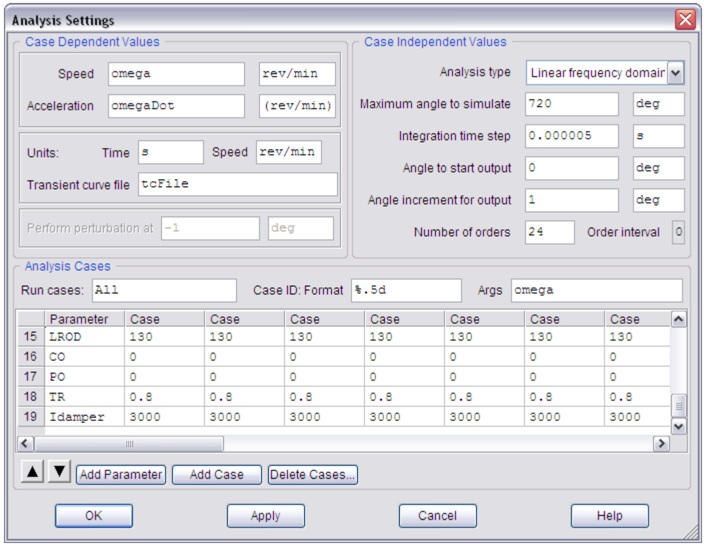




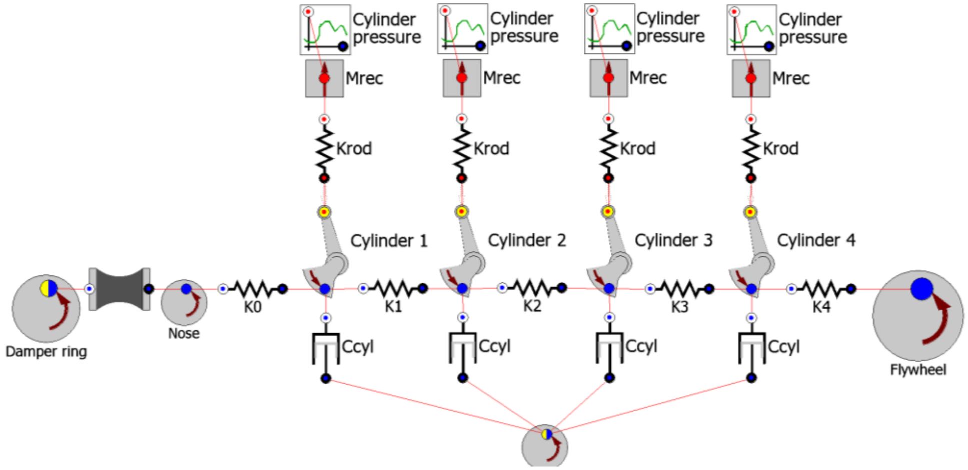
Contents

Add a tuned rubber damper

- Create two new parameters
  - TR, value = 0.9
    - This is the damper tuning ratio – which is the fraction of the damper's natural frequency relative to the crankshaft's 1st mode frequency
  - Idamper, value = 3000
    - This is the inertia of the damper ring

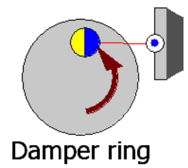


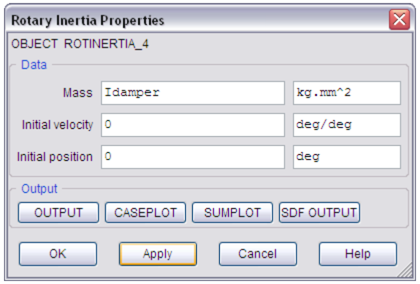
- Add a NODE and QSTIFF element to the crankshaft nose
  - The NODE represents the inertia of the damper ring / FEAD pulley
  - The QSTIFF represents the rubber ring inside the damper



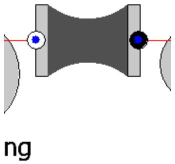
Add a tuned rubber damper

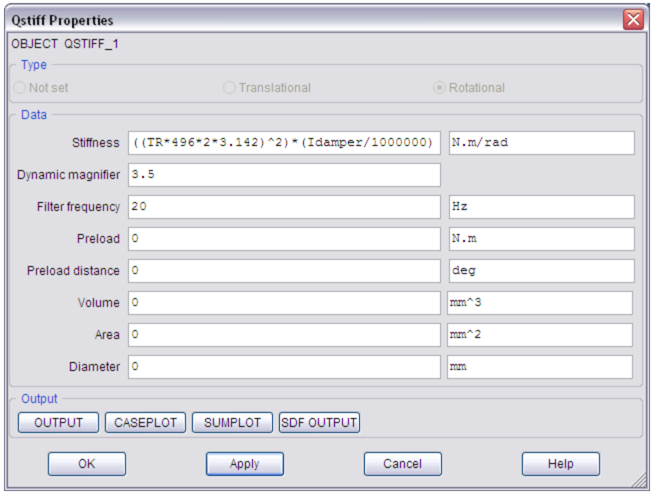
- Set damper ring inertia
  - Mass = Idamper [kg.mm^2]





- Set rubber (QSTIFF) properties
  - Let VALDYN calculate the required rubber stiffness based on the tuning ratio (TR), damper ring inertia, crankshaft 1st mode frequency (496 Hz)
    - Stiffness, $k = (TR \times 496 \times 2\pi)^2 \times \frac{Idamper}{1000000}$
  - Dynamic magnifier (M) = 3.5
    - This is the ratio of the amplitude of the response of the system relative to the excitation of the system at it's resonant frequency
    - The equivalent fraction of critical damping would be 1 / 2*M = ~14%, which is typical for rubber
  - Filter frequency = 20 Hz
    - The simulation results are not sensitive to this value. It just needs to be an order of magnitude lower than the lowest system natural frequency



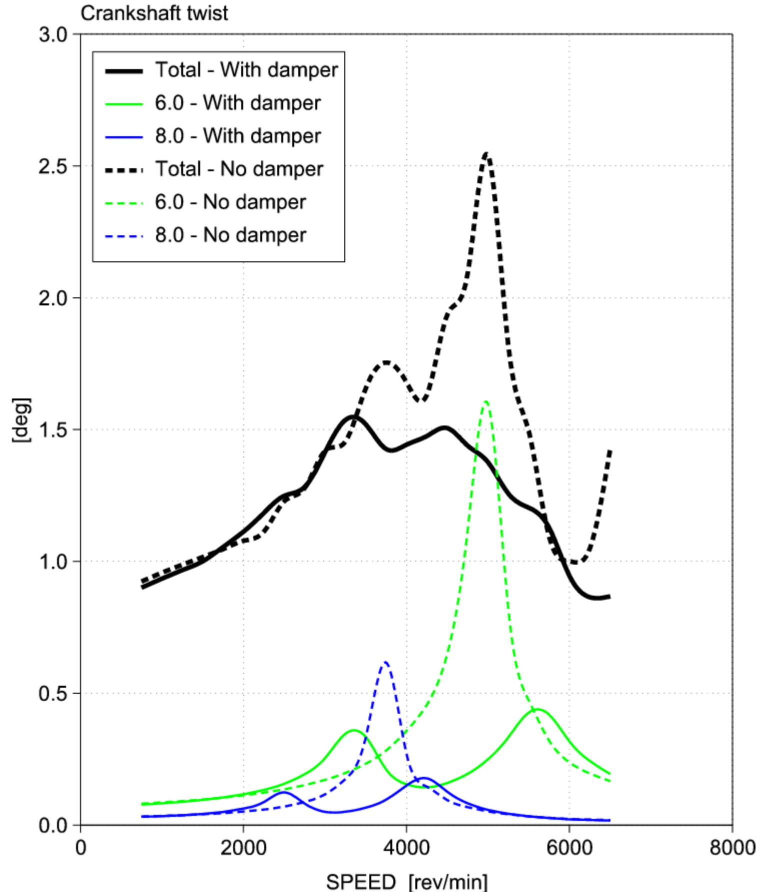


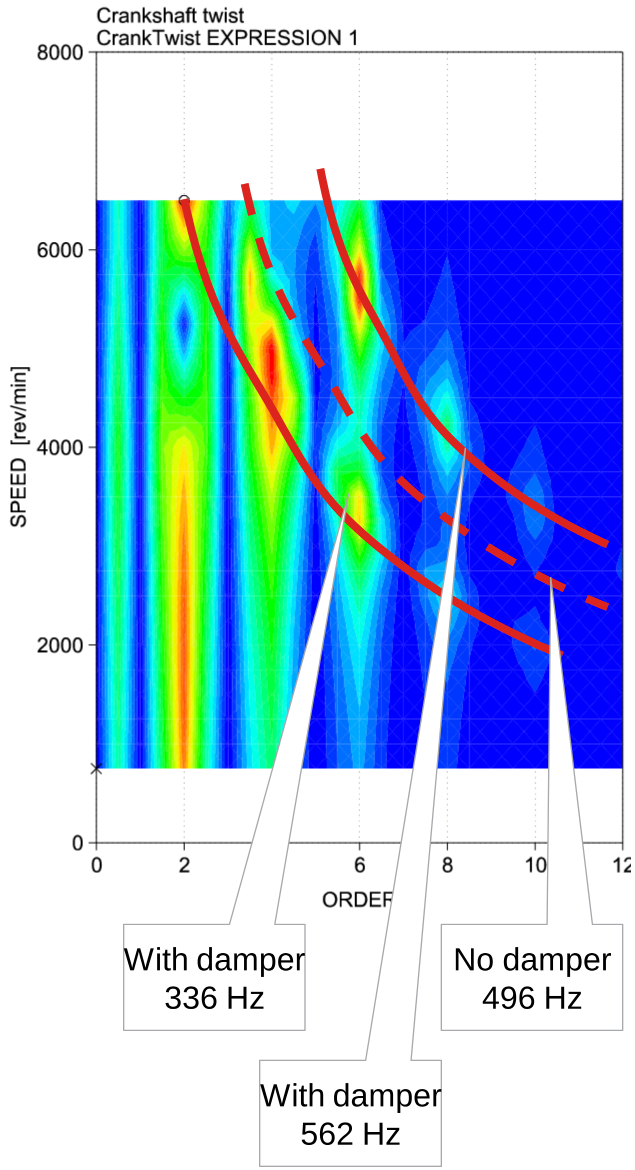
Contents

- Introduction
- Crankshaft torsional (1-D) modelling
- Crankshaft torsional analysis
- Crankshaft data
- Build model
- Define output plots
- Define analysis settings and run analysis
- Results
- Add a tuned rubber damper
- **Re-run the analysis**
- Create outputs for ENGDYN to import

Re-run the analysis

- Save the model under a new name
- Run the analysis
- View the SUMPLOTS in RPLOT
- In RPLOT, add a drive file (menu ‘Add’ > ‘Driver file…’ and add the .rpd file from the original analysis (without the damper)
- Some warnings will occur because it is not possible to overlay contour plots – just ‘OK’ the messages
- The new results show a significant reduction in crankshaft twist amplitude for the 4th and 6th order responses
- 496 Hz mode is replaced with two new modes
  – 336 Hz & 562 Hz





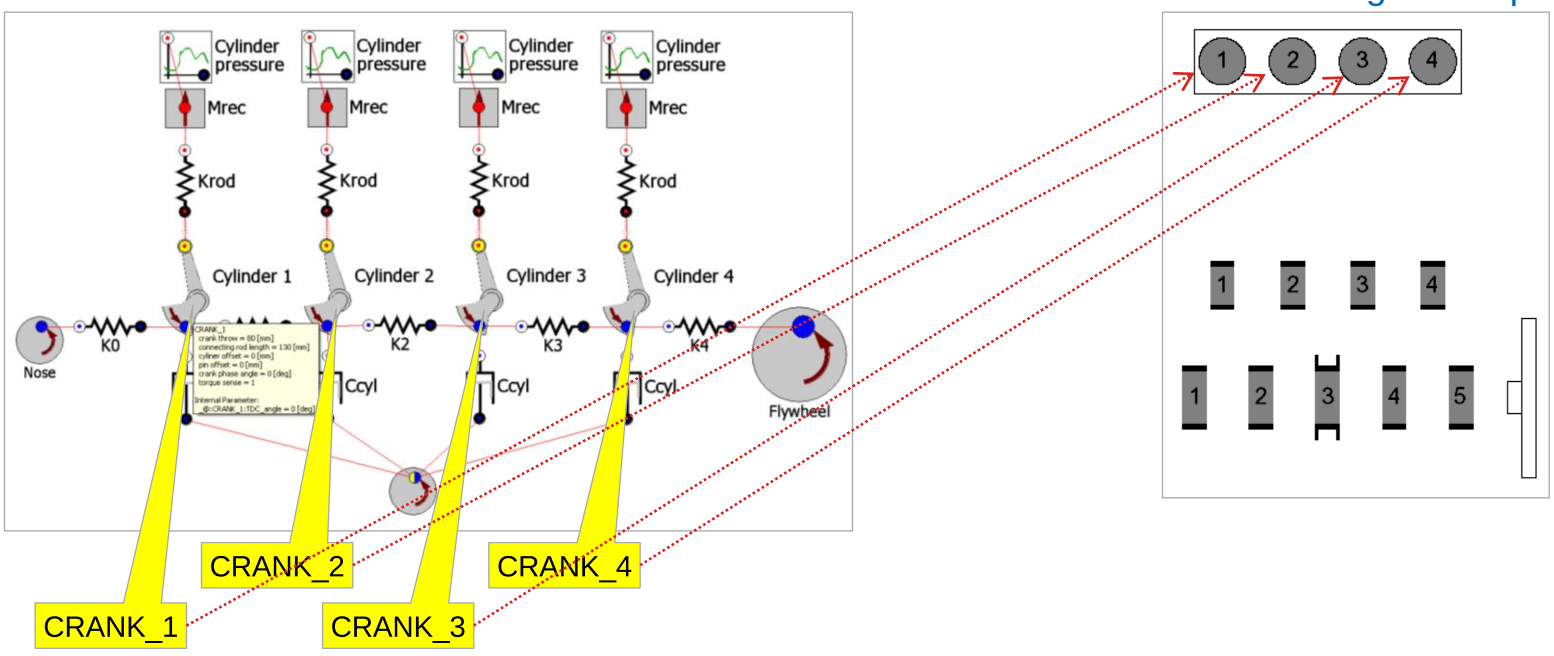
Contents

Create outputs for ENGDYN to import

- It is possible to export the calculated torques from the VALDYN torsional analysis for ENGDYN to import. ENGDYN can then use the results to perform a stress calculation – which can be a classical or FE calculation
  - The process is to write new results arrays to the VALDYN SDF file (this is a binary file which stores all the results from the simulation), then ENGDYN directly reads the data inside SDF file
- There are two stages to setting up the VALDYN mode to write the results arrays needed by ENGDYN
  - Stage 1: Ensure each CRANK element's numbering is consistent with it's respective cylinder in ENGDYN
    - Tip: Move the mouse pointer over the CRANK element to show tool tips – this will show the CRANK_* number

VALDYN model

ENGDYN configuration panel



Create outputs for ENGDYN to import

- Stage 2: Define additional SDF arrays for each SSTIFF element that represents part of the crankshaft
  - Open the properties panel for the SSTIFF ‘K0’
  - Press the ‘SDF OUTPUT’ button to open the ‘SDF_OUTPUT’ Properties panel
  - Set Type = ‘Crankshaft Stiffness’ (from the drop down menu)
  - Set Cylinder = 0
    - The SSTIFF element between the crankshaft nose and cylinder 1 should always be set to 0
  - Repeat the process above for the remaining SSTIFFs: K1 to K4
    - The ‘Cylinder’ number should be equal to the cylinder number that is attached to the left of it