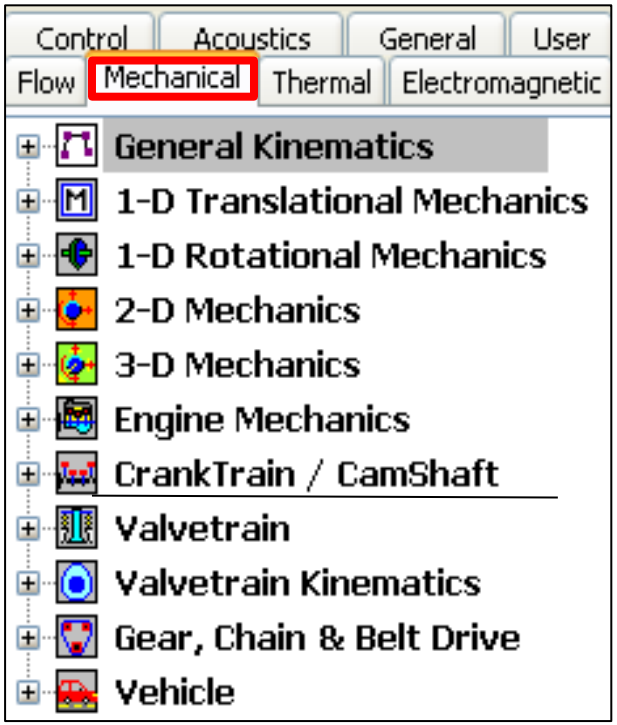
GT-SUITE
机械
多体动力应用



GT Gamma Technologies

机械仿真概述

- 通用多体动力学(MBD):GT-SUITE具有完整而强大的通用机械机构和1D(平动和转动），2D（平面运动），3D刚性和柔性模板库以及高效求解器
- 通用平面运动学: GT-SUITE 独特的平面运动学模板库

- 专用库:

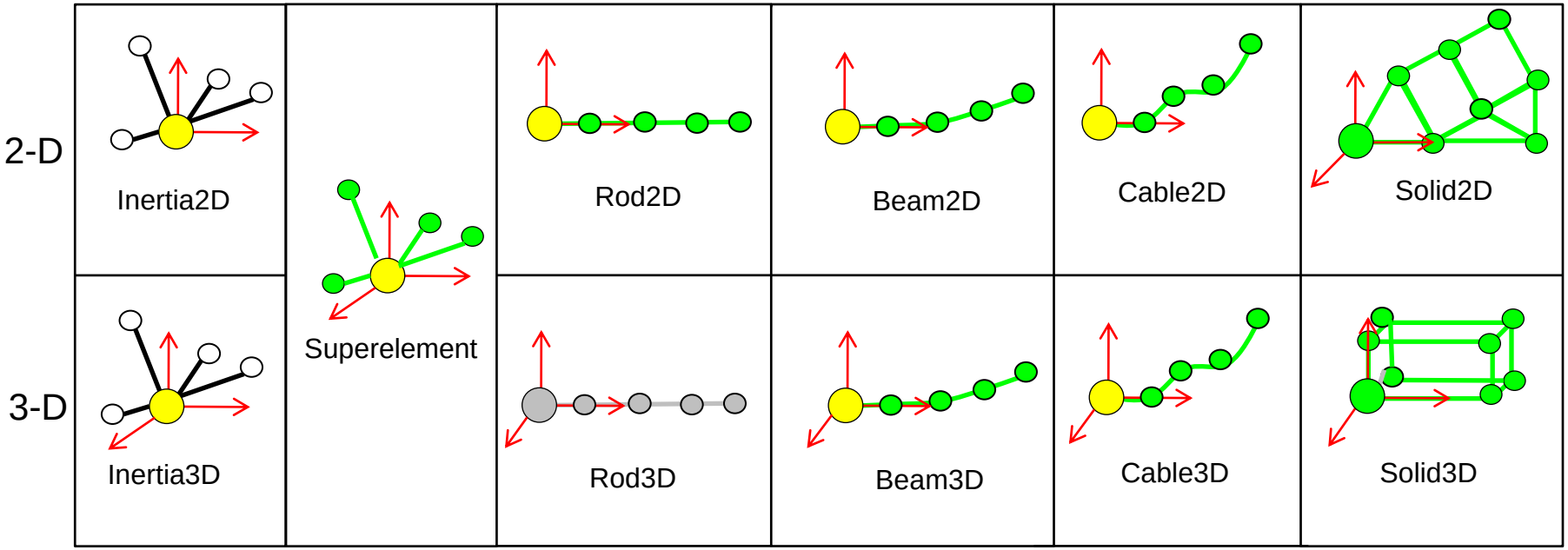
GT-SUITE 也提供了一些高级的专门模板库:

- 配气机构
- 曲轴机构
- 车辆&传动系统
- 齿轮、链和带传动
- 发动机
- 变速箱
- 电磁机械
- 液压机械

– 这些专用库使用更加方便，内置了许多“专家知识”，可以提供自动的专门输出

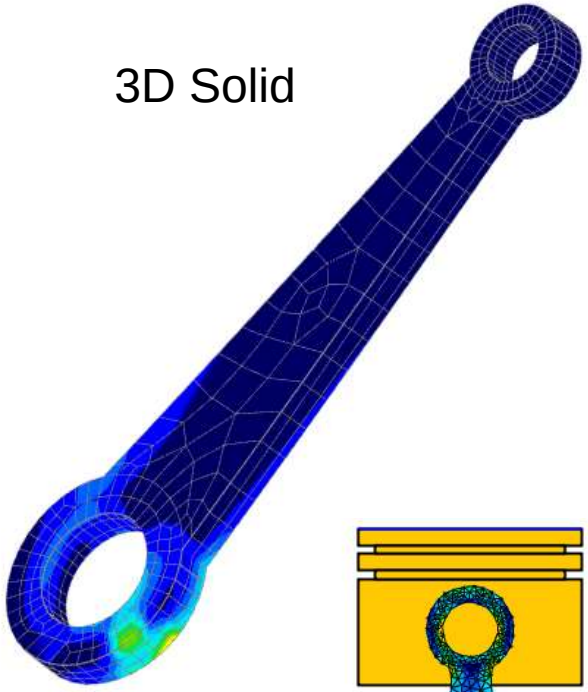
通用多体动力学库

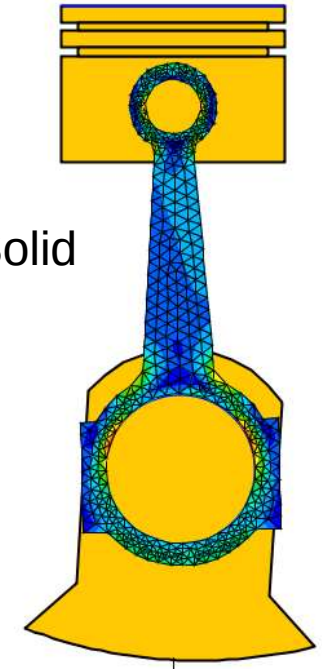
- 1D / 1DR / 2D / 3D 多体动力学(MBD)
- 柔性体 (2D/3D Rod, Beam, Solid, Superelement)
- 刚度/阻尼, 接触+摩擦, 接头
- 2D/3D 接触运动学和摩擦学分析

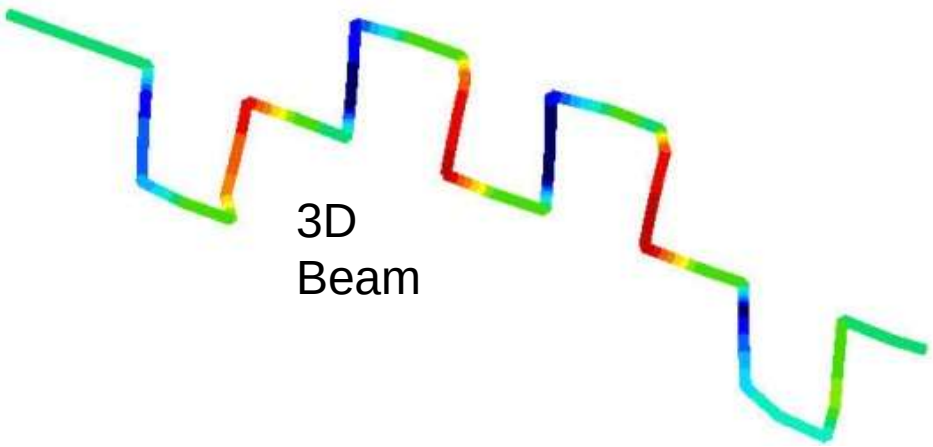


Flexible Bodies in GT-SUITE Mechanics

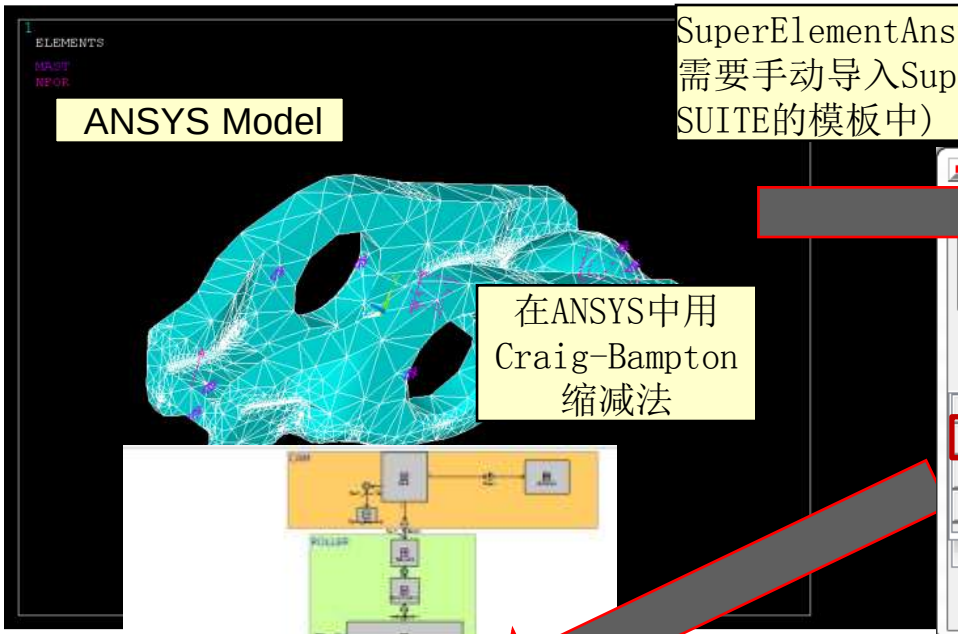
- 可与刚体应用于多体动力学分析
- 1D: 杆，扭杆，螺旋弹簧
- 2D: 杆，梁，实体
- 3D: 梁，实体，超级单元
- 线性单元或Quadratic elements
- (大变形，非线性)





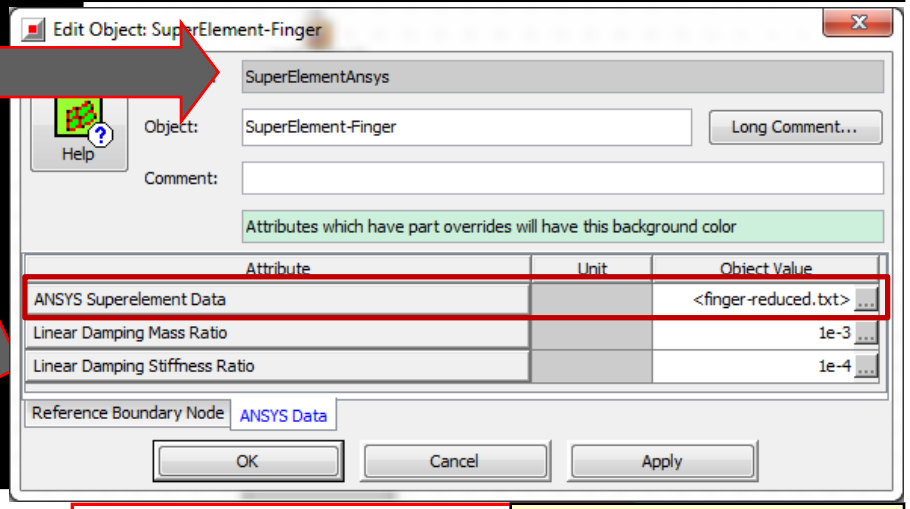


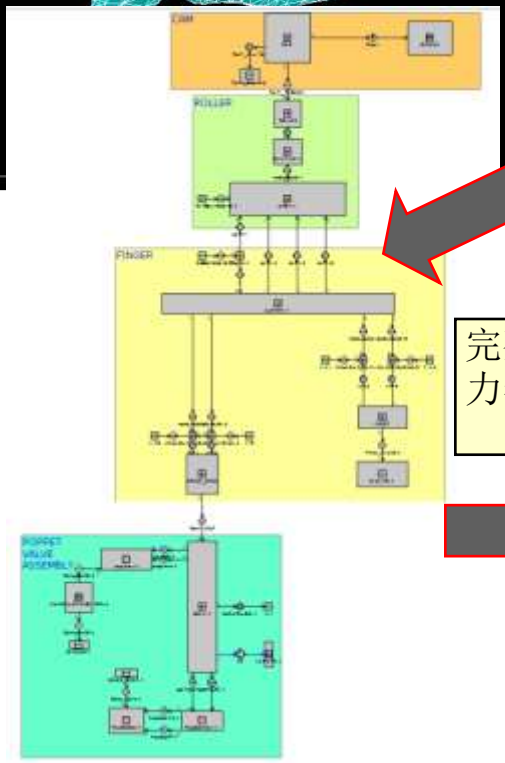
Importation of Reduced FE Models (SuperElement)



SuperElementAnsys 允许GT-SUITE直接导入 修正后的ANSYS FE 模型. 需要手动导入SuperElement (i.e. 从ANSYS中复制刚度矩阵粘贴到GT-SUITE的模板中)

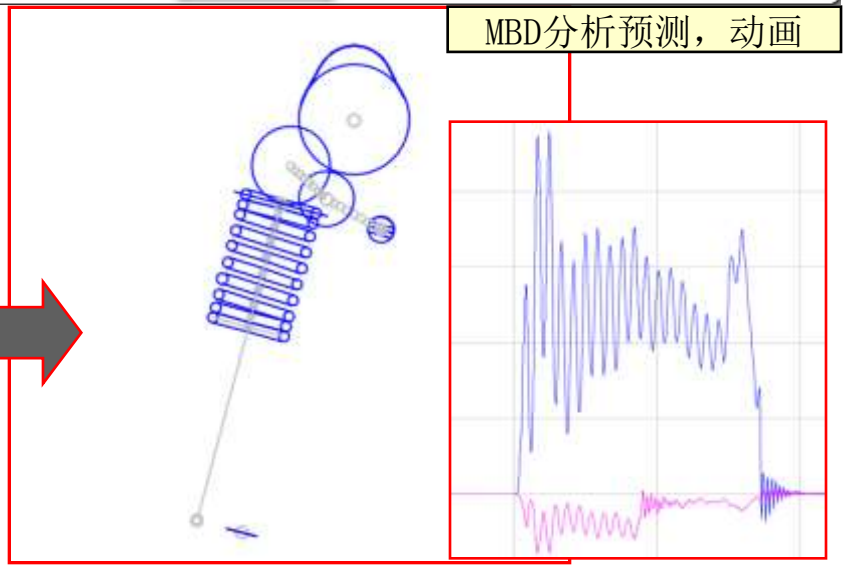
在ANSYS中用Craig-Bampton缩减法





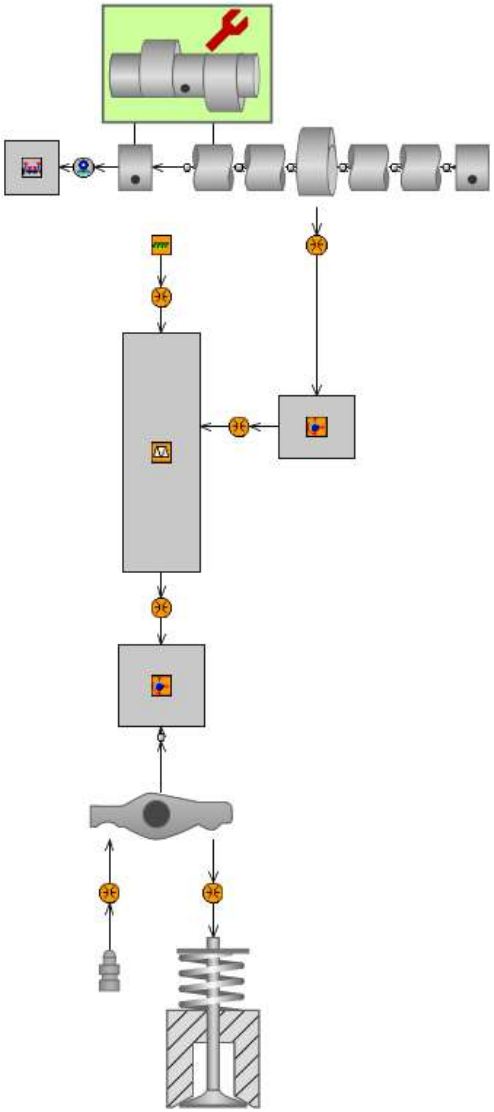
完整的配气机构多体动力学模型，其中指状随动轮为超单元

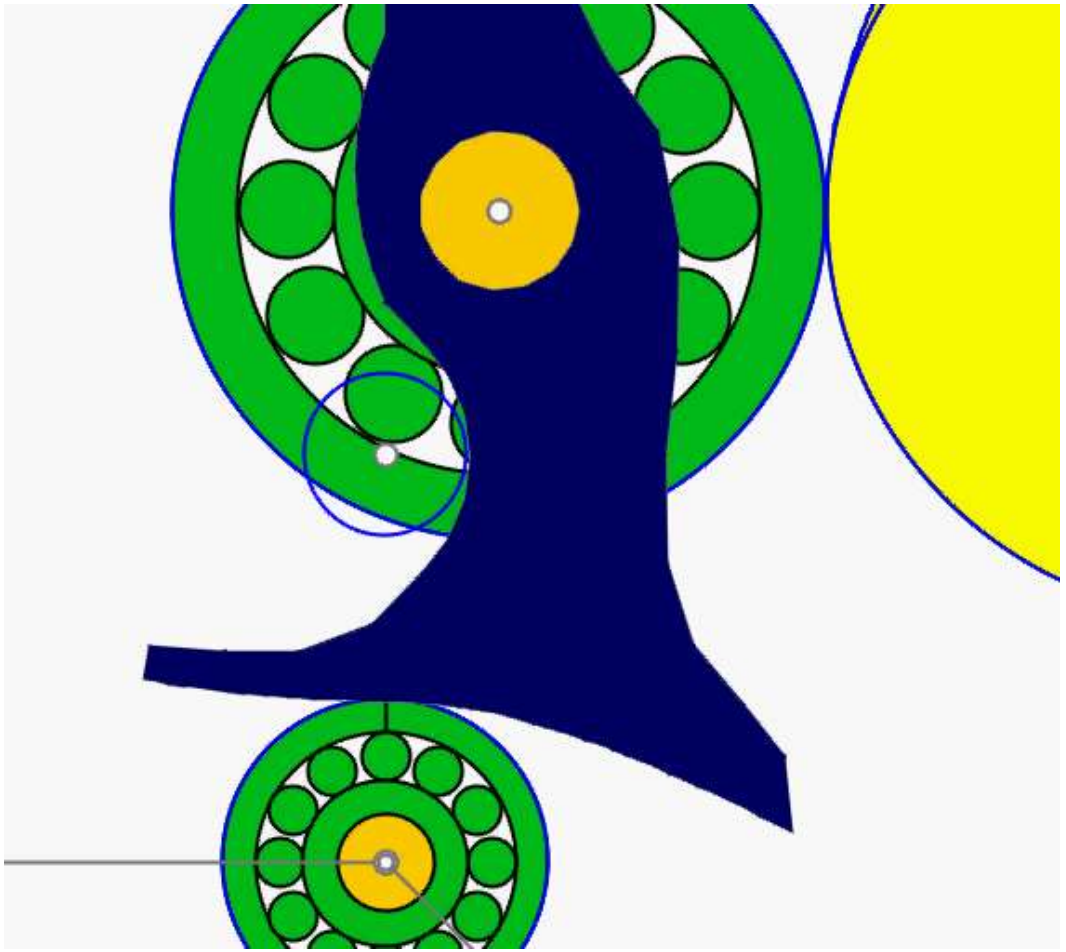
MBD分析预测，动画



Flexible Bodies Integrated in GT-SUITE MBD

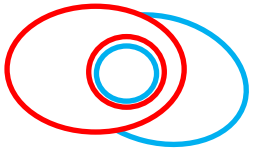
Example: VVA Valvetrain Swing Cam



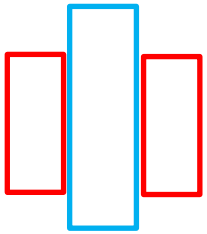


Common Joint Constraints in 2-D and 3-D

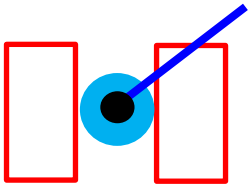
2-D



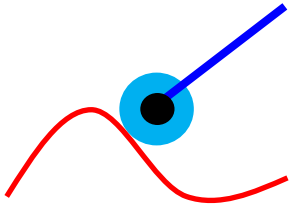
Revolute



Prismatic

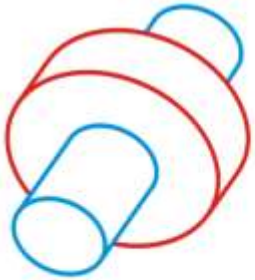


Sliding



Perfect Rolling

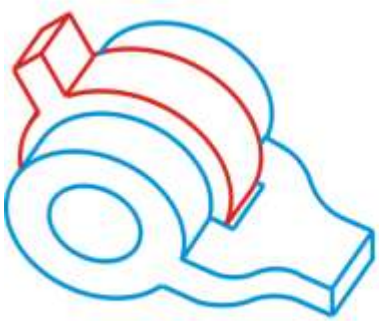
3-D



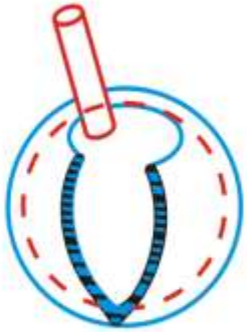
Cylindrical

Prismatic

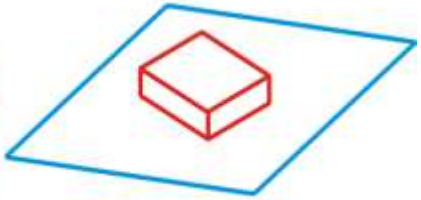
Screw



Revolute

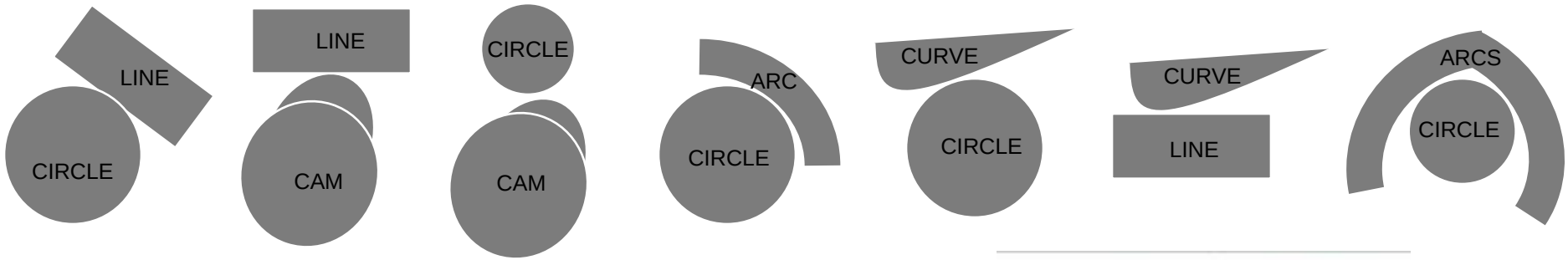


Spherical

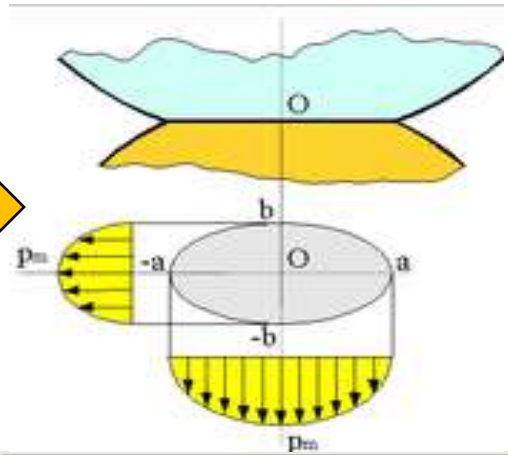


Planar

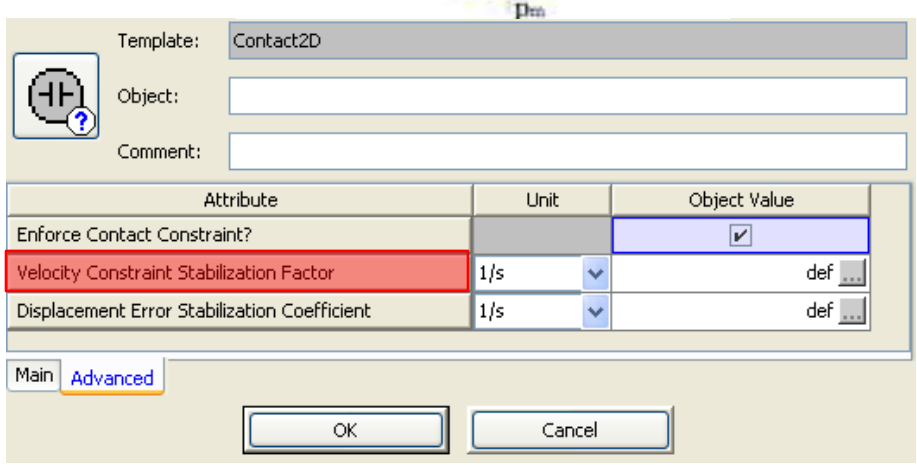
General Planar Contacts in 2-D MBD



- 在所有接触中进行Hertz接触和EHD分析:
  - Hertz 应力
  - 接触面尺寸
  - 油膜厚度
  - Scrubbing/Entrainment 速度
  - 水动力和表面粗糙摩擦

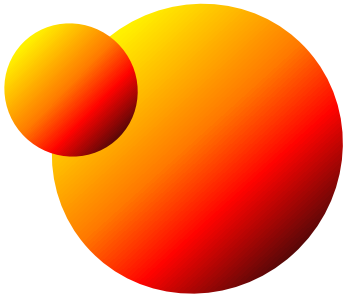


- 可选项：接触可以作为切向约束（无分离；在某些分析中有用）

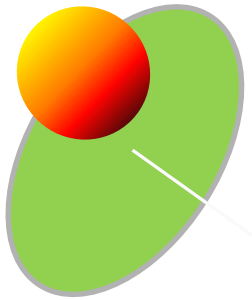


Contacts in 3-D

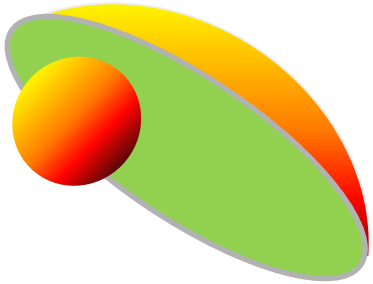
- 和二维接触相同模型，采用三维动力学
- 凸球面和平面或凹面之间的接触，以及球面、柱面、锥面、凸轮面在三维空间中任意朝向的接触



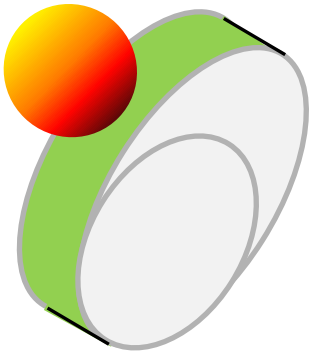
SPHERICAL (OUT)



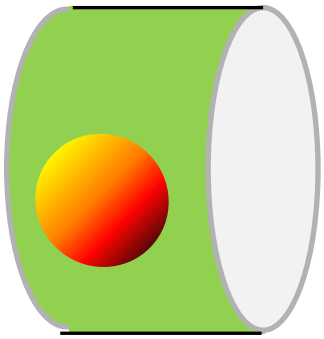
FLAT



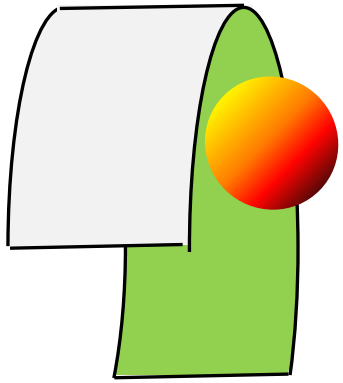
SPHERICAL (IN)



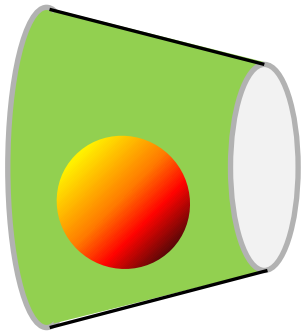
CAM LOBE



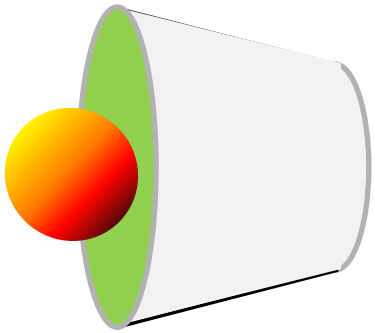
CYLINDRICAL (OUT)



CYLINDRICAL (IN)

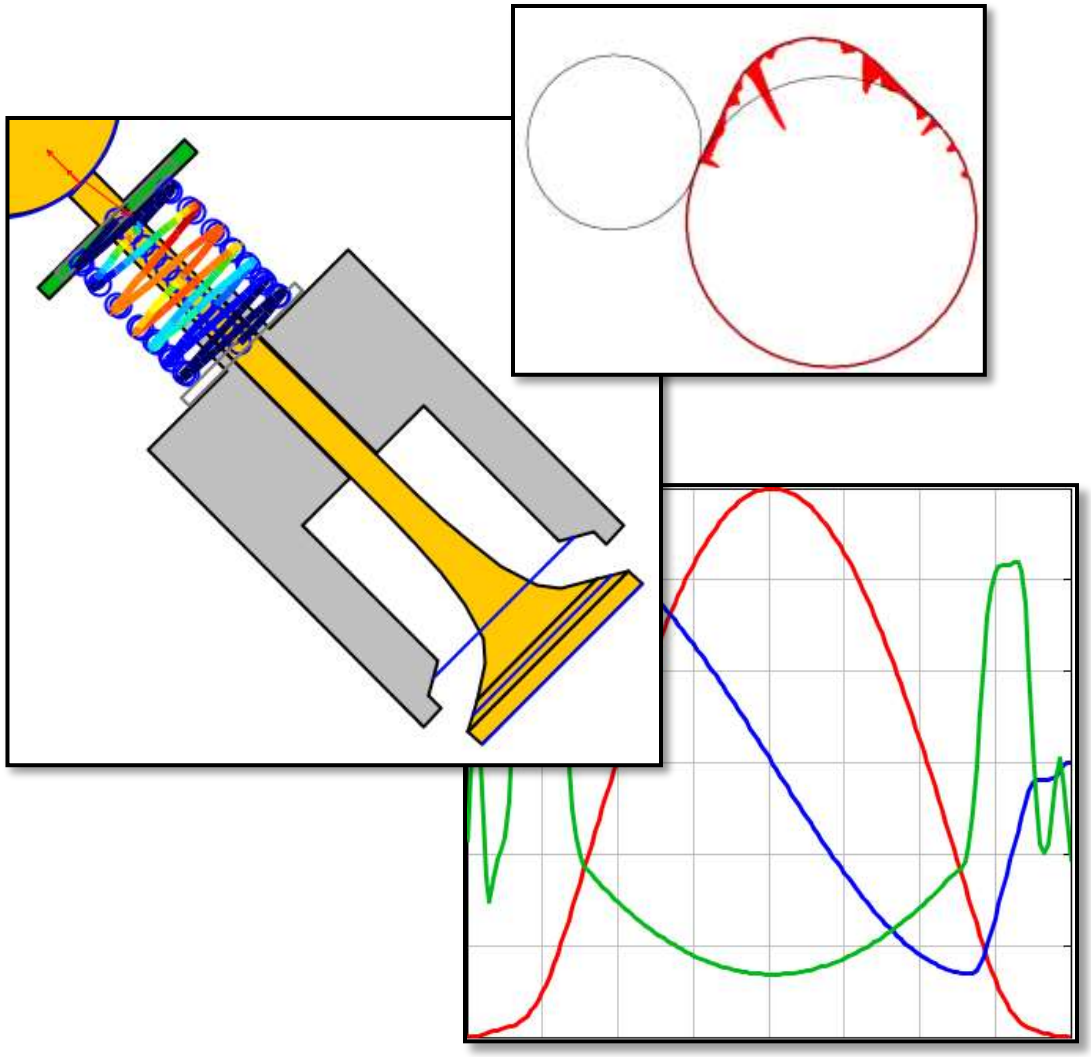


CONICAL (OUT)



CONICAL (IN)

Valvetrain



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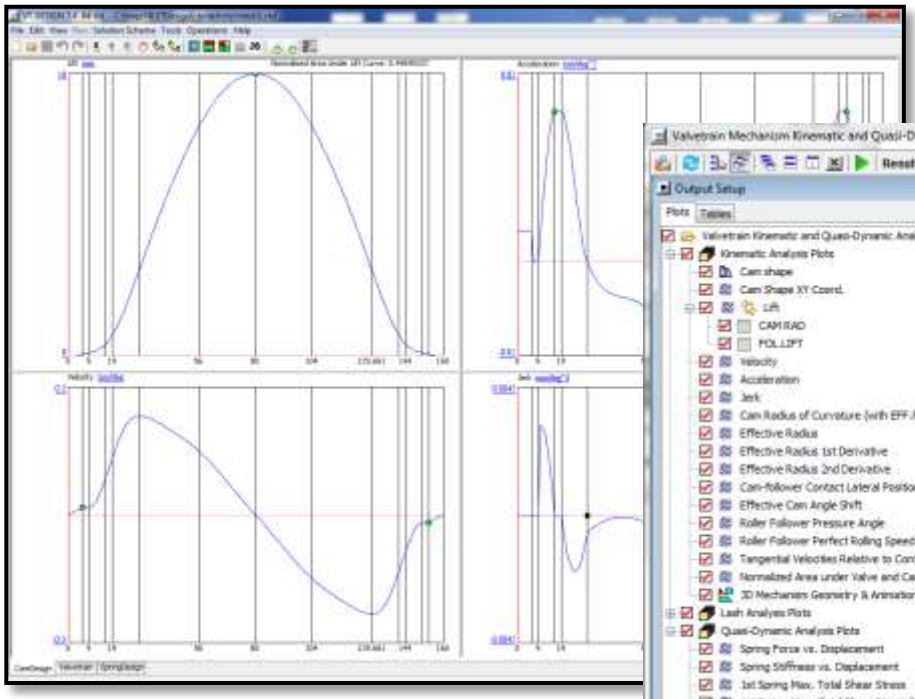
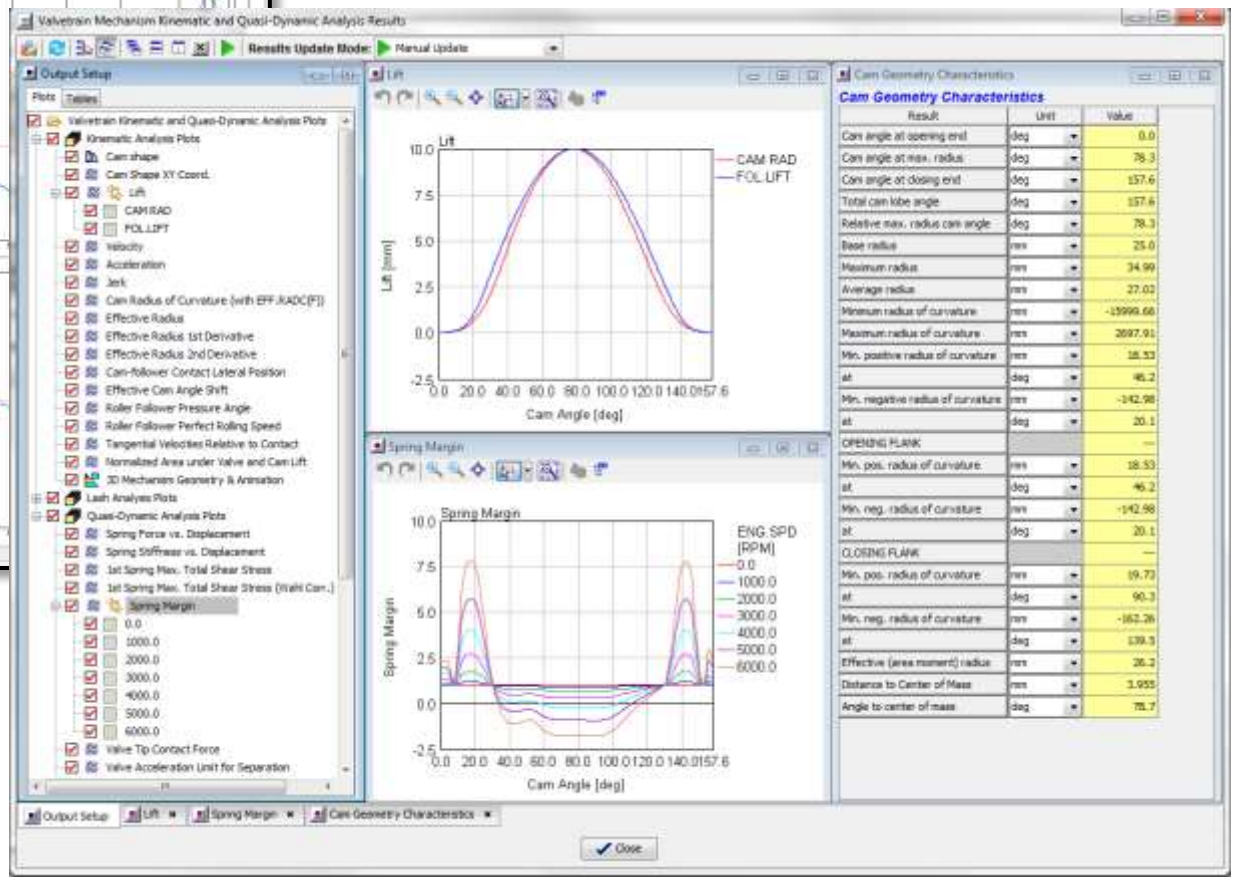
Integrated Valvetrain Analysis within One Tool

- VT-DESIGN:交互式凸轮设计界面，显示瞬时运动学/ QDA结果

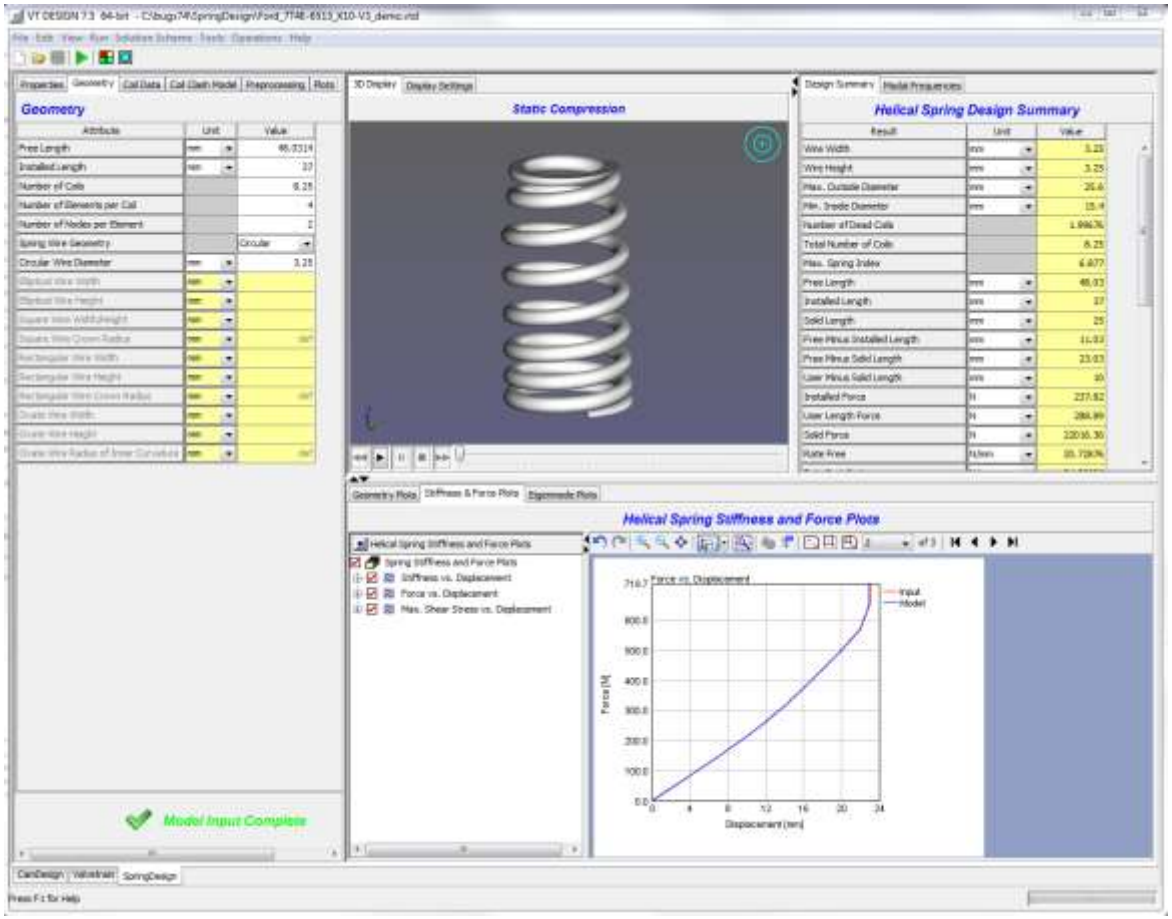


Interactive Kinematic & Quasi-Dynamic Results Output Window

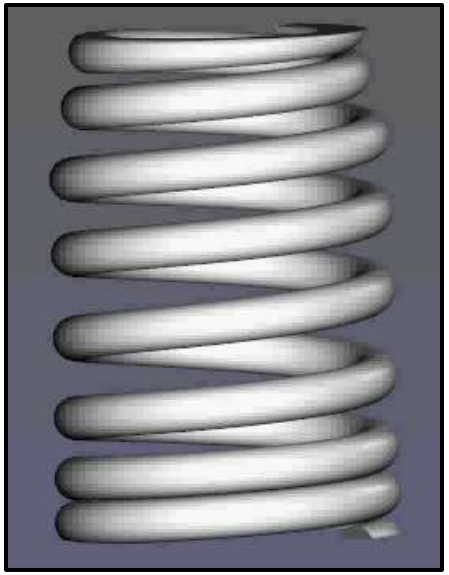


Integrated Valvetrain Analysis within One Tool

- VT-DESIGN: 交互式的弹簧设计界面，可进行螺旋弹簧的设计和分析
- 弹簧预测，自动导入并用于QDA分析

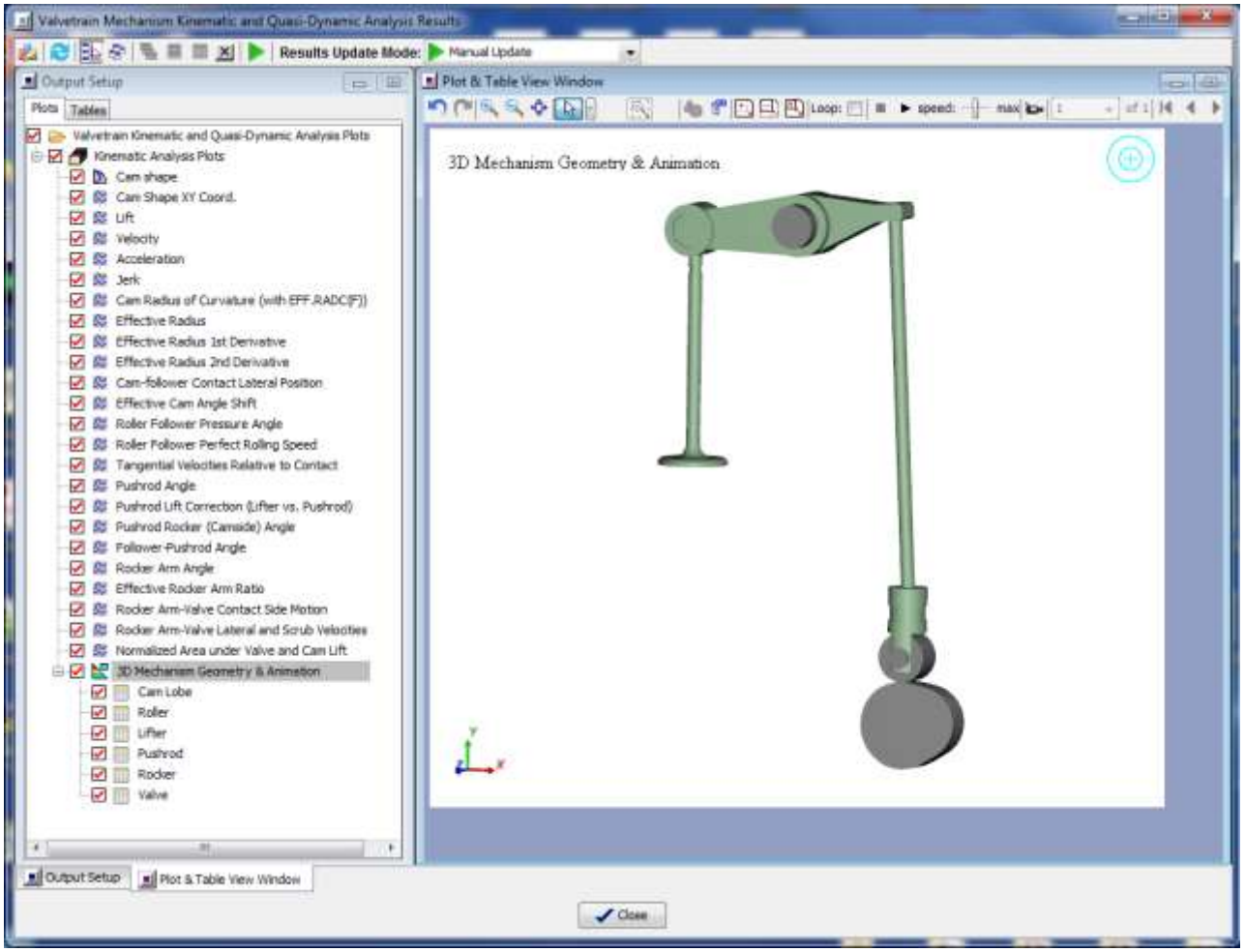


Animation of Helical Spring 1st Vibration Mode Shape



3-D Display and Animation of Models (v7.5)

- 在VT-DESIGN 和GT-POST能够进行动画显示

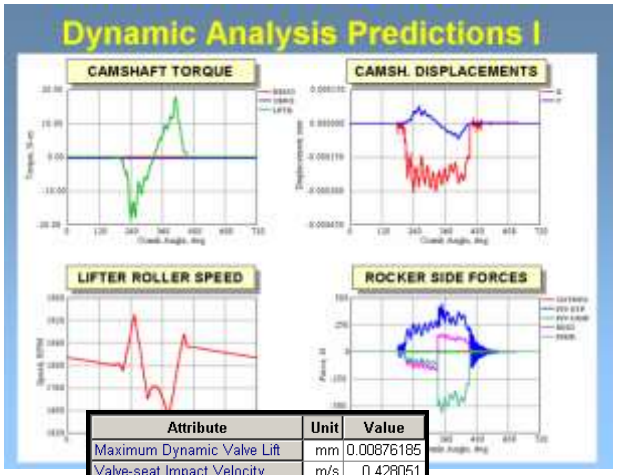


Animation of Kinematic Motions

Integrated Valvetrain Analysis within One Tool

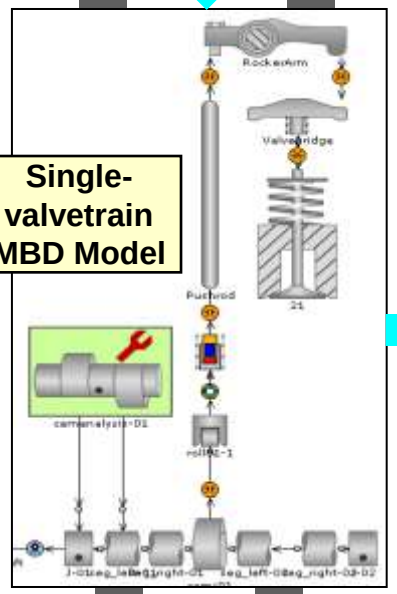
能够自动生成MBD 配气系统模型

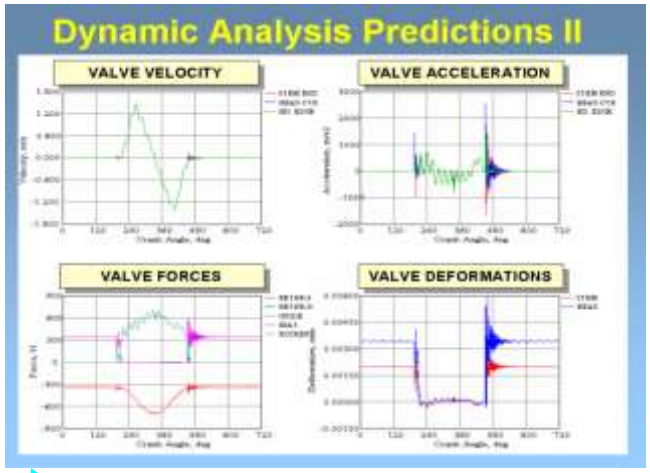
From Kinematic Analysis



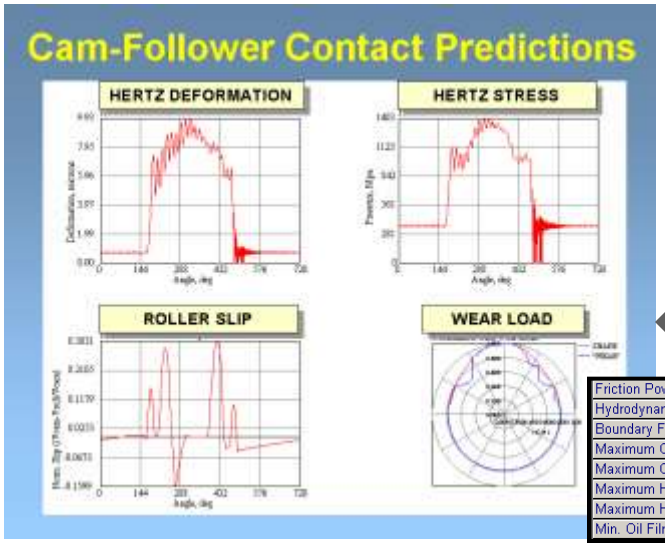
Attribute	Unit	Value
Maximum Dynamic Valve Lift	mm	0.00876185
Valve-seat Impact Velocity	m/s	0.428051
Valve-seat Force	N	1525.14
Valve-guide Friction Power Loss	W	1.76581

Single-valvetrain MBD Model

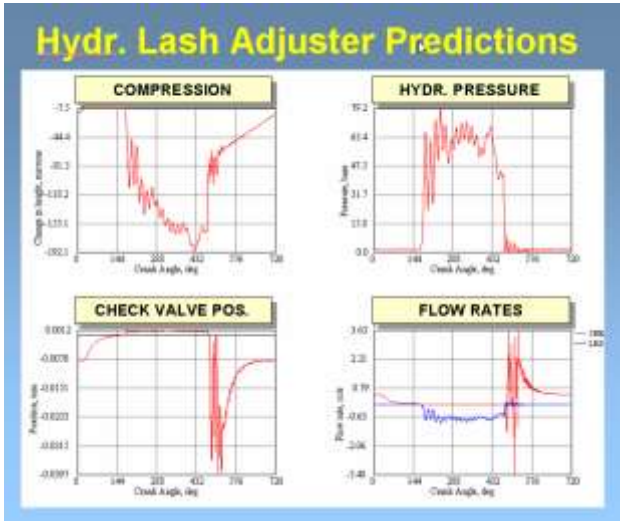




To multi-cylinder valvetrain dynamic analysis



Friction Power Loss	W	6.90014
Hydrodynamic Friction Power Loss	W	6.90008
Boundary Friction Power Loss	W	6.78339e-0
Maximum Cam Wear Load	kW/m^	1.48727
Maximum Cam Torque	N-m	21.4446
Maximum Hertz Deformation	micron	6.41281
Maximum Hertz Stress	MPa	1472.58
Min. Oil Film Thickness	micron	0.0477062



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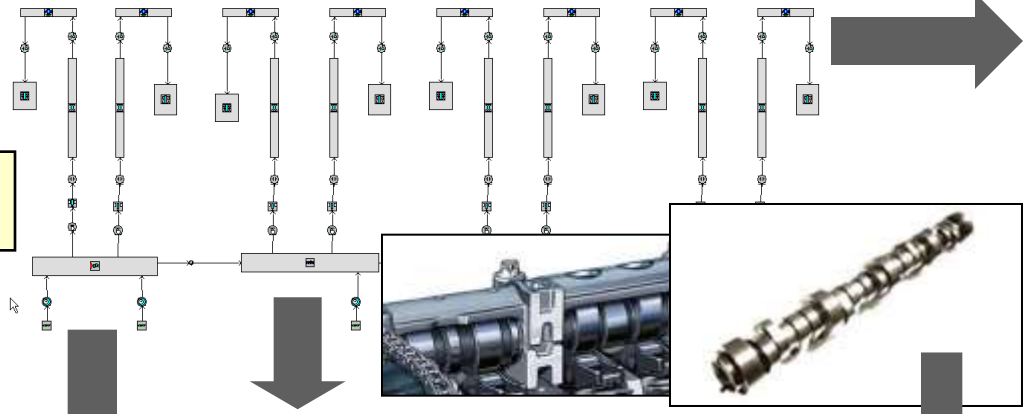
Integrated Valvetrain Analysis within One Tool

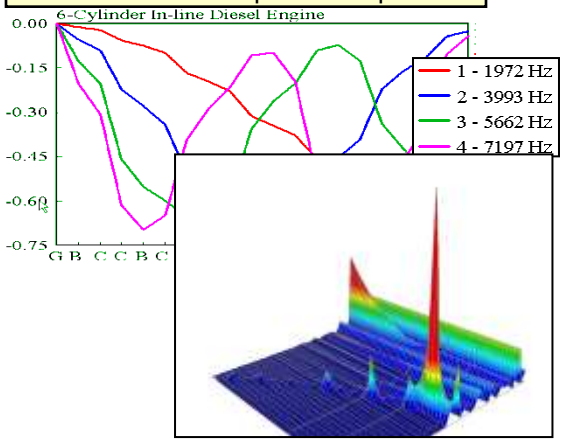
完整的配气系统建模, 凸轮轴扭振分析

Multi-valvetrain Model w/camshaft and bearings coupled to crank kinematically or through dynamic model of belt ,chain drive or geartrain

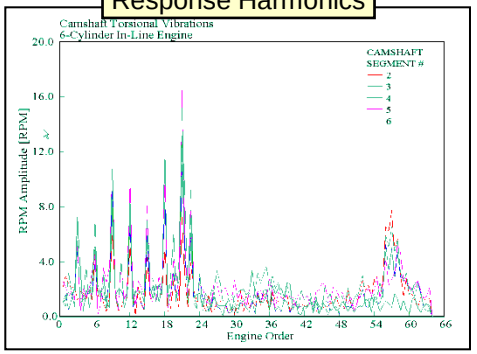
From Single Valvetrain MBD Analysis



Torsional Mode Shapes & Frequencies



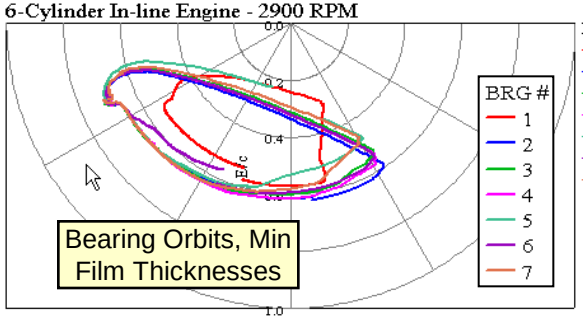
Torsional Vibration Response Harmonics



Max Bearing Loads, Bearing Friction

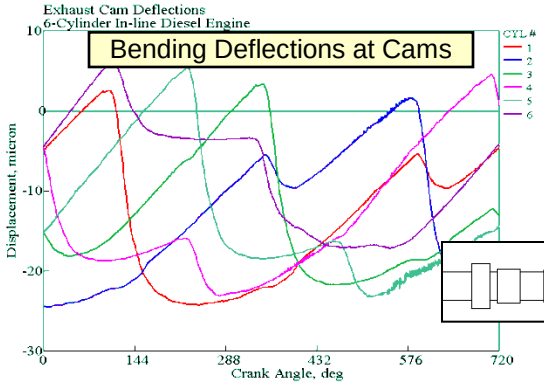
Bearing Friction Power Loss	W	48.03	109.	112.	103.	110.	101.	90.7
Bearing Hydr+Bdy Friction	W	46.99	106.	110.	100.	108.	99.4	88.2
Bearing Oil Squeeze Friction	W	1.035	2.41	2.34	2.44	1.86	2.42	2.54
Bearing Min. Film Thickness	micron	16.98	11.5	11.5	11.7	11.5	11.7	11.6
Bearing Maximum Load	N	2988.	382					

Bearing Orbits
6-Cylinder In-line Engine - 2900 RPM

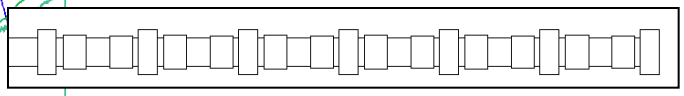


Bearing Orbits, Min Film Thicknesses

Bending Deflections at Cams



Camshaft Geometry Visualization



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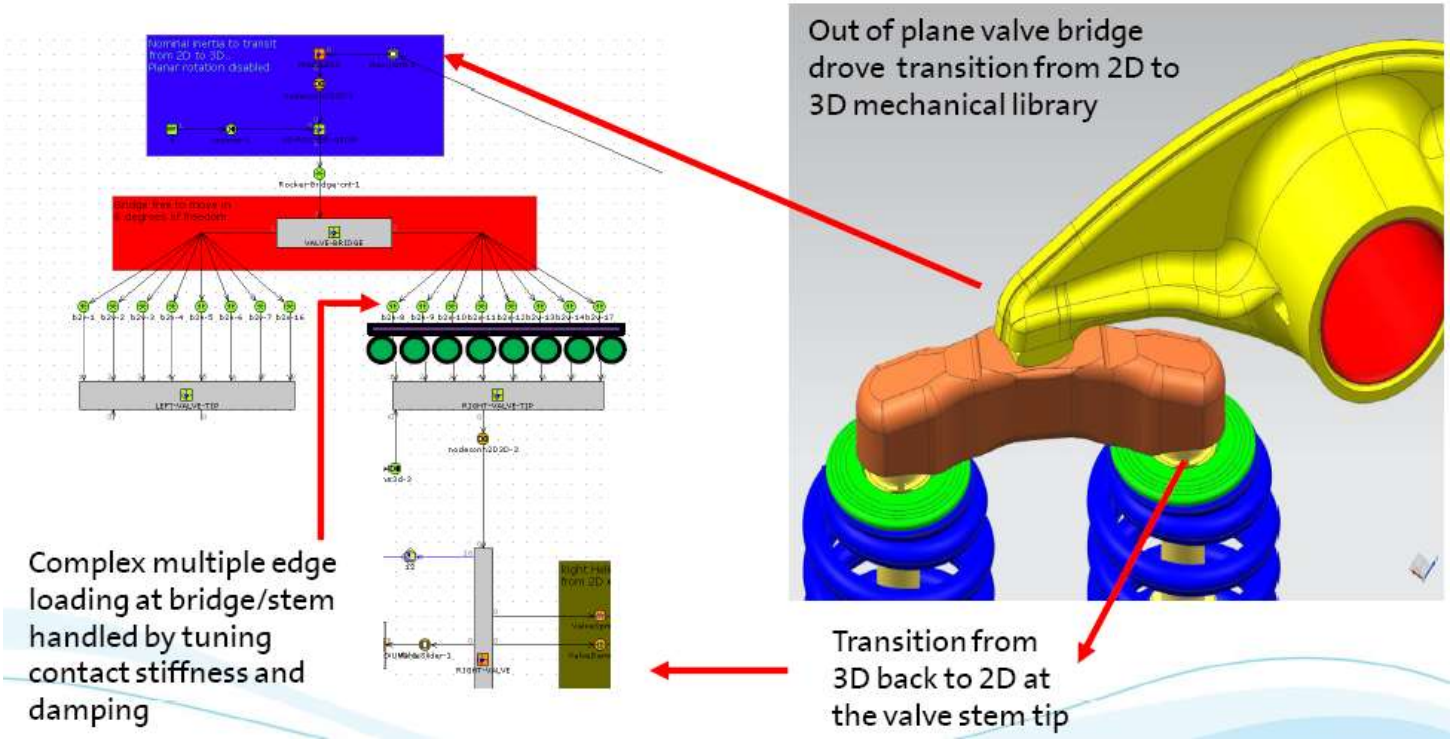
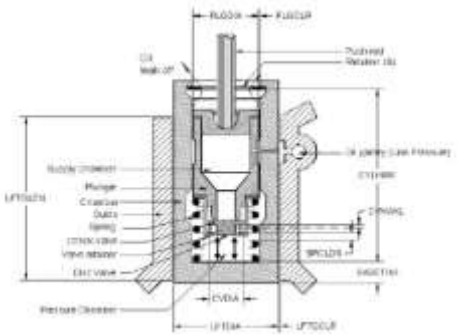
Transition Connection Example (3D-2D)
Out-of-Plane Valve Bridge

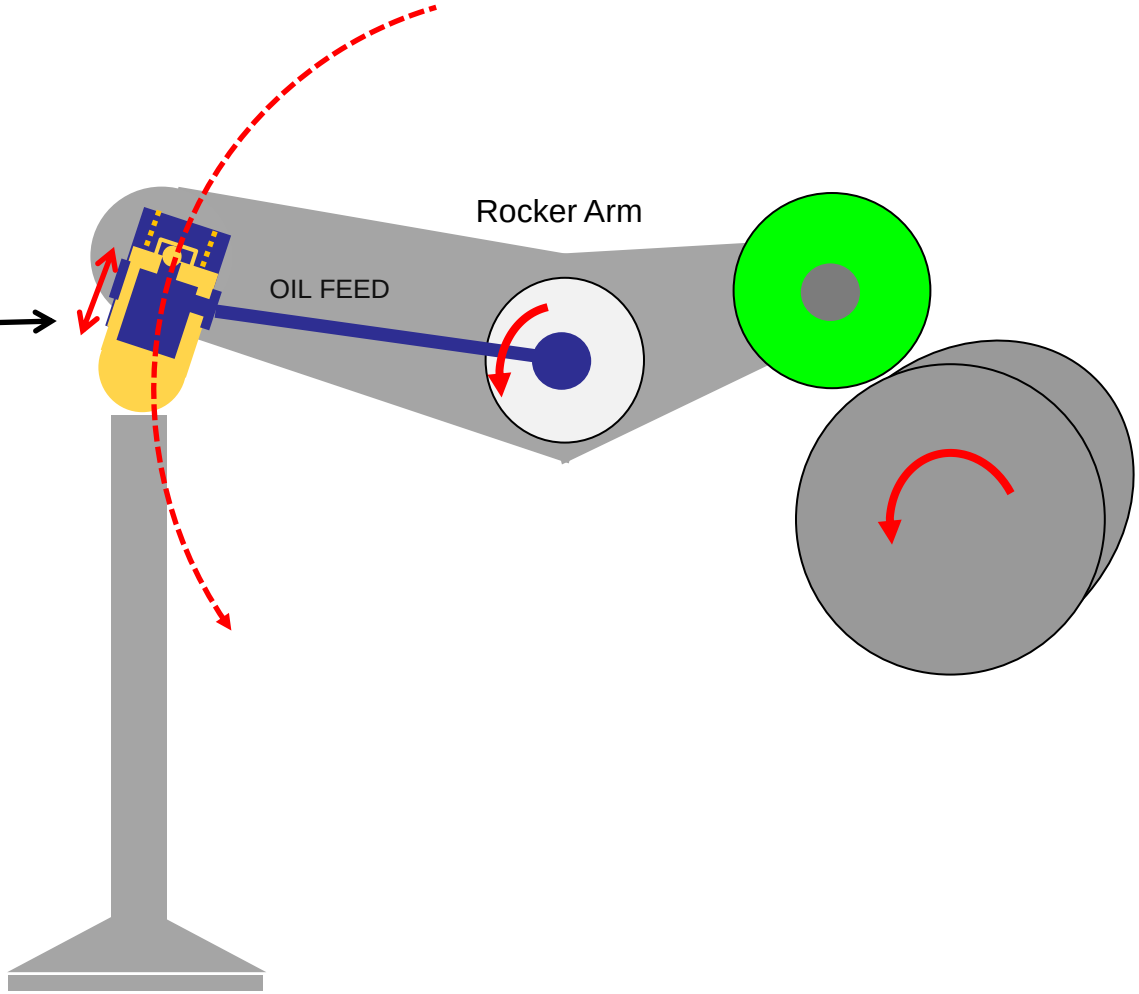


- 对于离面角度> 15 – 20°的情况可能需要三维的阀桥模型
- 和三维模型间的过渡只在需要的地方进行，尽量减少对CPU计算时间 的影响

Hydromechanics in 2-D Topology
Example: Embedded HLAs in Valvetrains

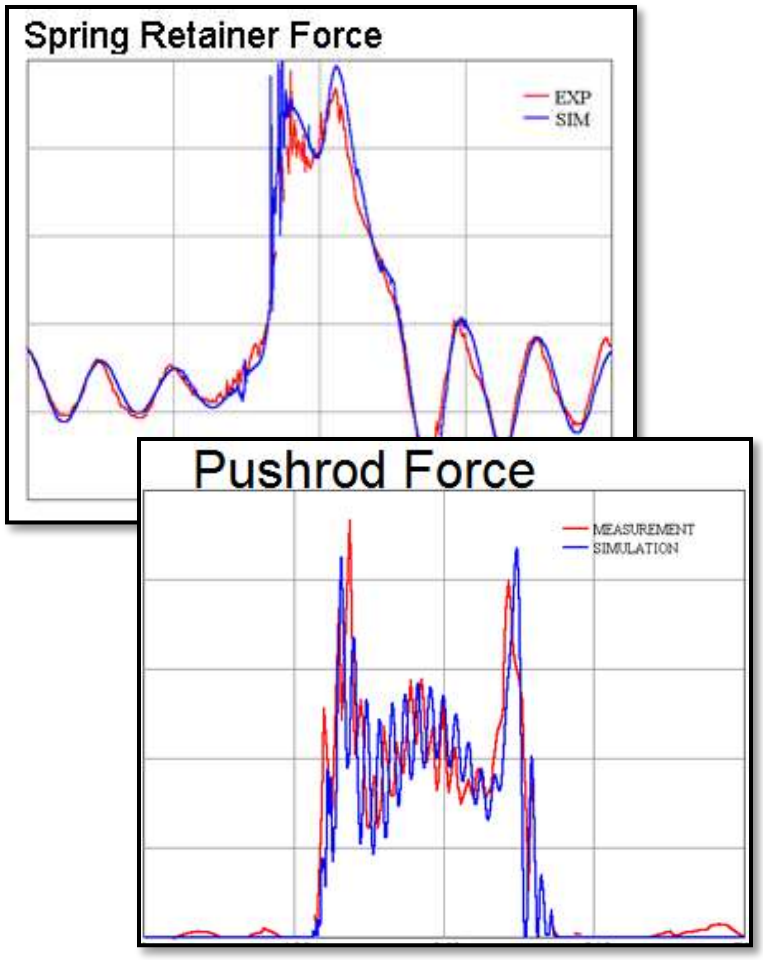
HLA柱塞在一个柱状铰接位置相对于摇臂架进行滑移

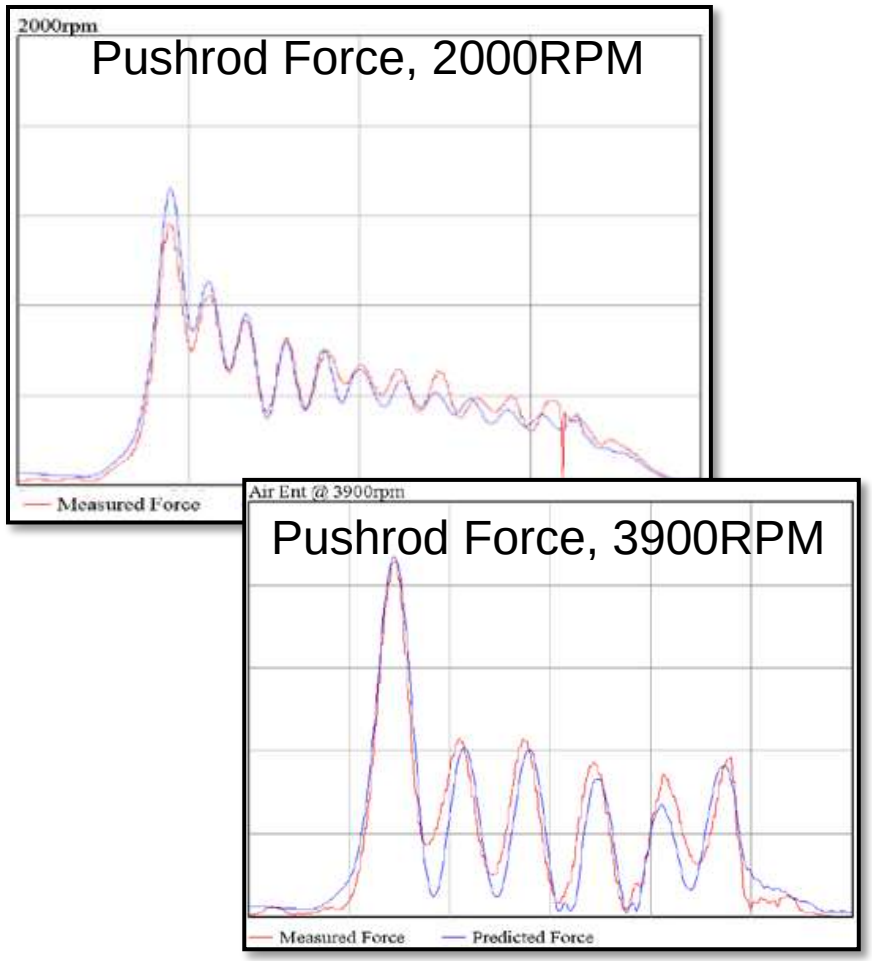




Valvetrain Validation Results

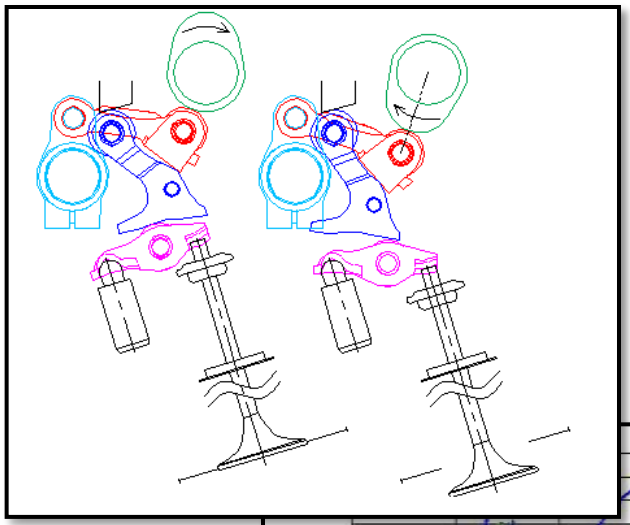
- 两个独立的推杆系统
- Left: 机械间隙螺杆, Right: 液力间隙调节器

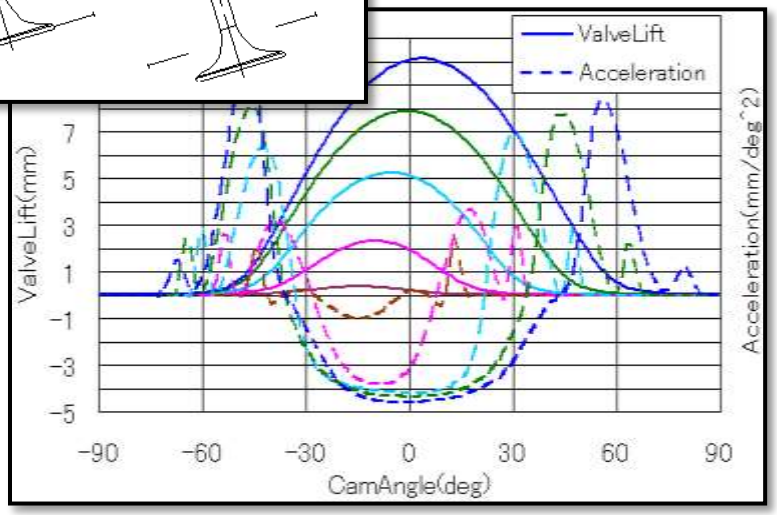


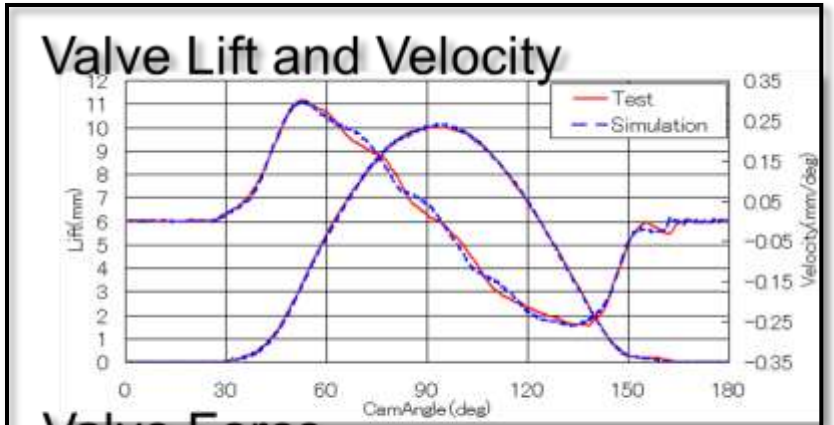


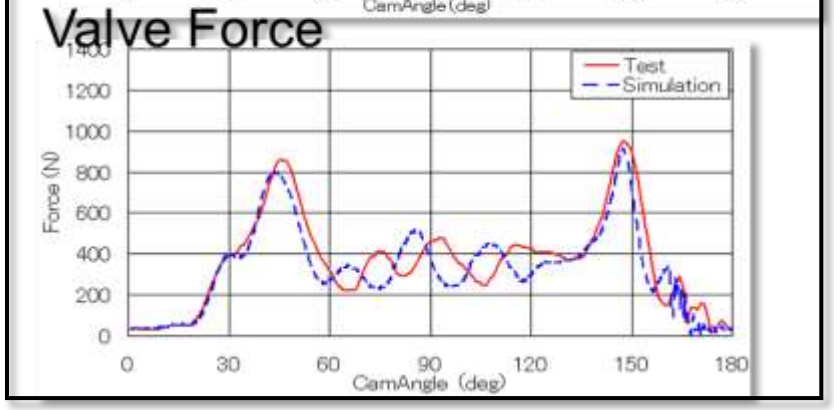
Valvetrain Validation Results

- GT-SUITE基础模板建立VVA系统
- 生成不同的凸轮位置下对应的升程曲线

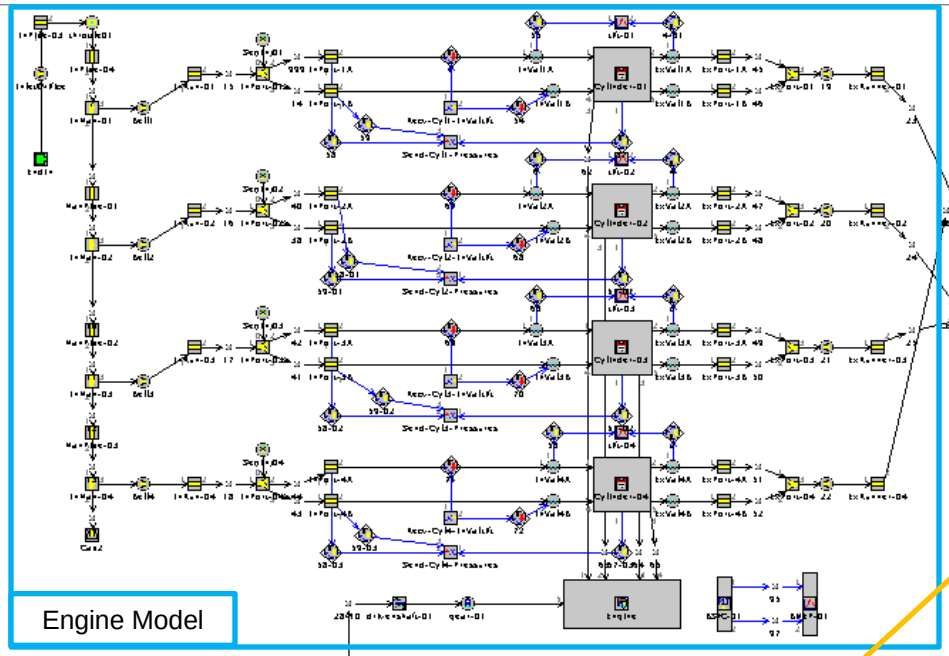


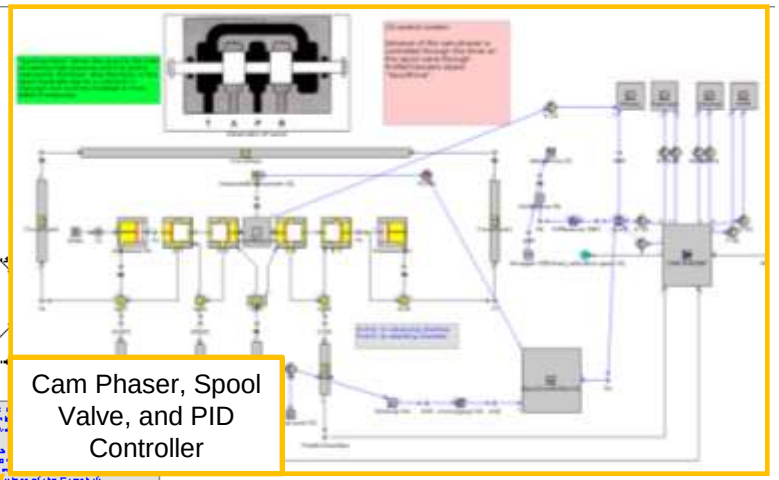


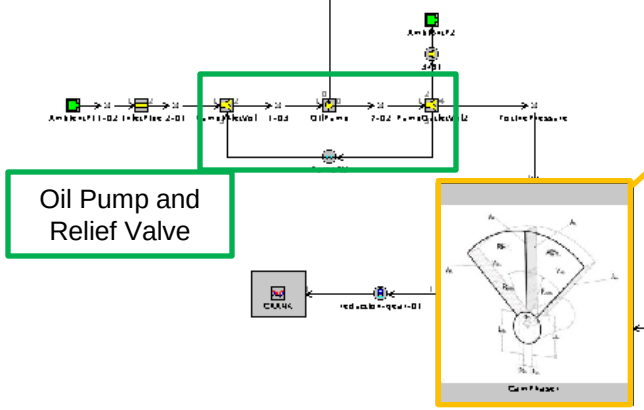


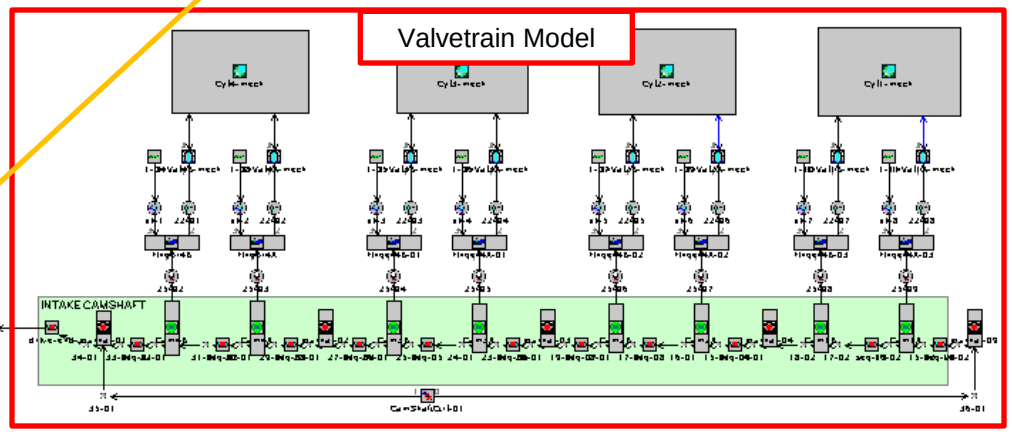


Integrated (Engine+Cam-Phaser+Valvetrain) Model for Optimizing Lube Oil Pump Size

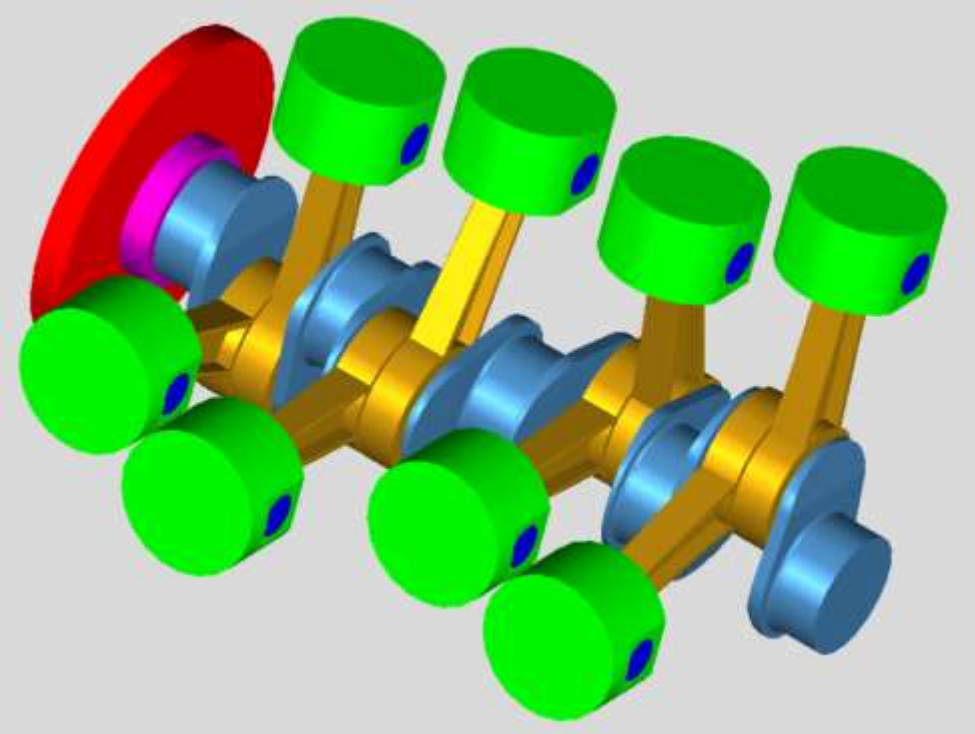






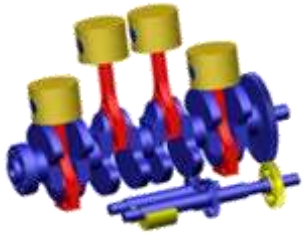


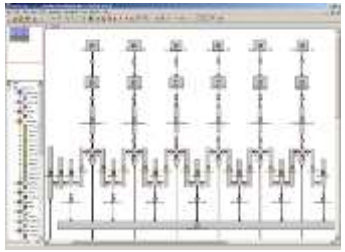
Cranktrain

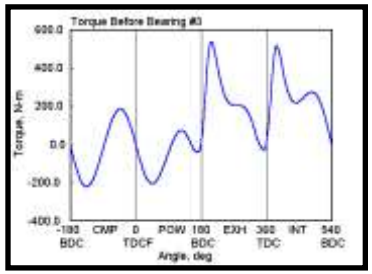


Crankshaft Dynamic Analysis

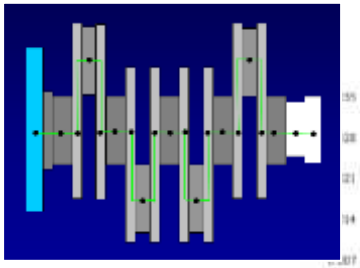
- 刚体，平衡分析

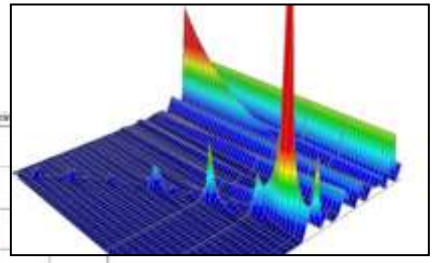


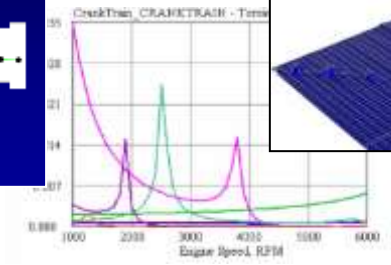




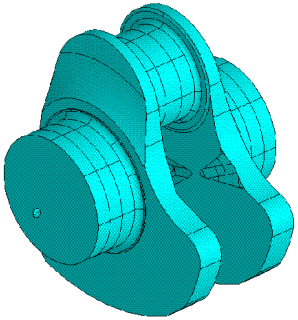
- 扭振分析(时域或频域)

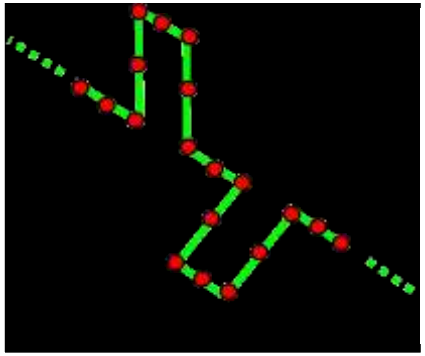


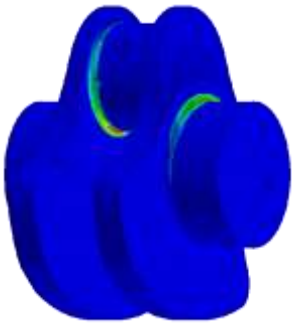




- 弯曲分析(梁三维有限元模型)

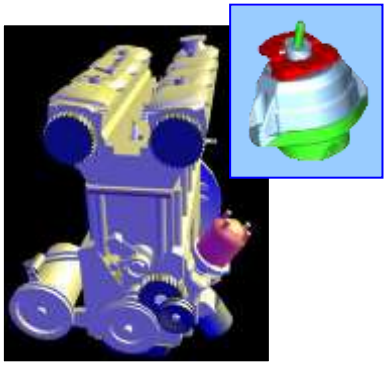


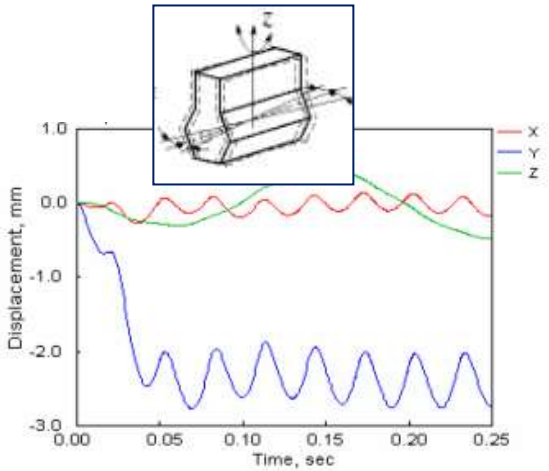




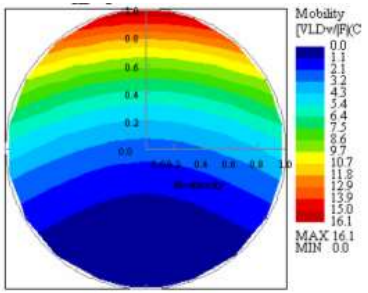
Other Cranktrain Design Analysis Calculations

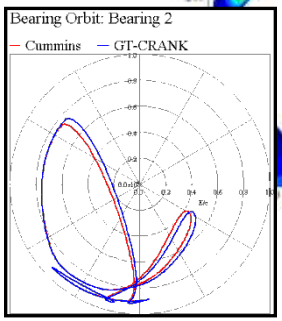
- 缸体 + 机架动力学

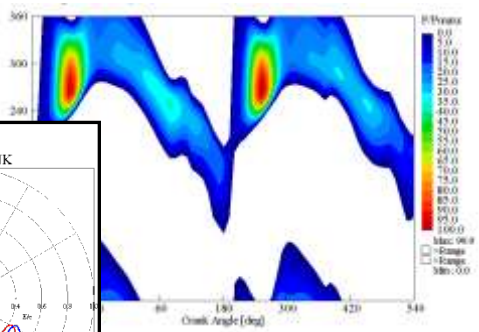




- 主轴 & 连杆轴承

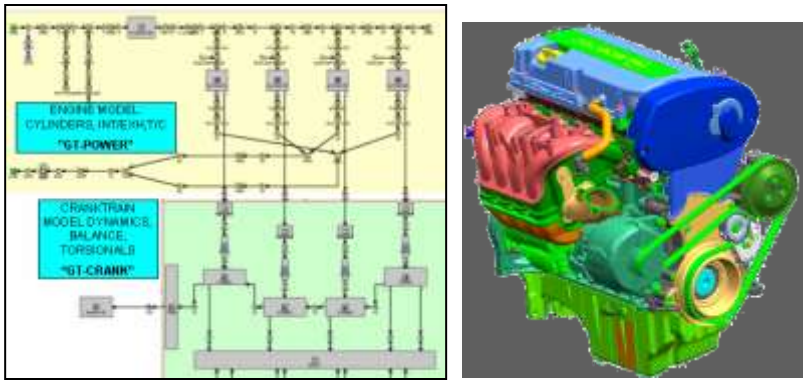




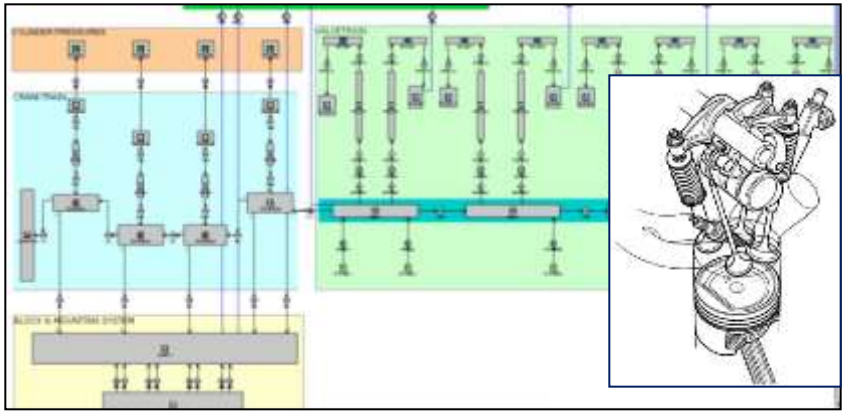


Integration w/ Engine/vehicle Subsystem Models

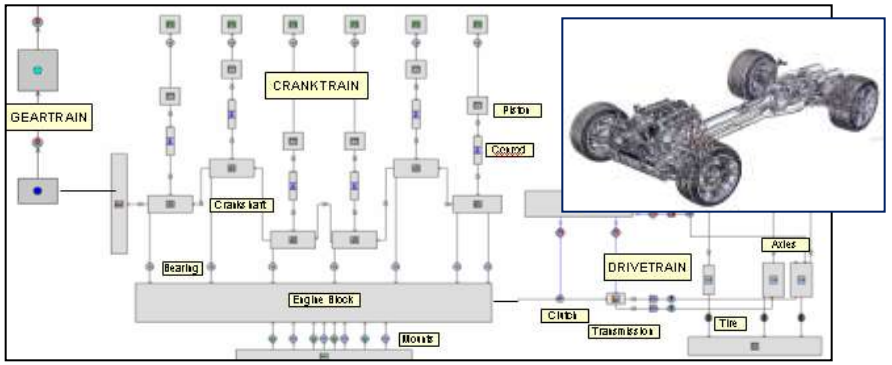
- 发动机，燃烧(GT-POWER)



- 配气机构/凸轮轴

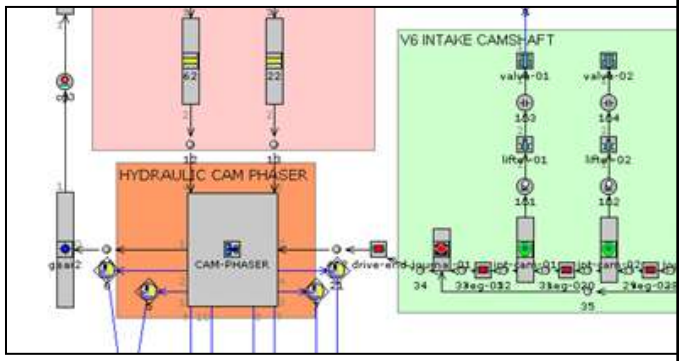


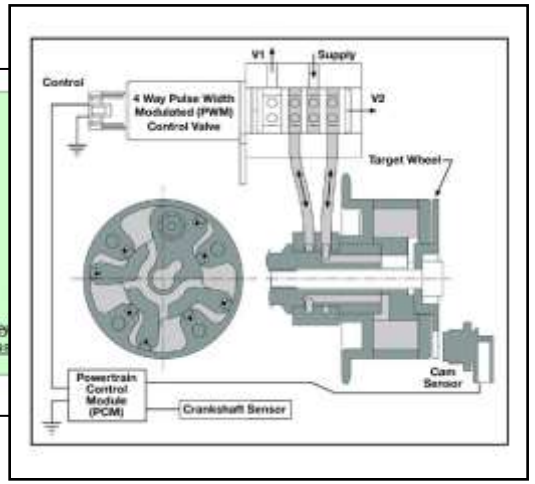
- 车辆传动系统



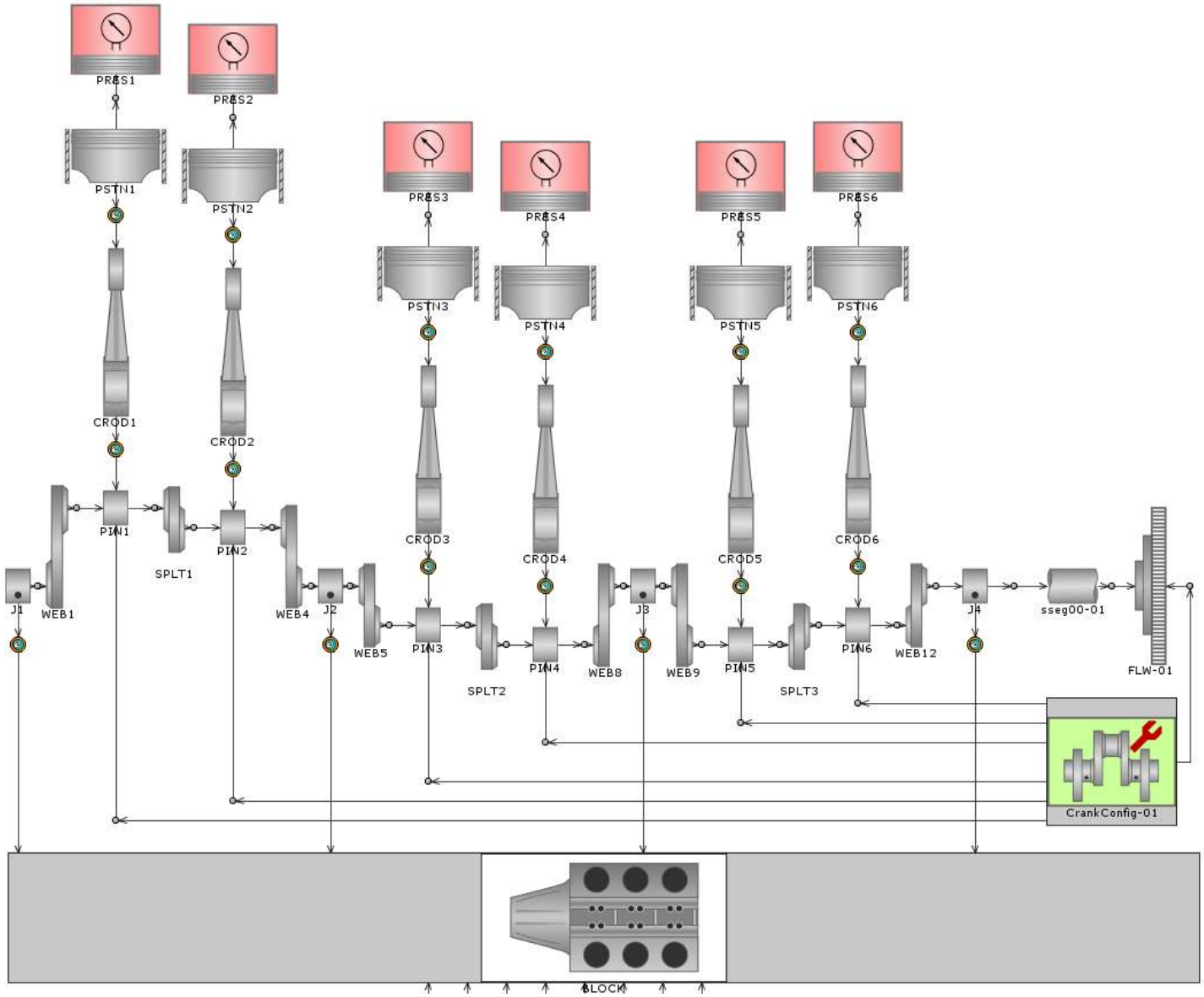
Integration w/ Engine/vehicle Subsystem Models

- 润滑系统
  (凸轮相位器)



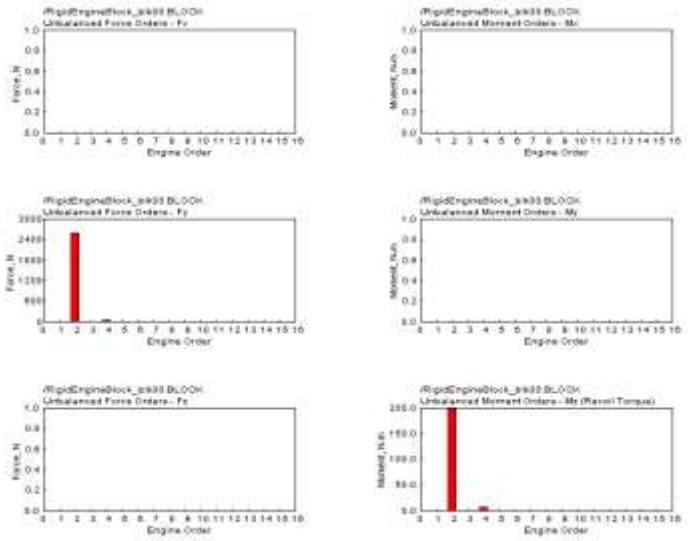


Split-pin V-6 Engine CrankTrain Model w/ Bearings

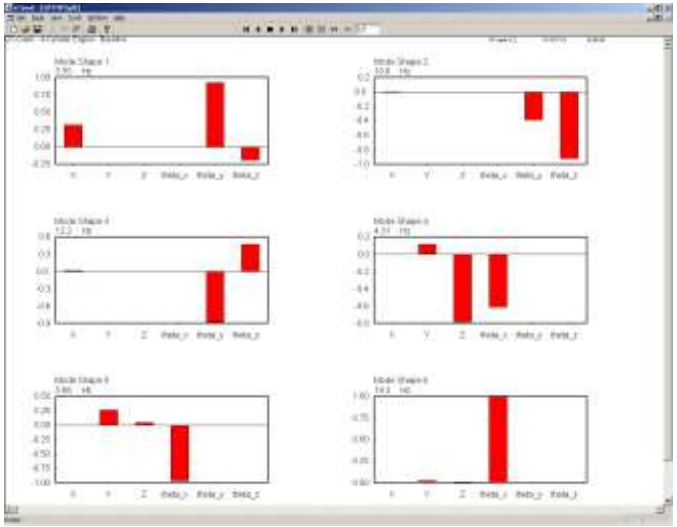


Engine Unbalanced Force/Moments and Mounting System Analysis

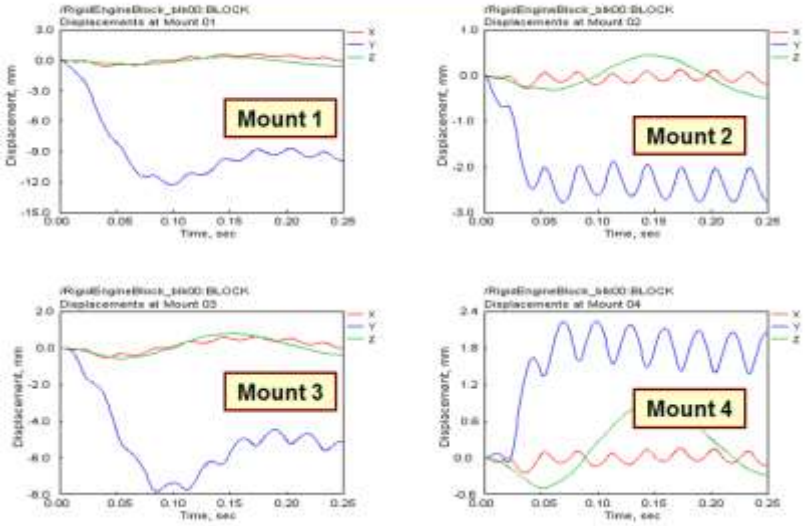
Unbalanced Force/Moment Orders



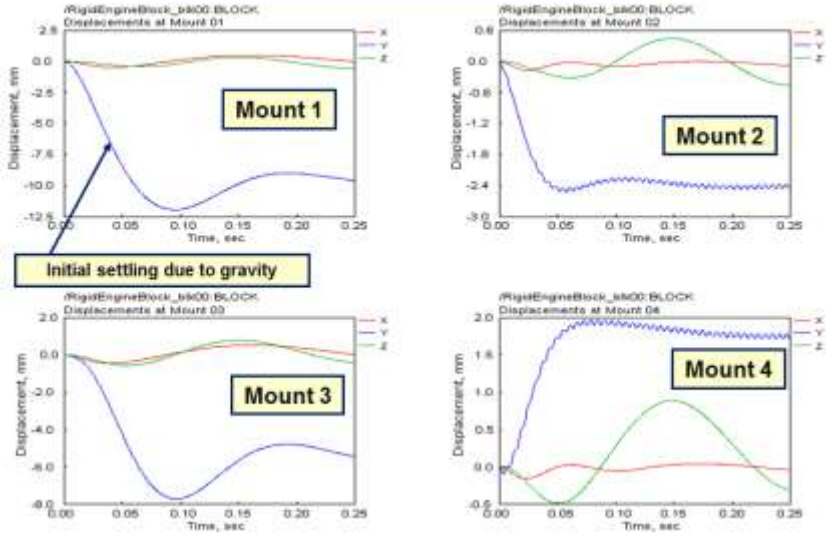
Mounting System Mode Shapes



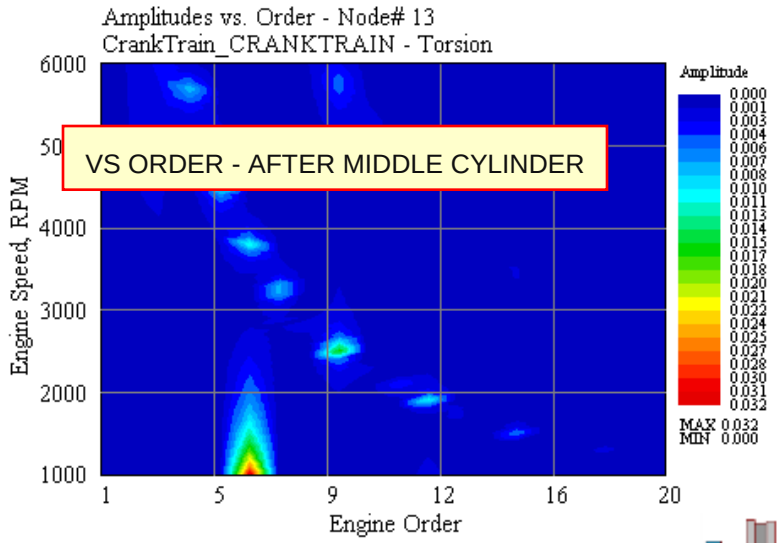
PRESSURE+INERTIA FORCES – 1000 RPM

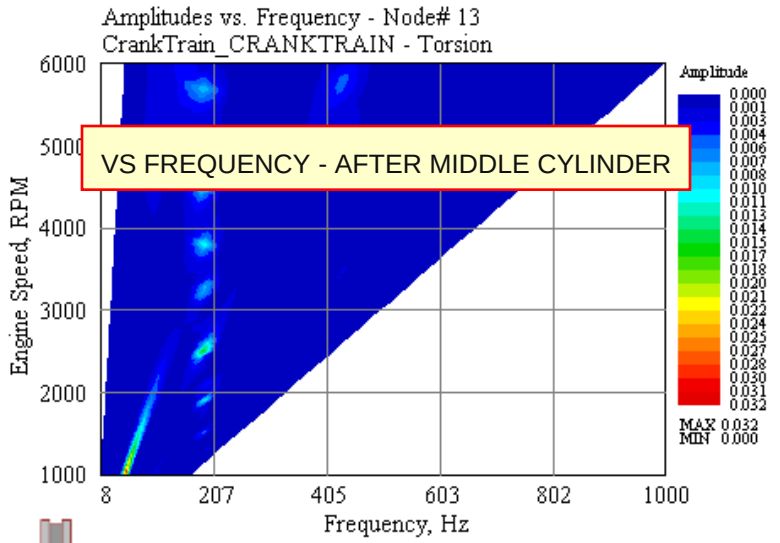


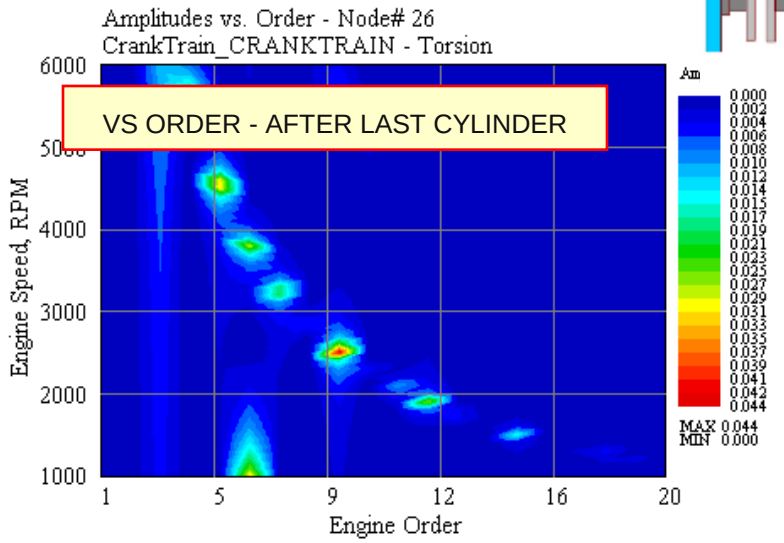
PRESSURE+INERTIA FORCES – 5000 RPM

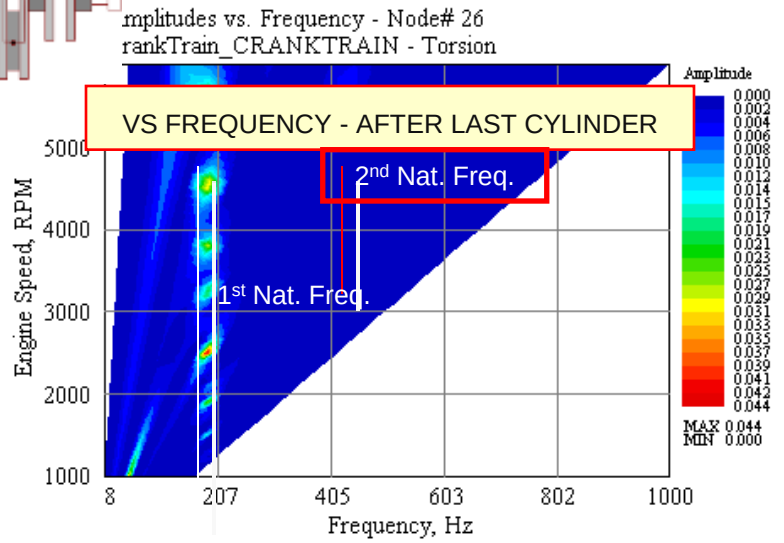


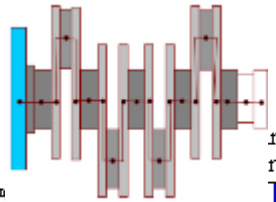
Forced FD Torsional Analysis
Response vs. Order/Frequency & Speed



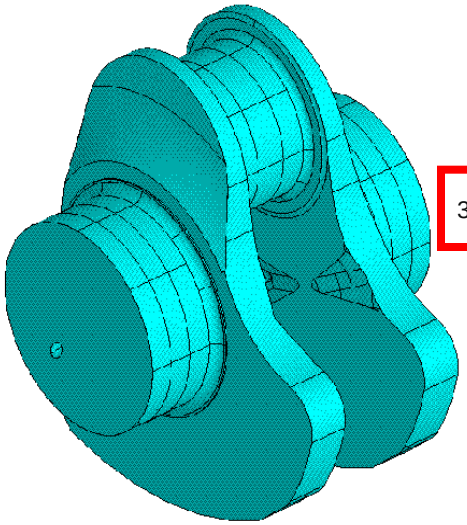




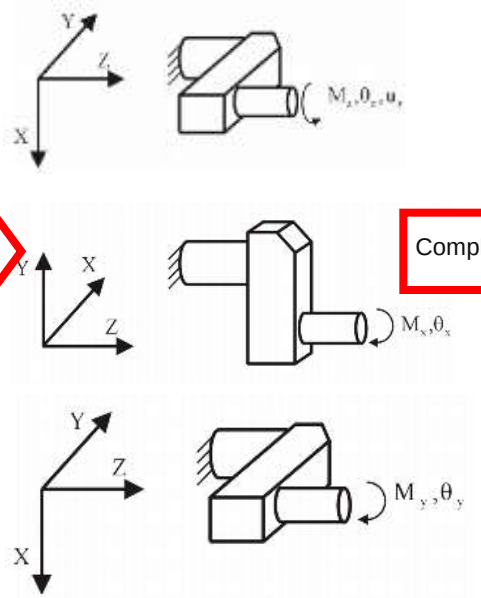




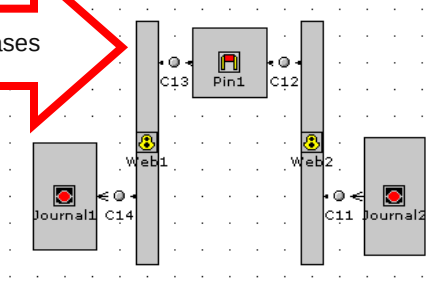
Equivalent 3D Beam FE Model



3D FE Analysis

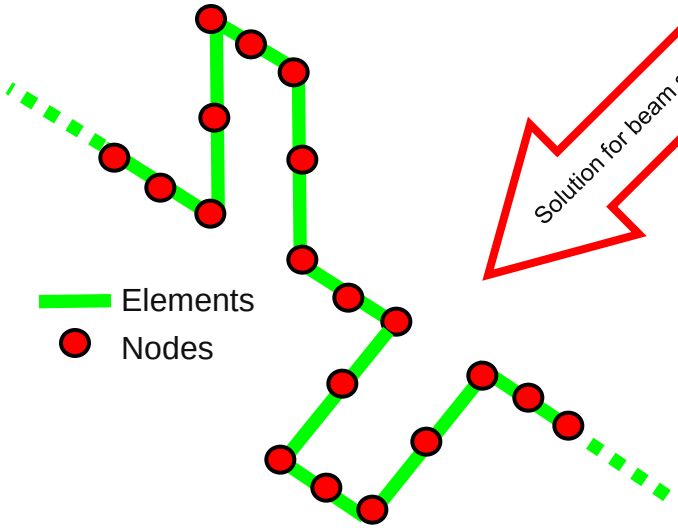


Compliance for 3 load cases



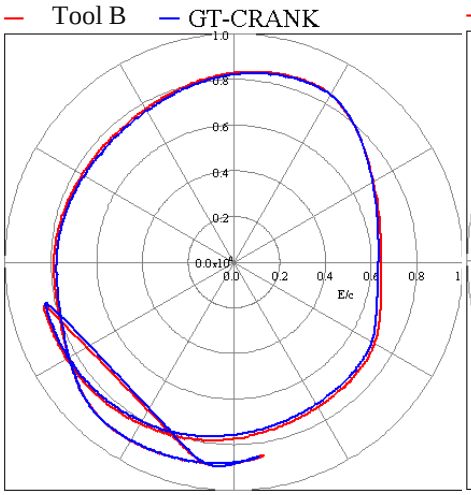
Solution for beam section properties

3D曲柄实体FE模型，用于自动创建当量的3D梁FE模型

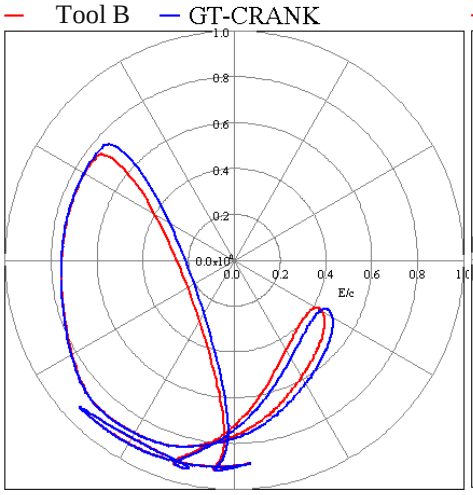


I-6 Engine Bearing Orbits – Comparison to Tool B

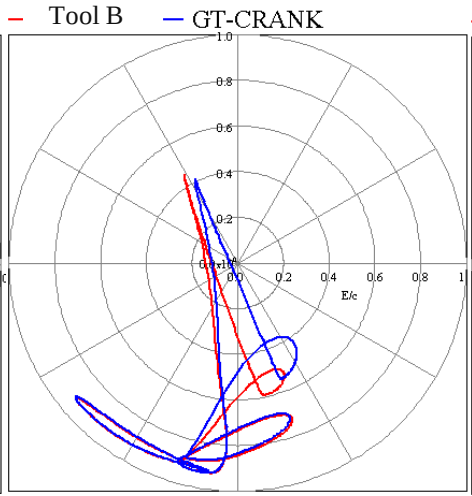
Bearing Orbit: Bearing 1



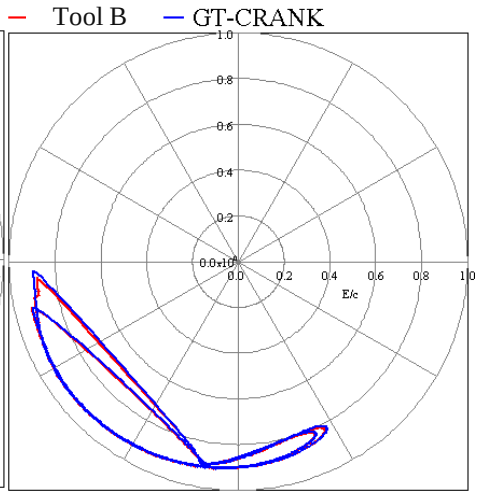
Bearing Orbit: Bearing 2



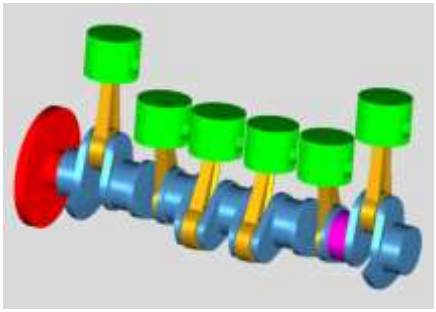
Bearing Orbit: Bearing 3



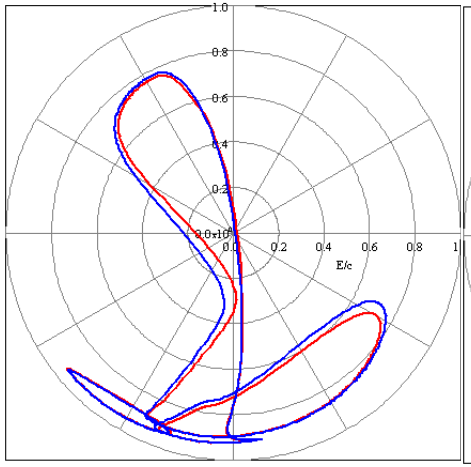
Bearing Orbit: Bearing 4



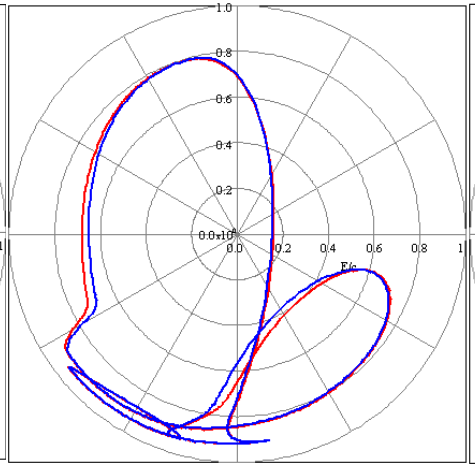
Tool B



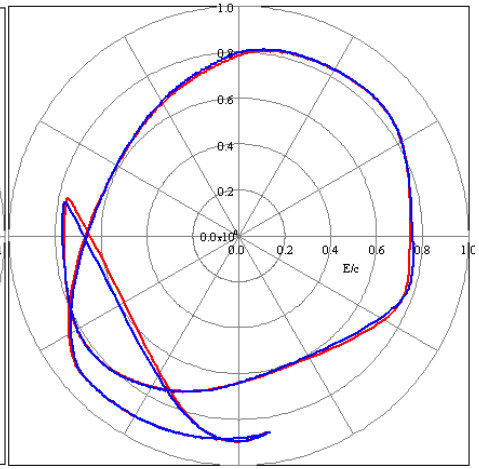
Bearing Orbit: Bearing 5



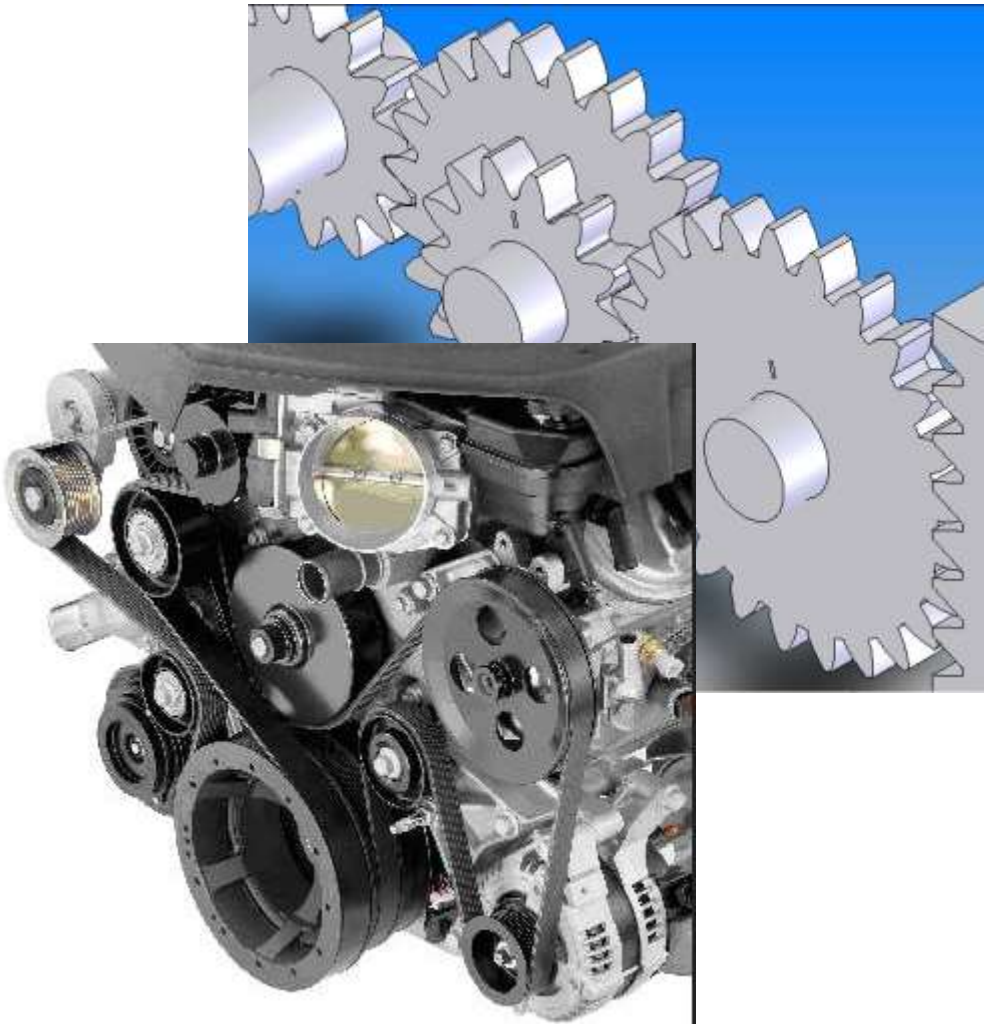
Bearing Orbit: Bearing 6



Bearing Orbit: Bearing 7



Timing Drives & FEAD

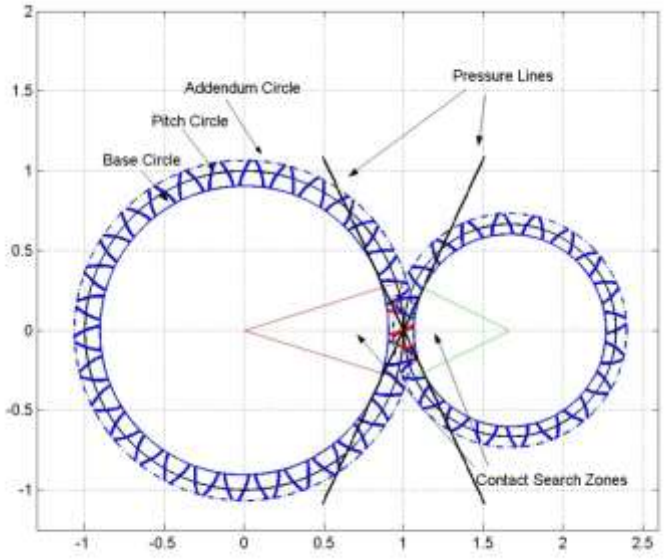


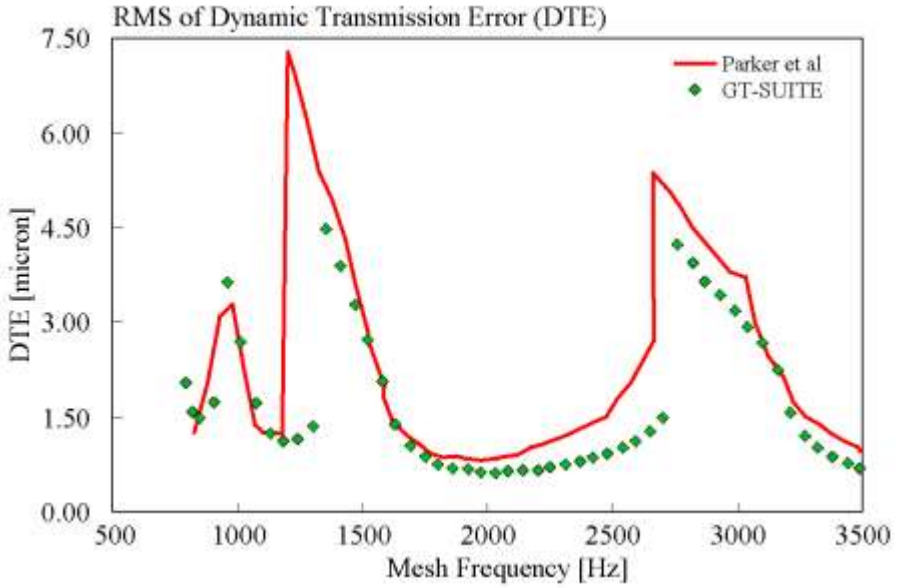
GT Gamma Technologies

Gear, Chain and Belt Drive System Modeling: Overview

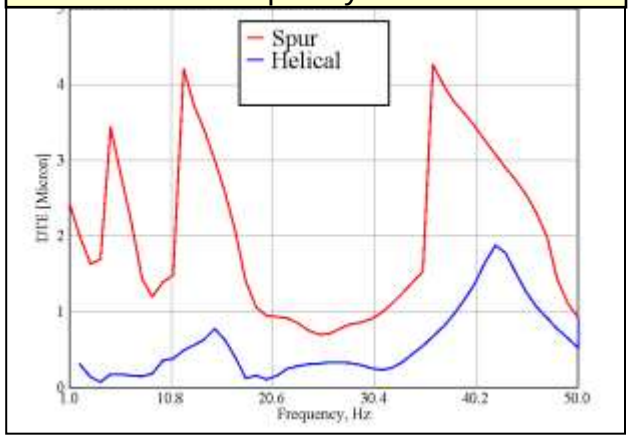
- 可以仿真有多个齿轮，链轮，惰轮，机械和液压张紧，导板，带等组成的整个系统
- 物理，主要是平面2D模型，有横向运动/振动
- 轮毂，刚性，刚度和阻尼，轴承
- 组合（齿轮，链，带）传动
- 无缝集成仿真::
  - 发动机内如：轴，曲轴，配气机构模型
  - 整车传动系
  - 其他的多物理模型：流体，泵，电机械系统

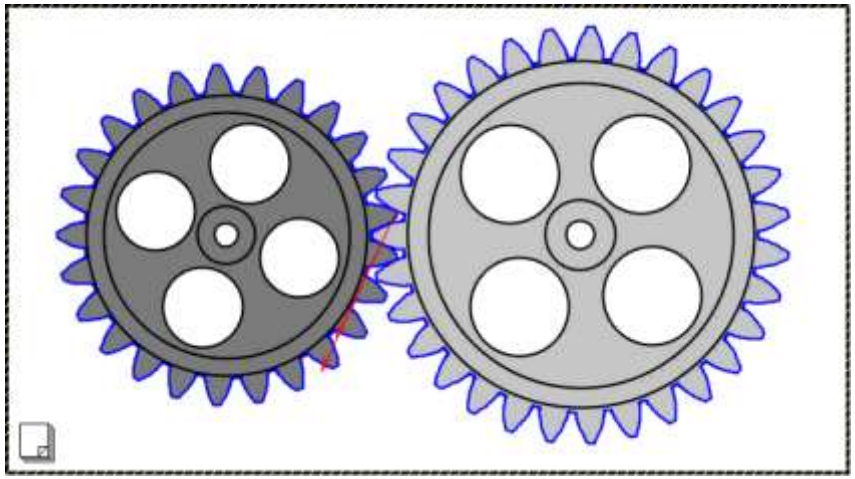
Gear Contact Kinematics Mesh Cycle Stiffness Variation: Spur or Helical Gears



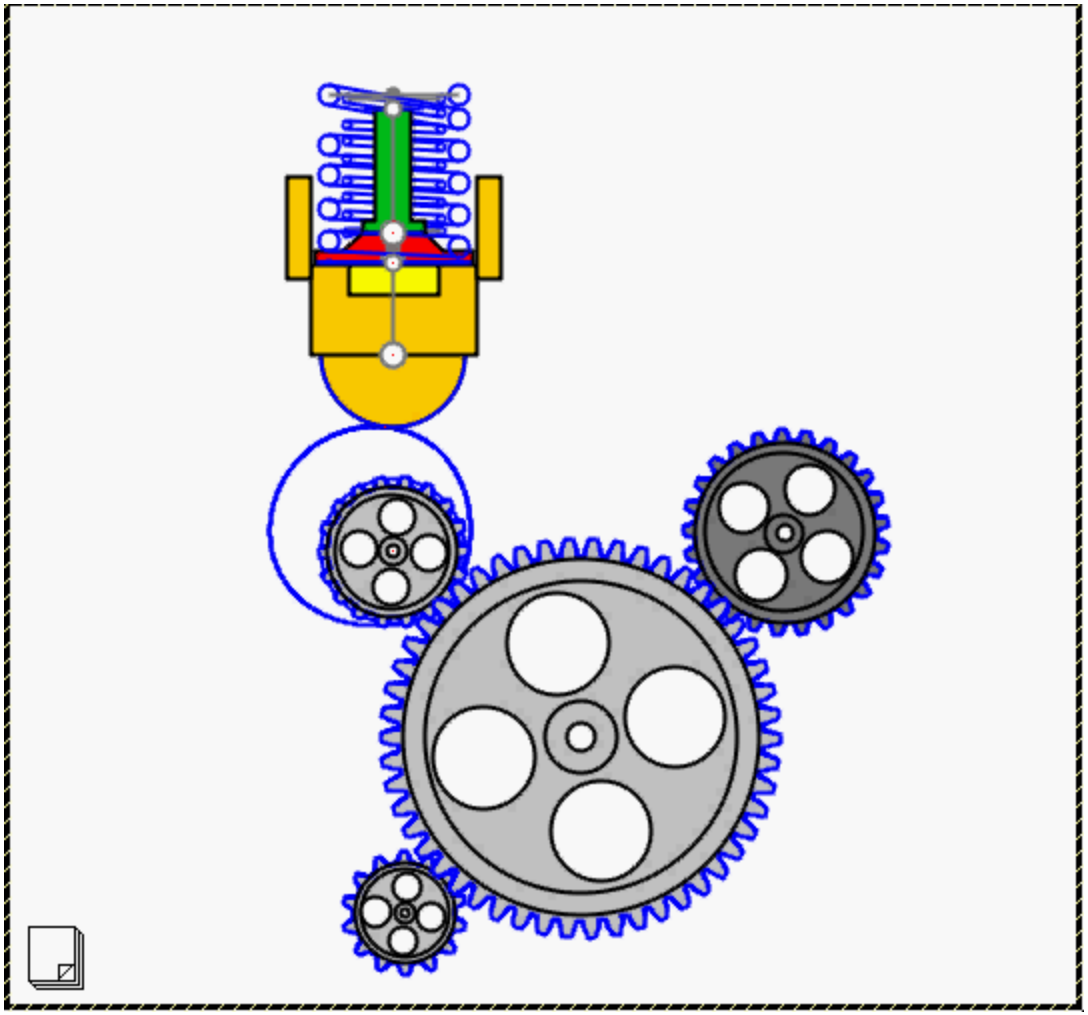


Dynamic behavior:
RMS DTE vs. Frequency

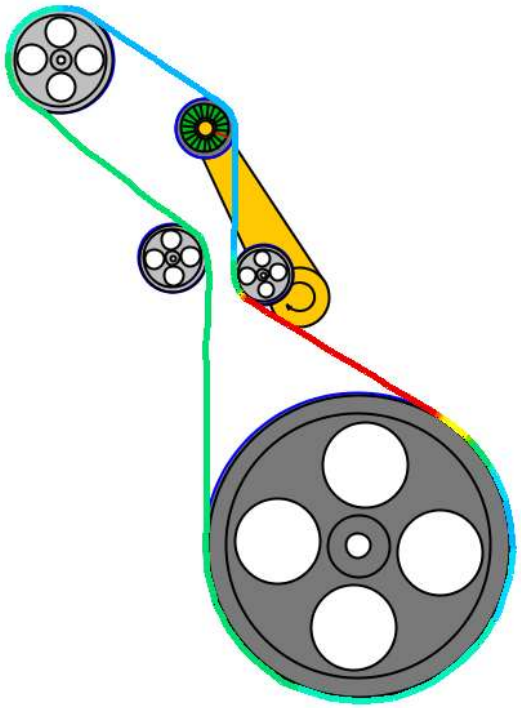




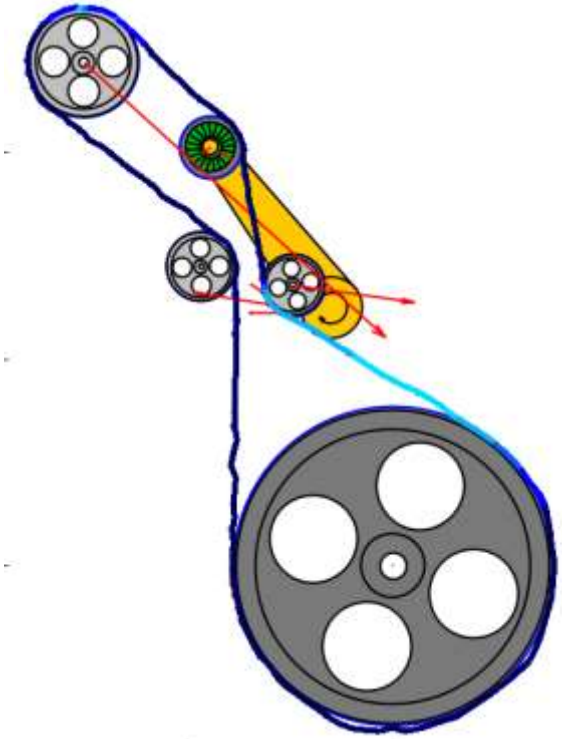
Integrated Geartrain, Cam & Pump Plunger Model



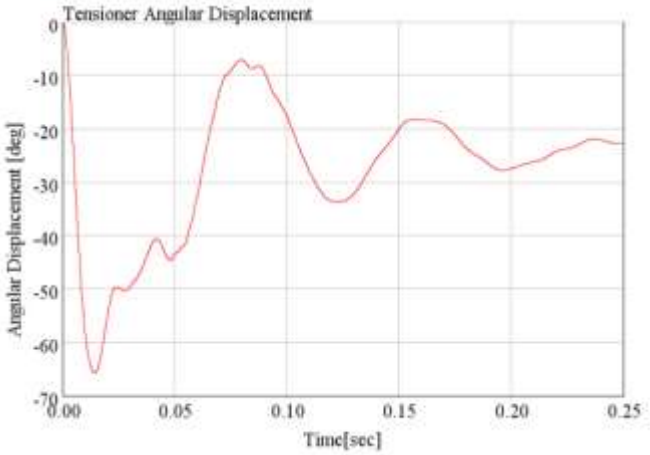
Power Turbine Belt Drive with Idlers and Tensioner Belt Dynamics Predictions

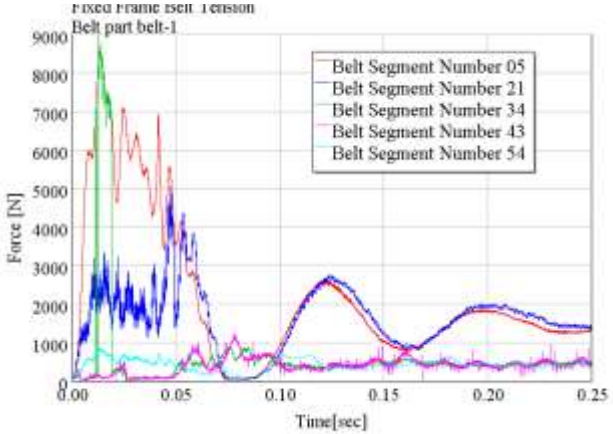


Contours: Belt Tension



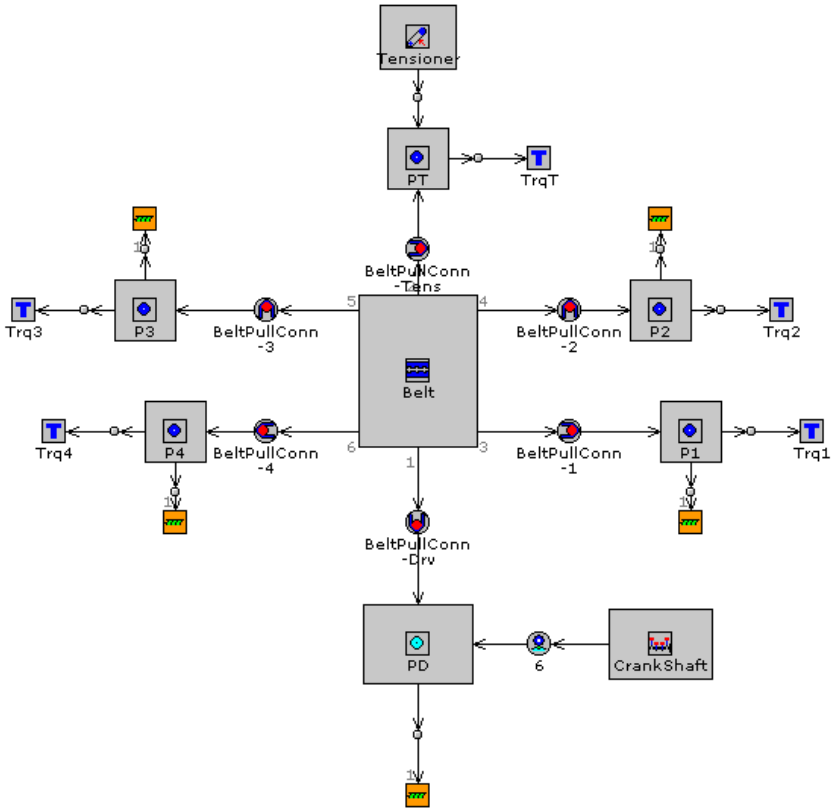
Arrows: Contact and reaction forces



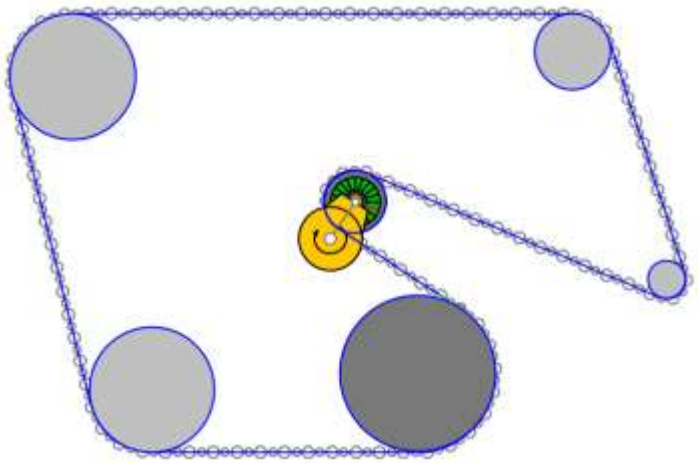


FEAD System Model Example

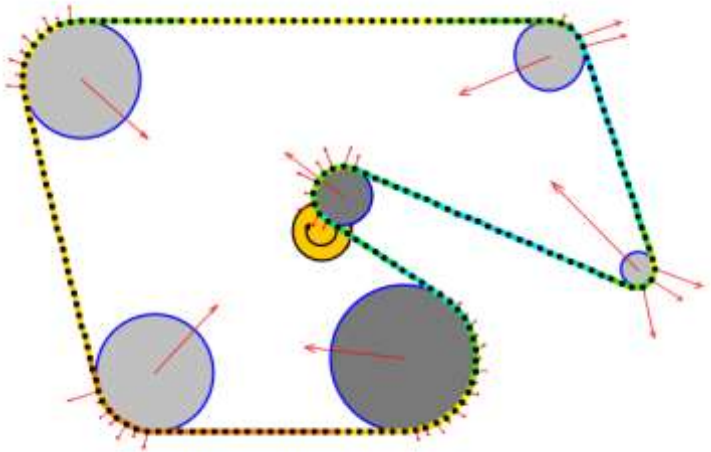
FEAD Model in GT-ISE



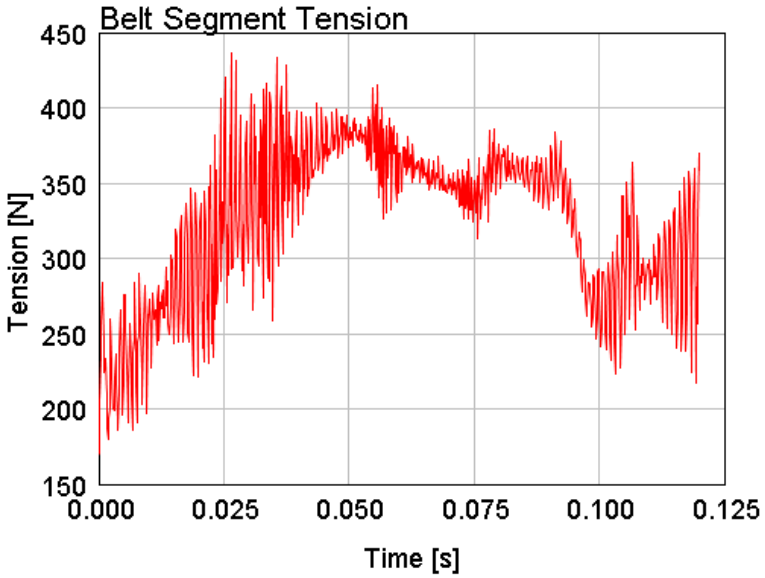
FEAD Layout Plot (GT-POST)

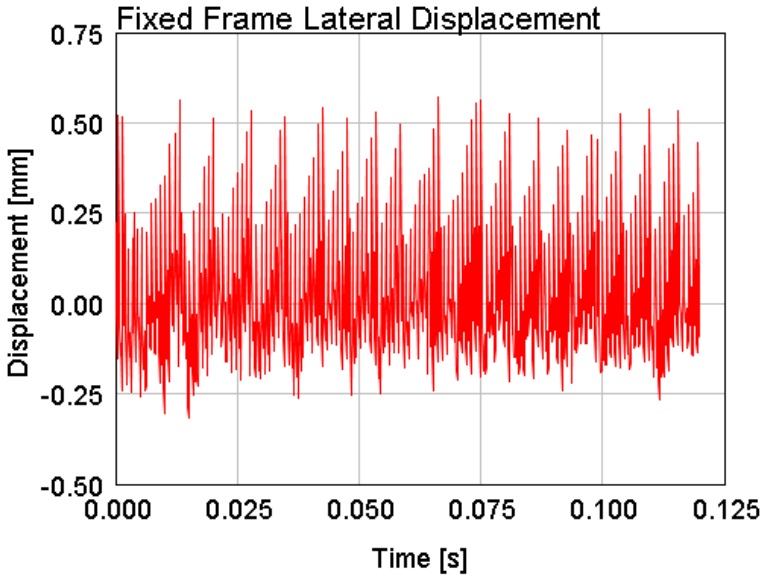


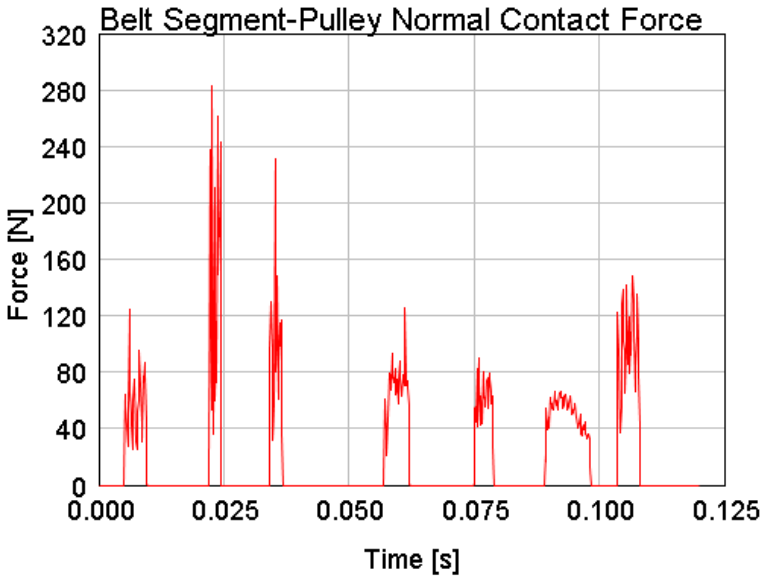
FEAD Animations (GT-POST)

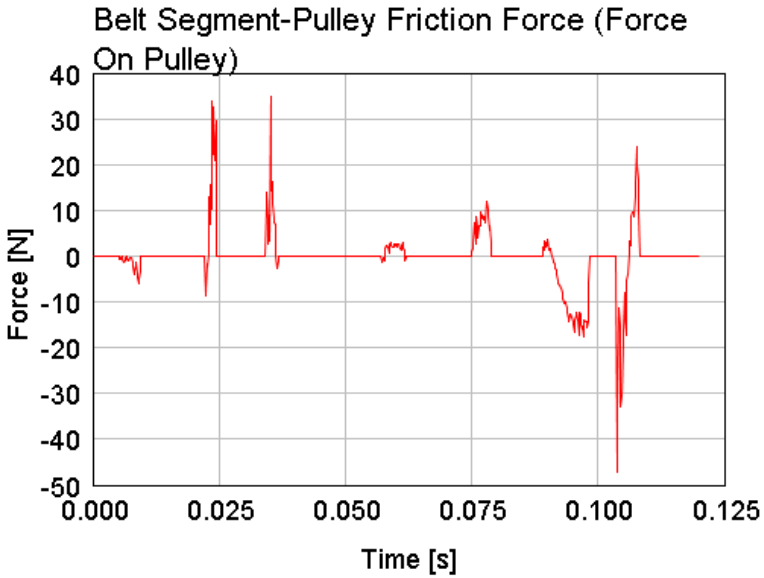


FEAD System Model Predictions - Time Plots





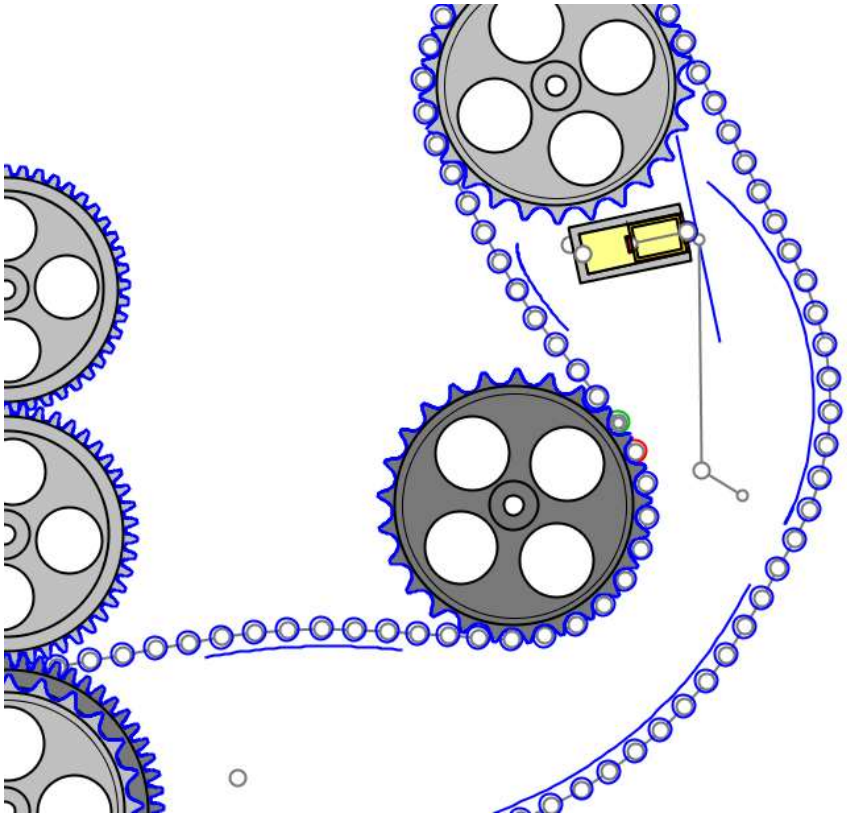


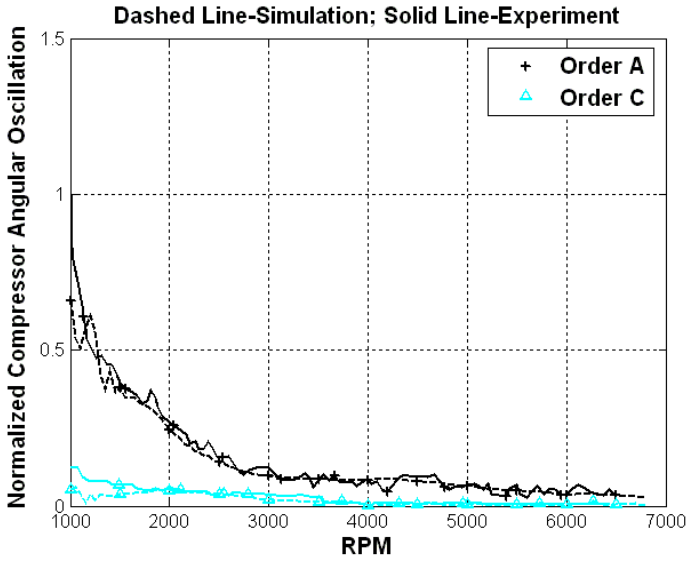


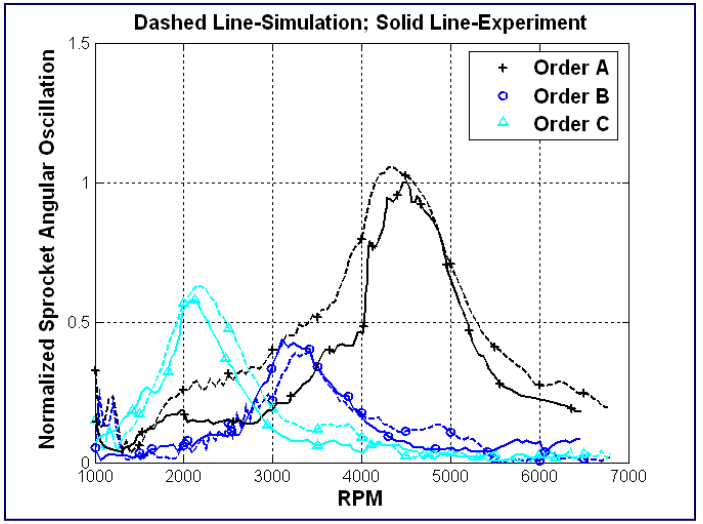
Chain Drive Modeling:
Chain Model Details and Predictions

- 2D平面(3自由度)链-链动力学(ROLLER or SILENT chain) 与刚性或者柔性链轮+驱动/被驱系统（曲轴，凸轮轴）扭转动力学耦合
- 详细建立链/滚子链轮接触几何与接触运动学:
  - 链– 链轮
  - 导板-张紧器
- 链轮的平面惯量，质心偏置量
- 导板/张紧器的形状可为任意的 (平直，圆弧或曲线）
  - 固定，平动或铰接, 机械/液压张紧器
- 椭圆形链轮
- 所有作平动的链接和惰轮，凸轮轴链轮、链接-链接，滚子链轮的力，扭矩，Hertz 接触的结果输出
- 可视化链传动系统以及动画

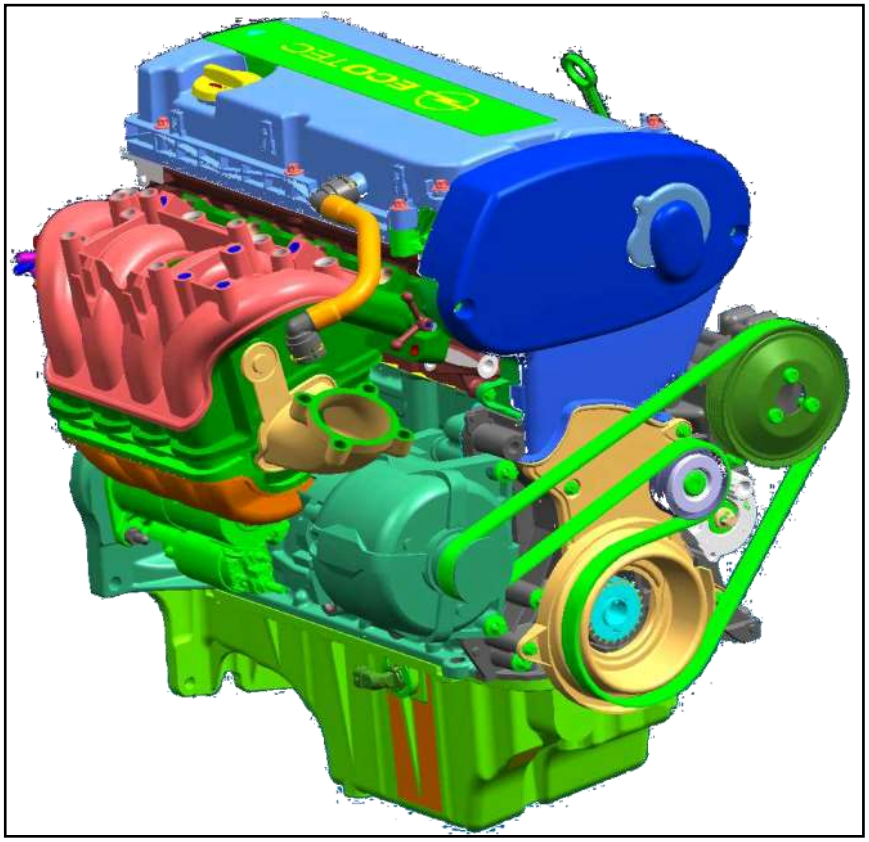
Detail of Roller Chain Drive Model with Hinged Hydraulic Tensioner

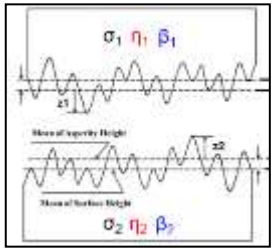


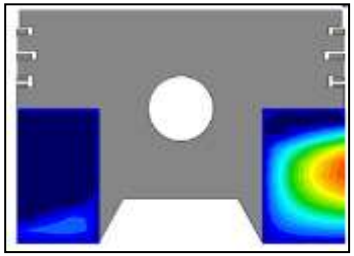




Engine Friction



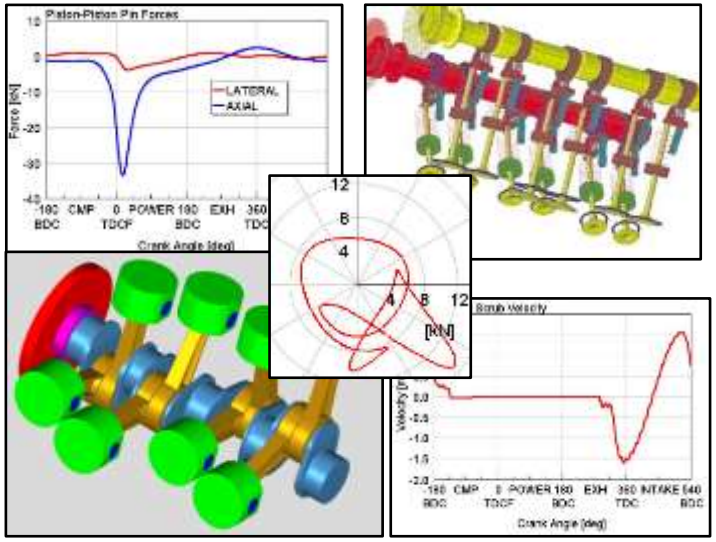




GT Gamma Technologies

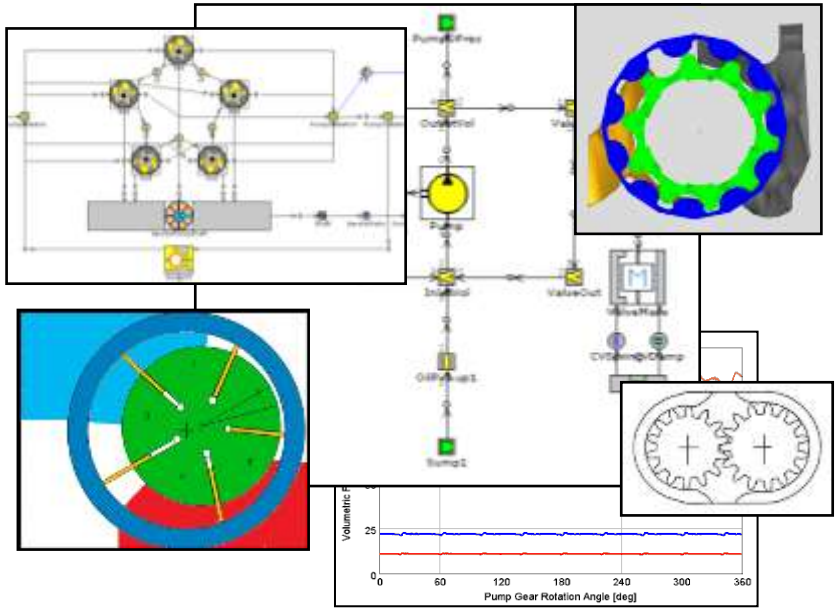
Enablers For Friction Prediction 1

机械
机械建模/MBD:
速度/负载



- ✓ Primary & secondary motions shear/scrub speeds
- ✓ Pressure, inertia, spring loads on piston/rings, at bearings, contacts, joints, guides etc.

流体
流体系统, 压力 & 泵损失

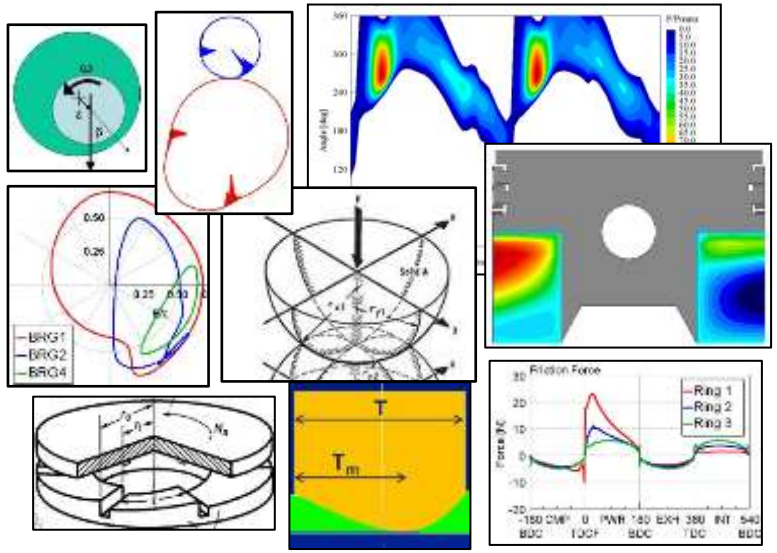


- ✓ Coolant, oil, gas pressures, flow rates
- ✓ Pump PdV work, leakage, friction etc. losses
- ✓ Fluid pressure BCs

Enablers For Friction Prediction 2

摩擦学:模型

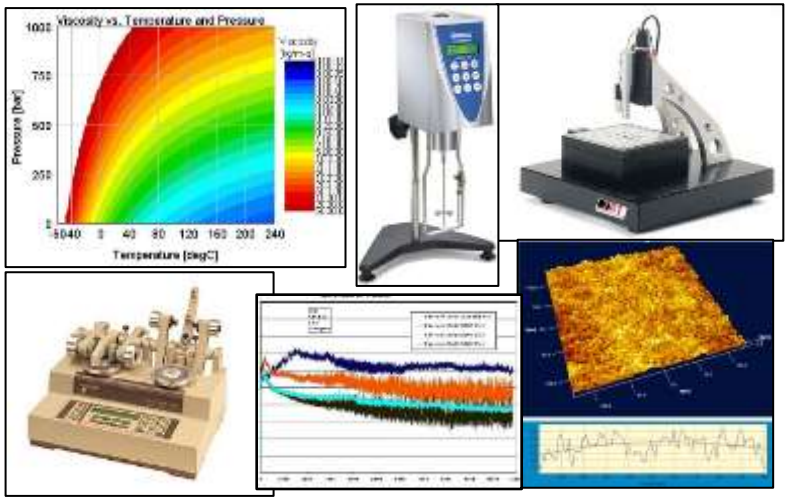
油膜，表面粗糙度相互作用



- ✓ OFT, Oil pressure, shear stress distributions
- ✓ Asperity contact pressures
- ✓ Oil temperature, thermal effects

摩擦学:特性

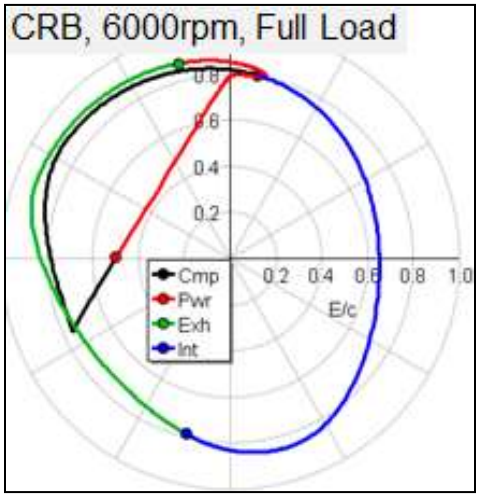
输入/测量敏感性强的参数：
润滑油，表面粗糙度，摩擦

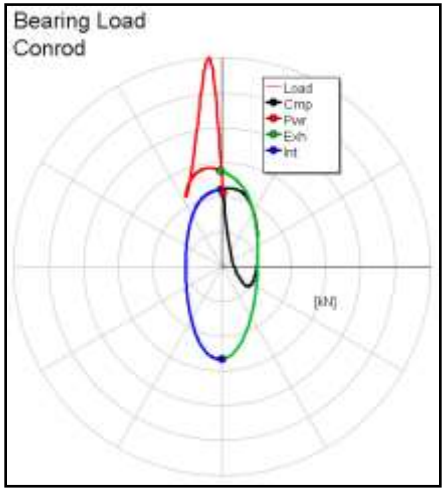


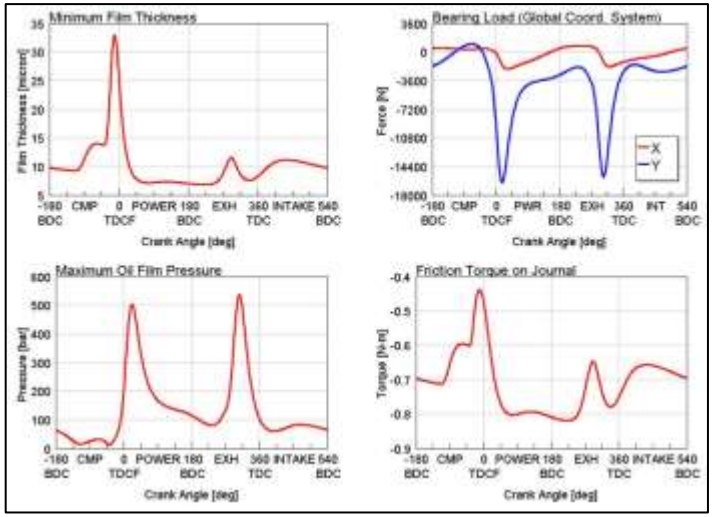
- ✓ Oil viscosity vs. T,P, shear rate
- ✓ Surface roughness
- ✓ Friction and wear coeff. for friction surface matl. pairs

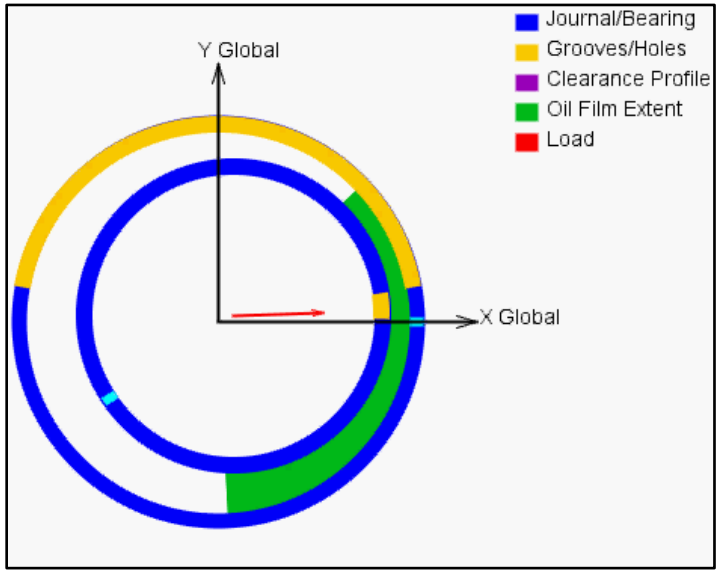
Journal Bearing Oil Film & Friction I
Mobility or Impedance Solutions

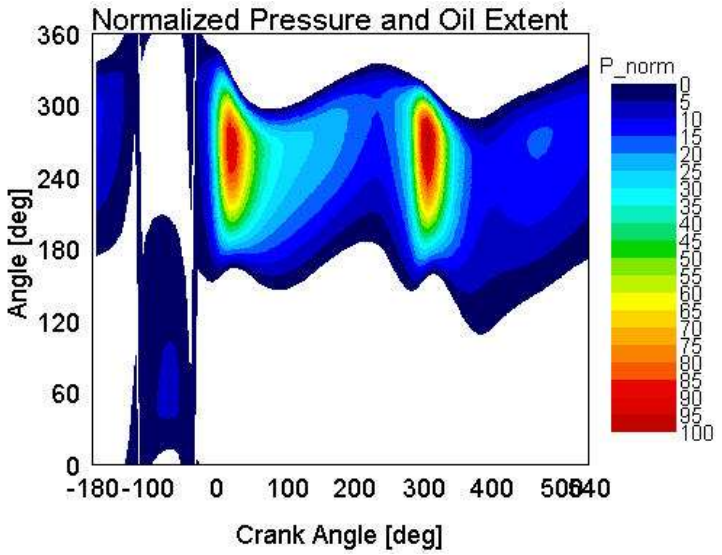
包括摩擦接触,油温, Martin方程计算油的流量





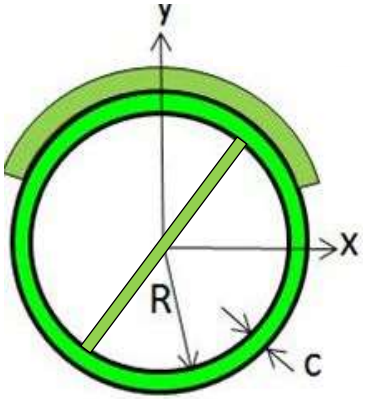




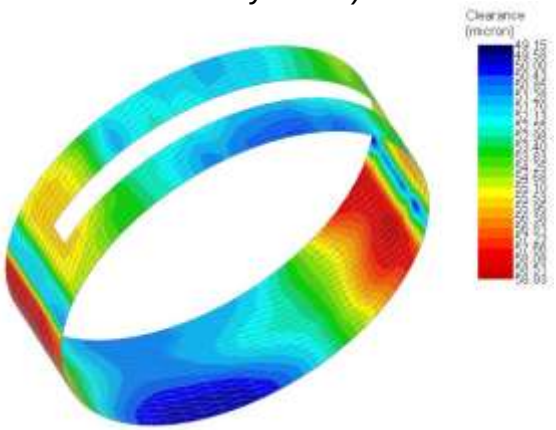


Journal Bearing Oil Film and Friction II
Mass-conserving HD Model

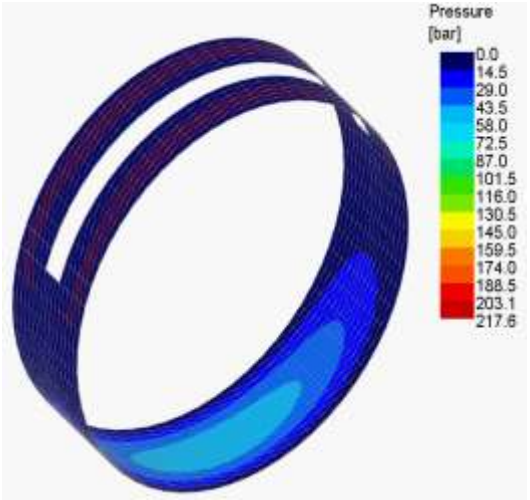
- 气蚀模型
- 半宽度的模型（对称），或者全宽度
- 轴承间隙
- 轴承，轴颈上的槽，孔
- 不规则的宽度，槽/孔，自动网格划分
- 热平衡 (油温）



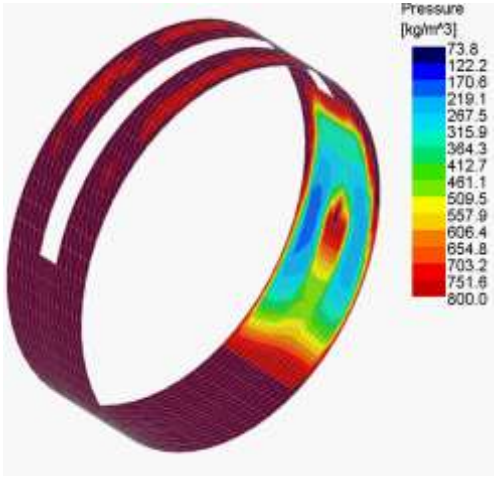
Bearing clearance profile (variation in clearance due to assembly crush)



Oil Film Pressure

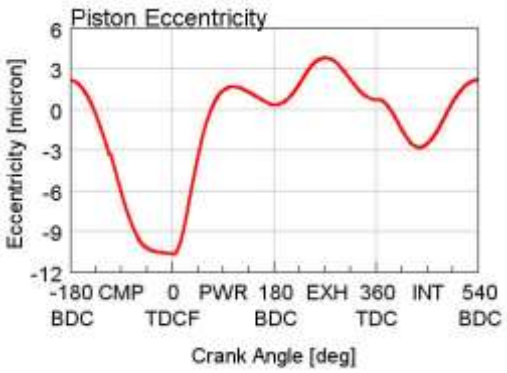


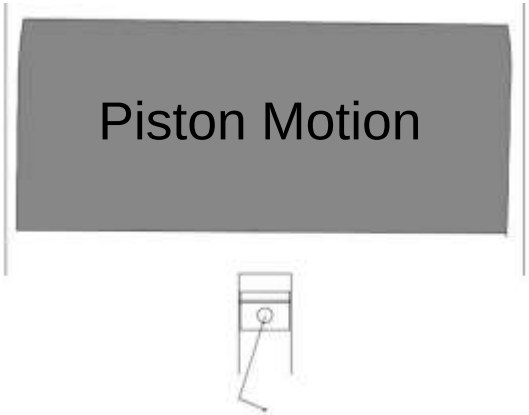
Oil Film Density

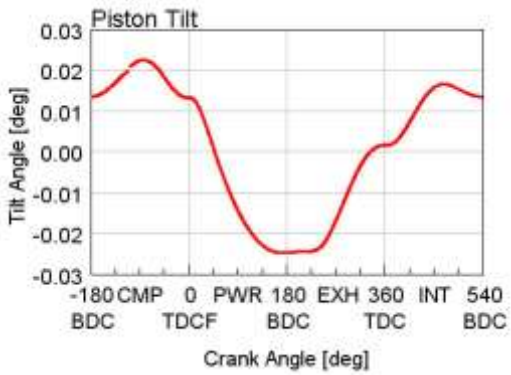


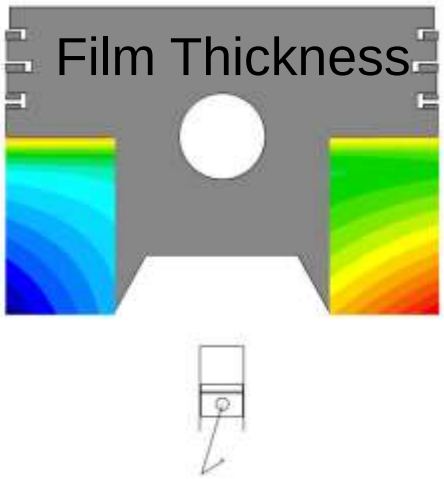
Piston Skirt Lubrication/Friction Model

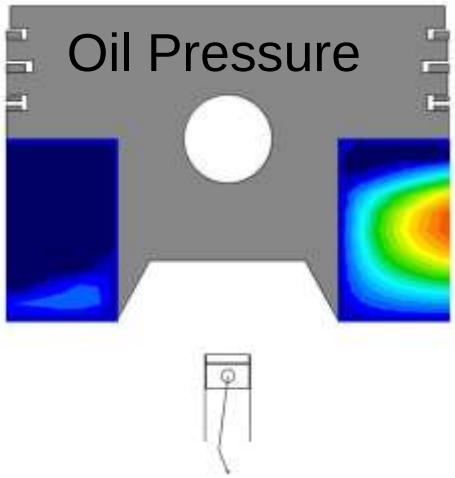
发动机，活塞设计，运行工况，润滑油，活塞裙部的表面特性，裙部及缸壁温度，FE热应变，接触模型，磨损载荷的影响

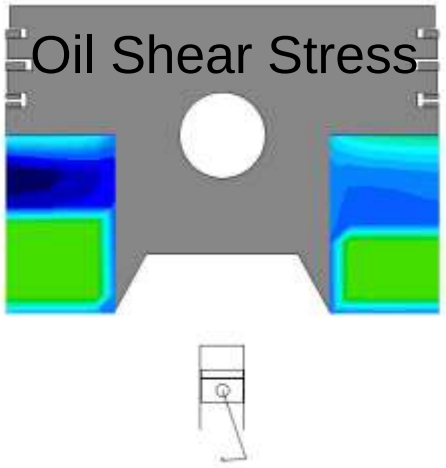








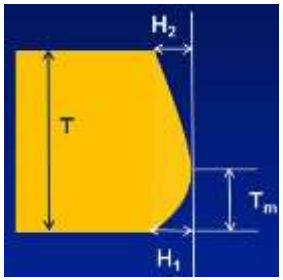


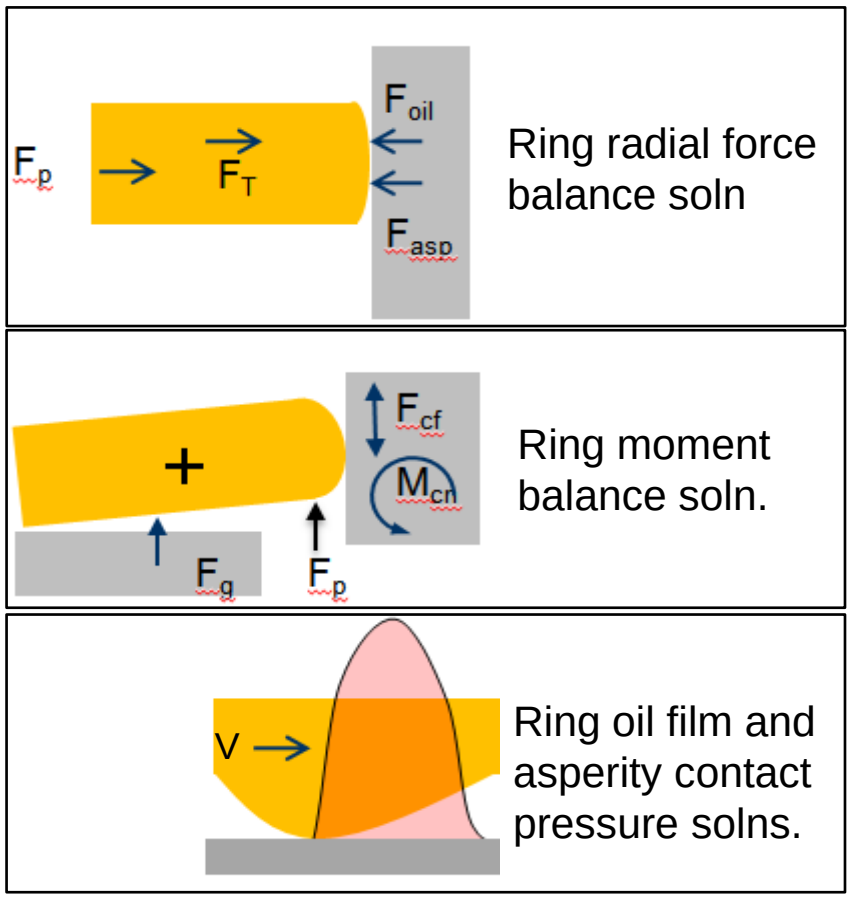


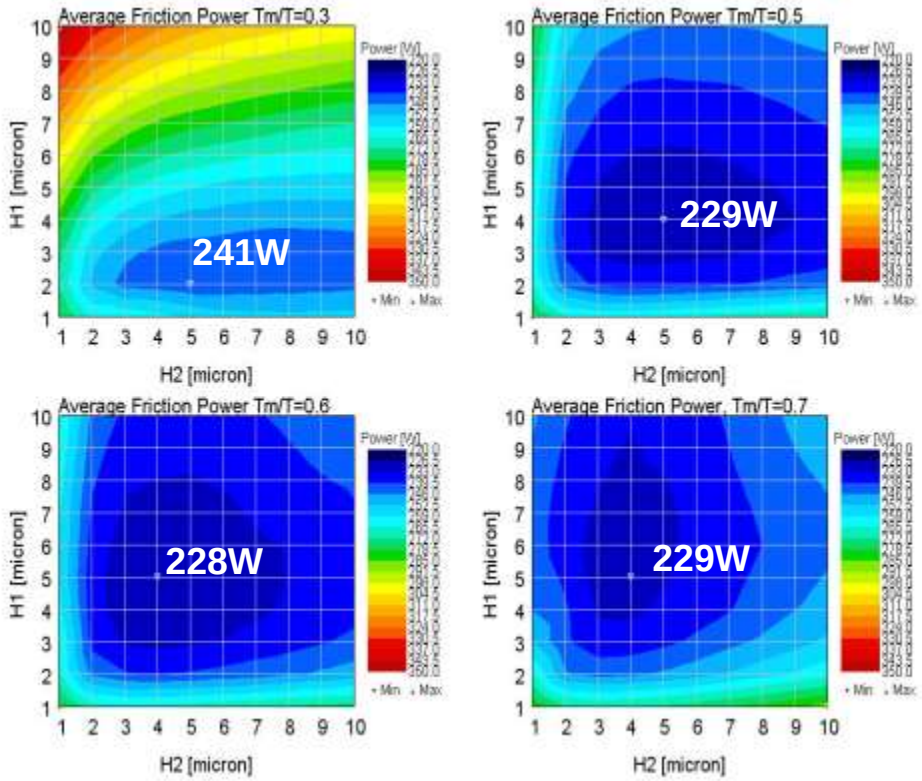
Piston Ring Lubrication/Friction

发动机转速/负荷，气体压力，活塞环参数，活塞环/缸壁温度，润滑油，表面特性，热应变的影响

活塞环的摩擦功率损失:
H_1, H_2 T_m的影响

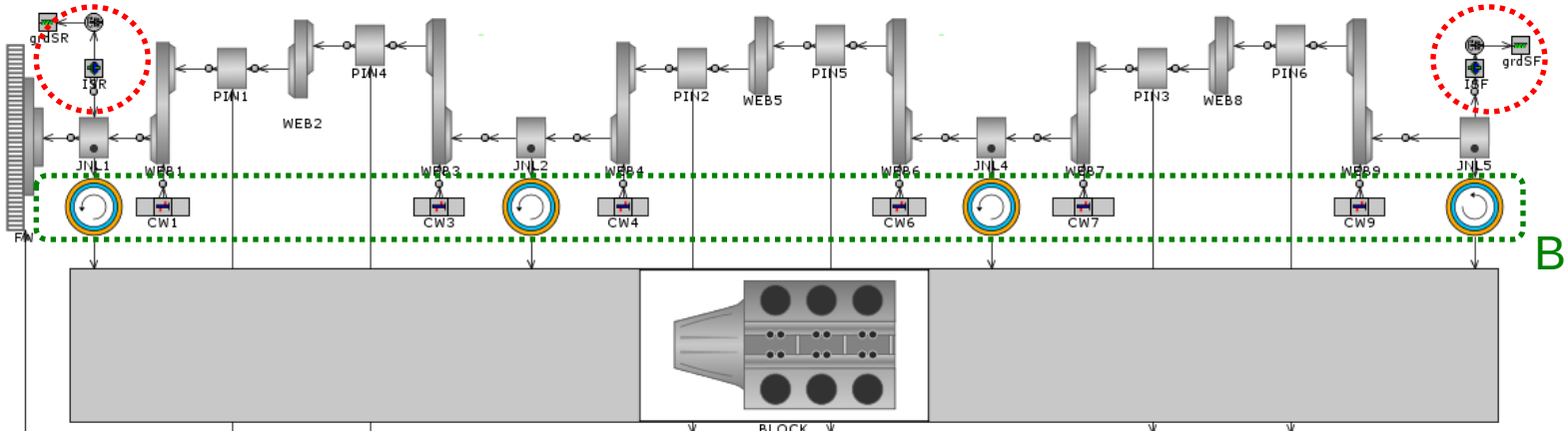






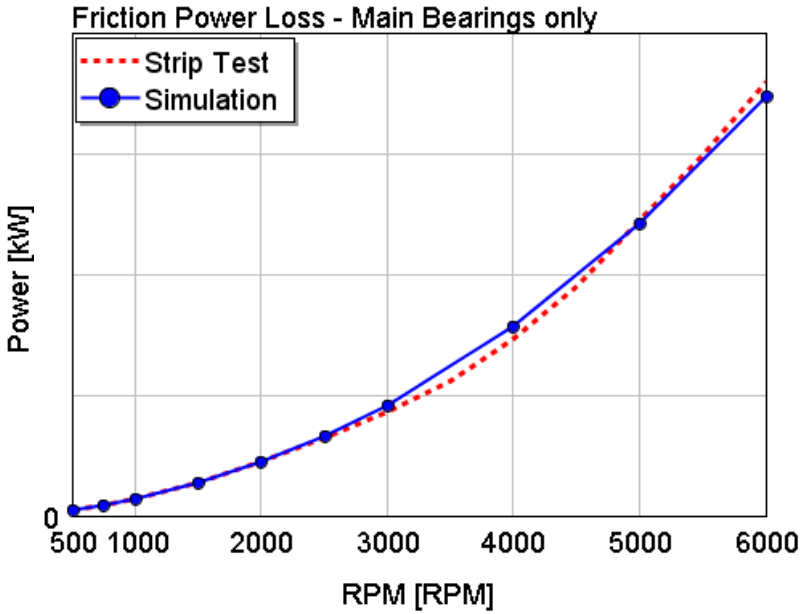
Comparison to Engine Strip-down Test Data

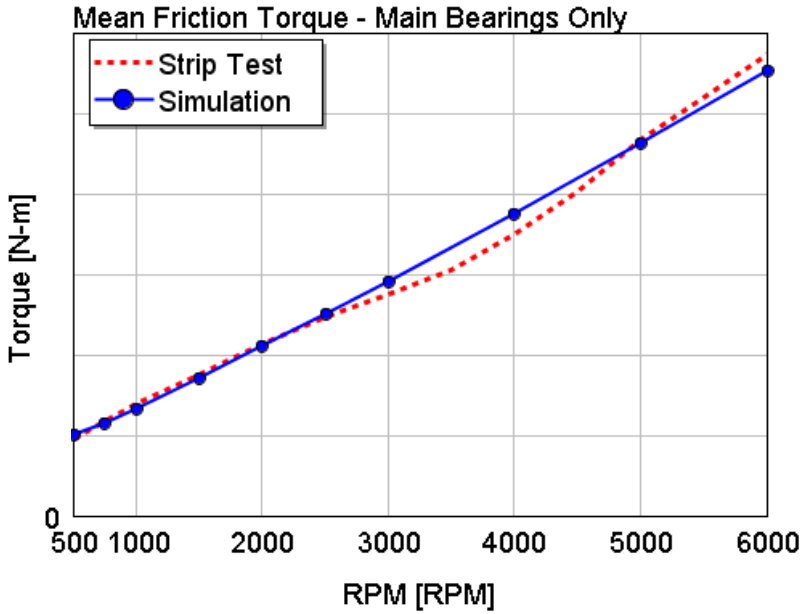
主轴承+密封件的FMEP (仅曲轴)



FRONT & REAR SEALS

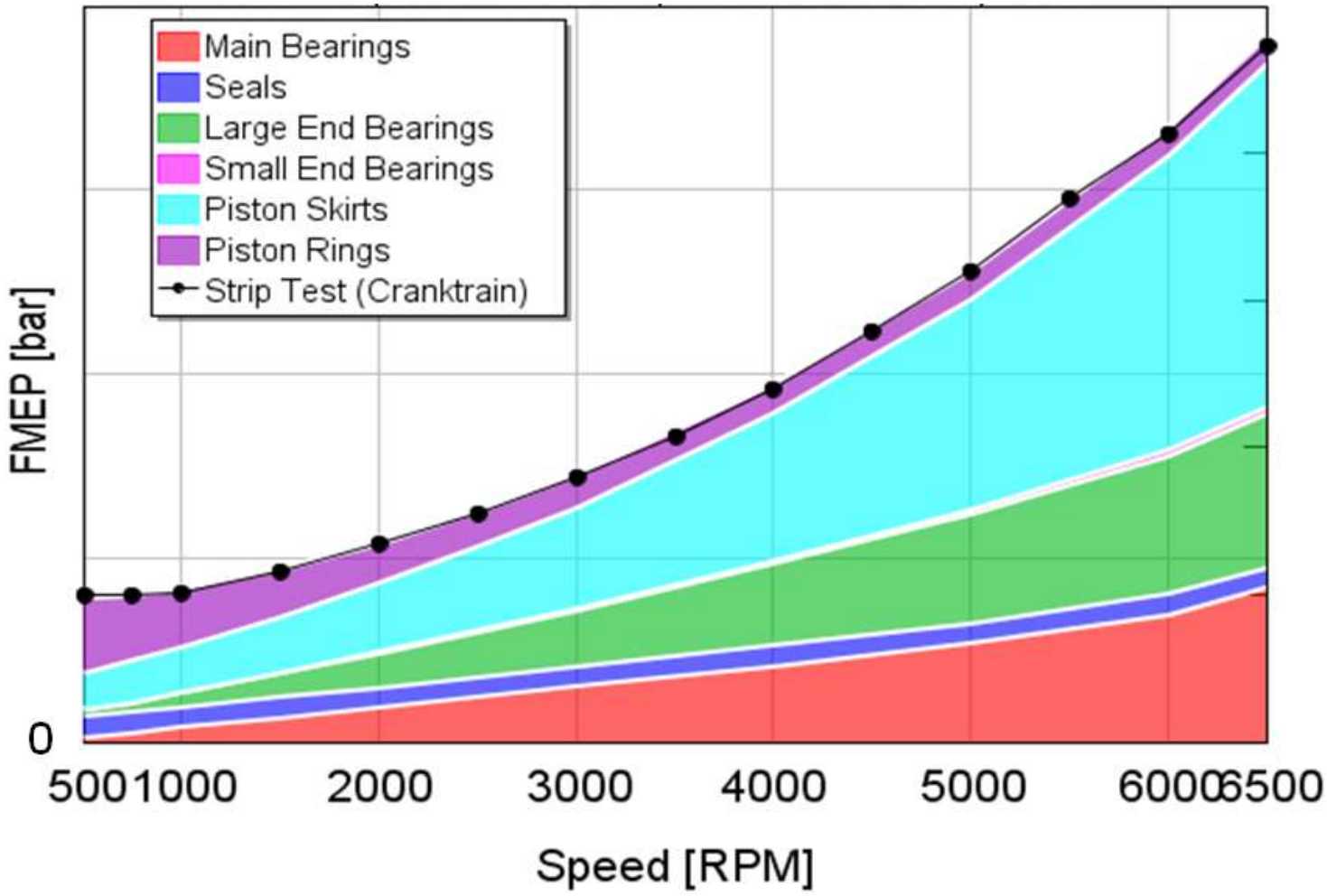
MAIN BEARINGS





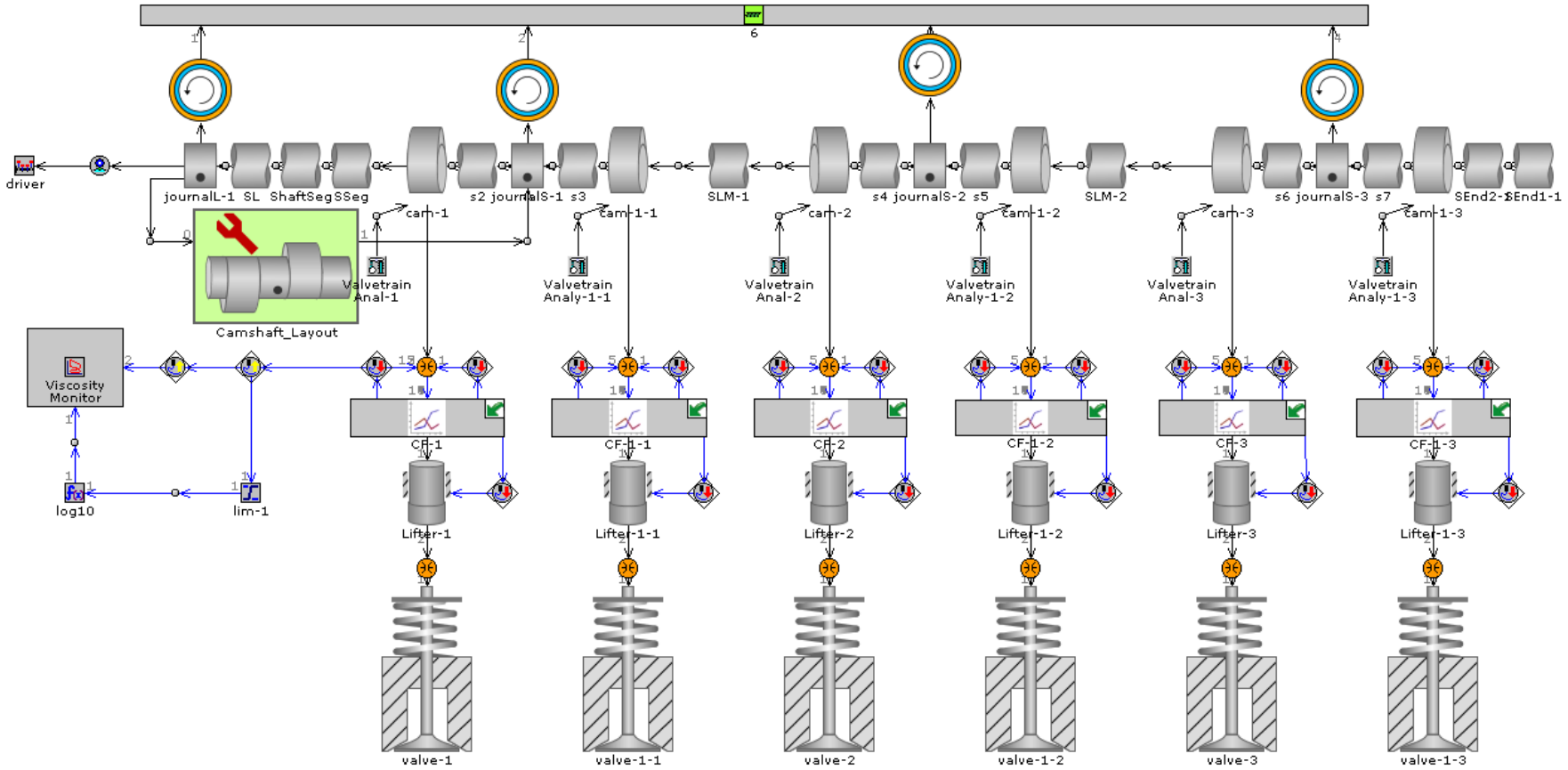
Comparison to Engine Strip-down Test Data

完整的曲轴系统的FMEP



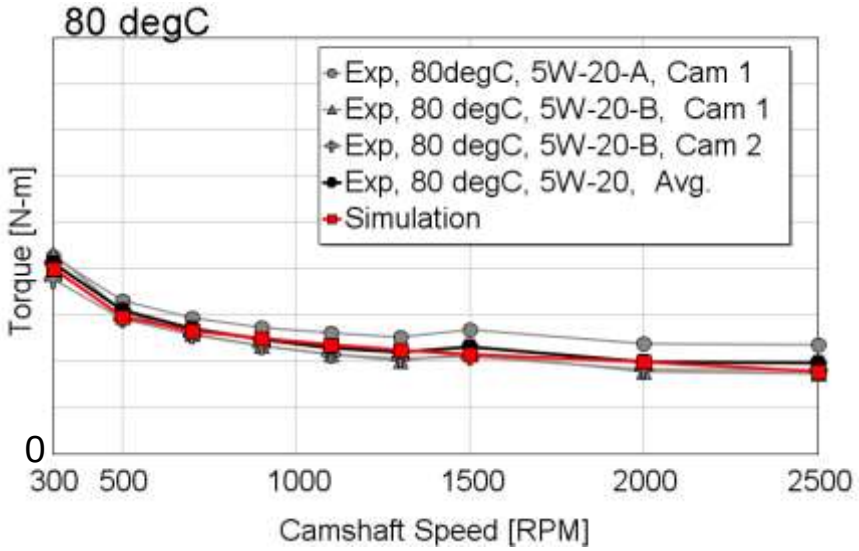
Valvetrain Friction Torque Test Data

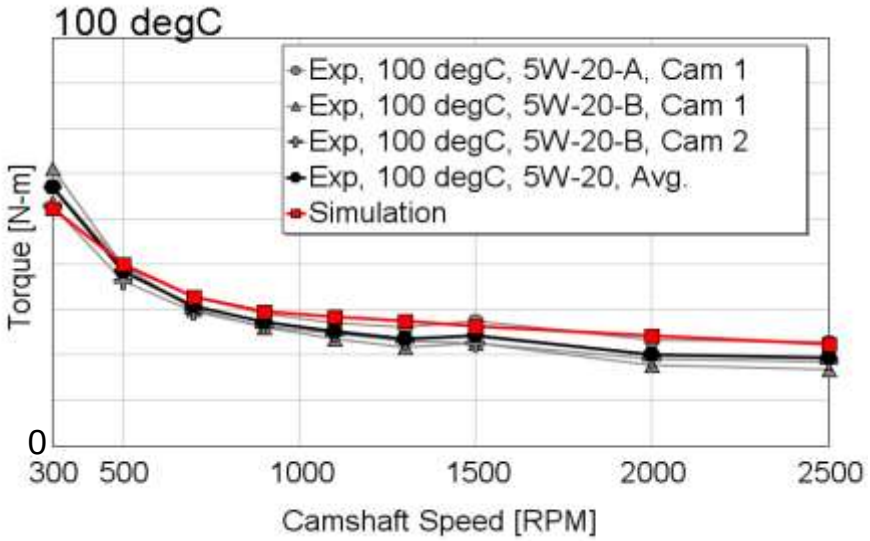
凸轮轴+配气机构模型 (直接作用，挺杆)

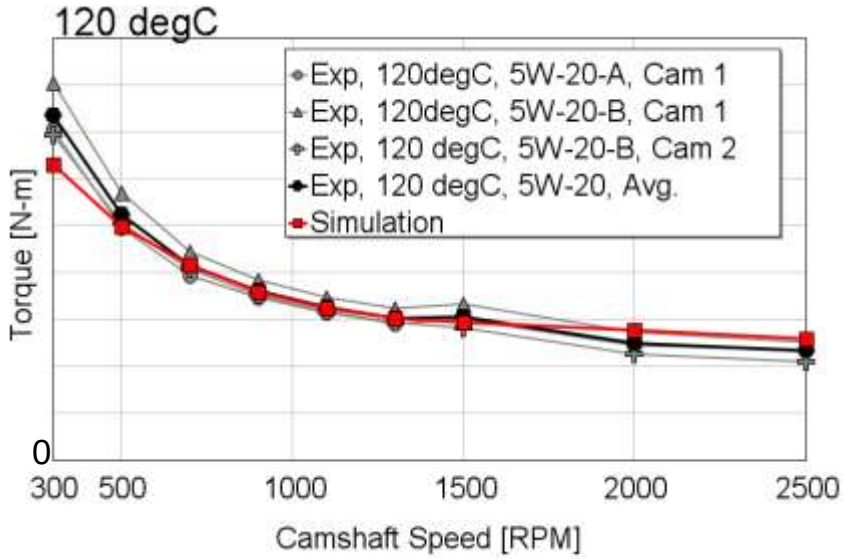


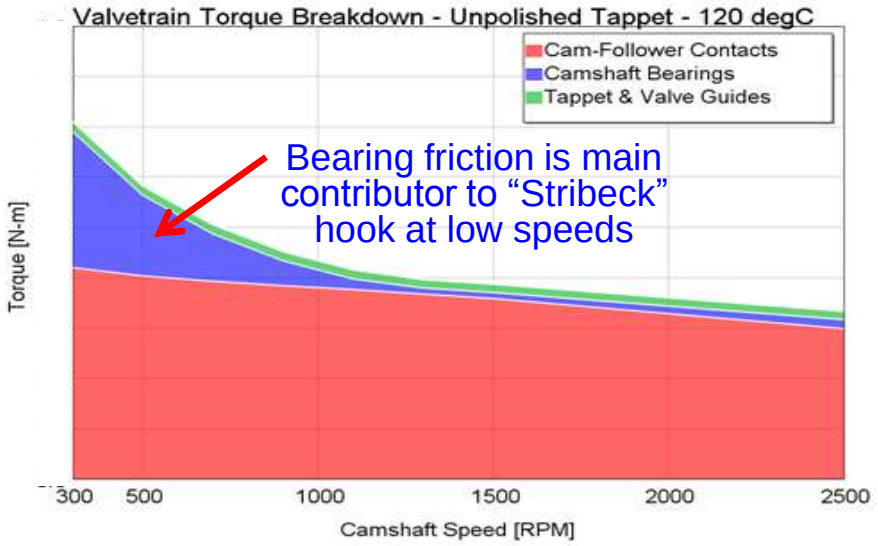
V-6 Engine Valvetrain Friction: Direct-acting, Flat-tappet

配气机构 (凸轮轴) 扭矩





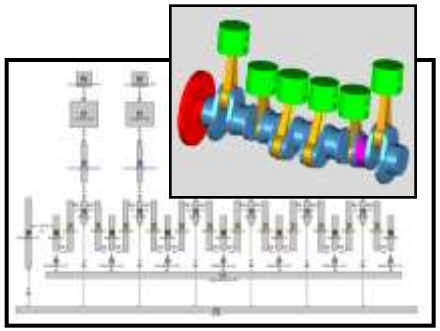




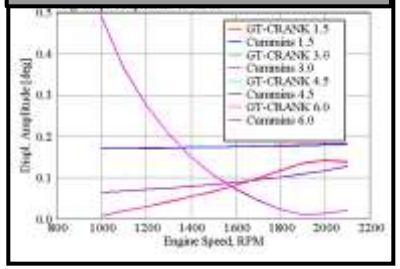
Example
Engine Mechanics
Applications

Cummins: Deployment of GT-SUITE for Cranktrain Design Analysis

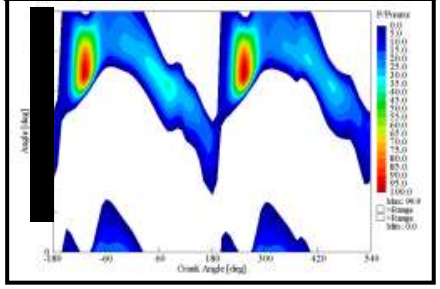
I-6 HEAVY-DUTY DIESEL CRANKSHAFT



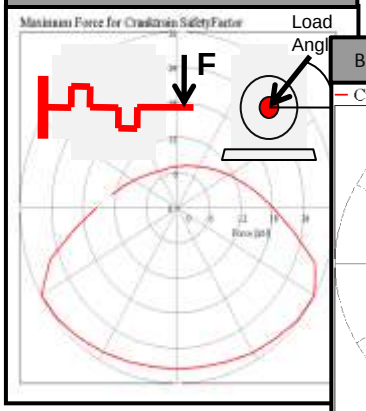
Angular Displ. Amplitude vs. Speed: Orders 1.5, 3.0, 4.5 and 6.0



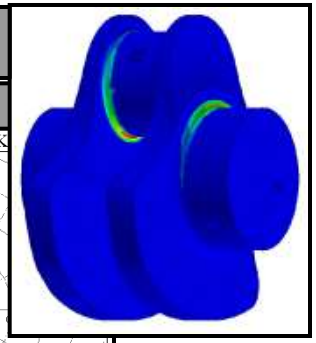
Bearing Oil Film Extent & Pressure Contours



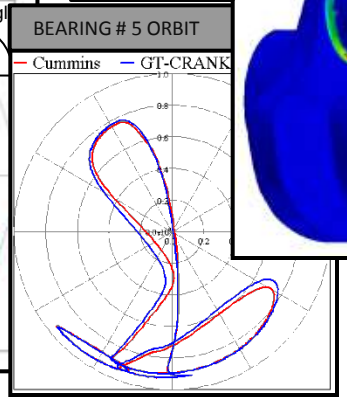
Max. Acceptable End Load vs. Angle Acceptable Safety Factor



MAX. EFR STRESS



BEARING # 5 ORBIT



Objectives

在单个的工具进行曲轴设计仿真分析。再与其他的分析整合。

Value Proposition

GT-SUITE作为先进的平台，可以实现曲轴系统与其他系统的集成

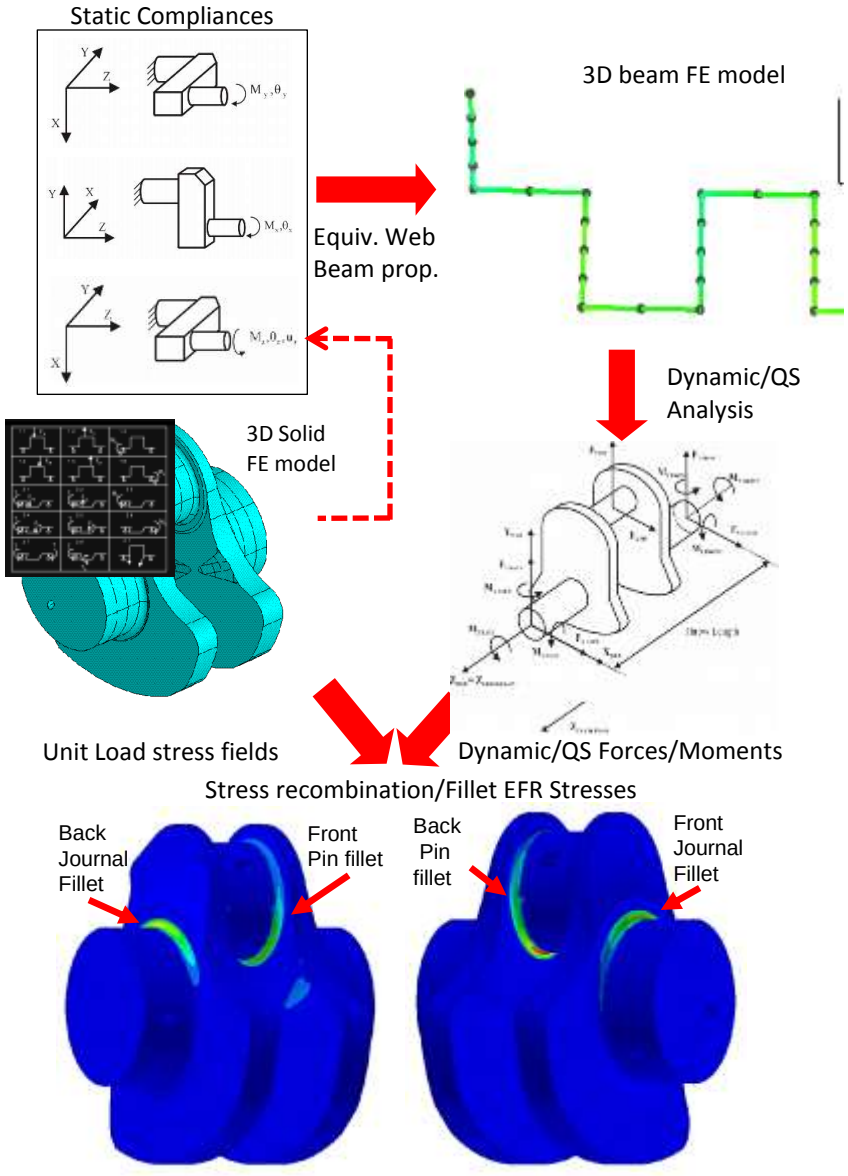
Approach

GT-SUITE吸收了康明斯曲轴分析的经验，并将GT-SUITE结果与康明斯内部工具进行了对比测试及验证。

Results

2年多的项目已经完成，GT-SUITE完全能够满足并超出康明斯的预期要求。

Fast Crankshaft Durability Analysis



Objective

曲轴耐久性，满足快速分析，DOE，优化

Value Proposition

3D静态FE模型集成3D梁FE模型，进行动力学或者准静力学分析，计算EFR 应力

Approach

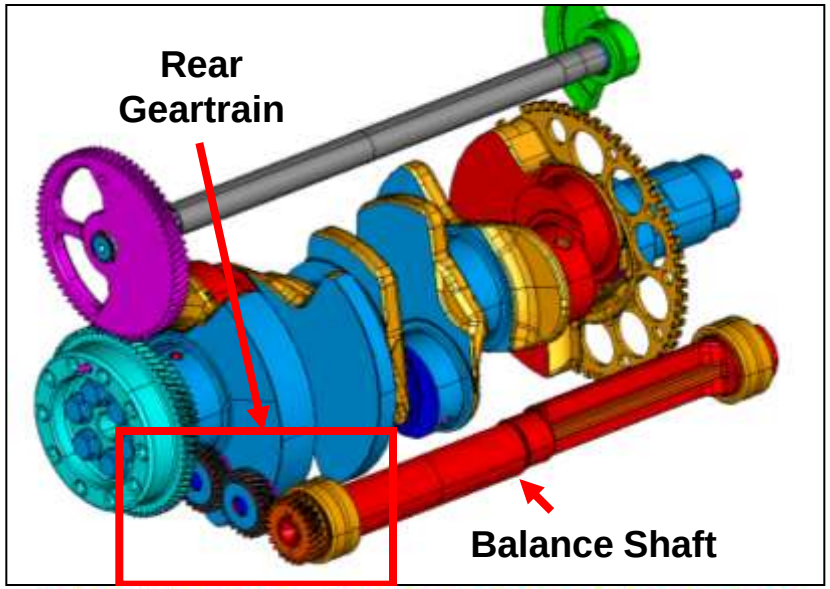
使用一个3D实体FE模型描述一个当量的3D梁FE模型。结合动态/静态有限元结果和QS的梁单元荷载应力的三维有限元应力场，重现动态应力。计算节点和最大应力的均值和EFR / min，最大应力，整体功能和故障概率。

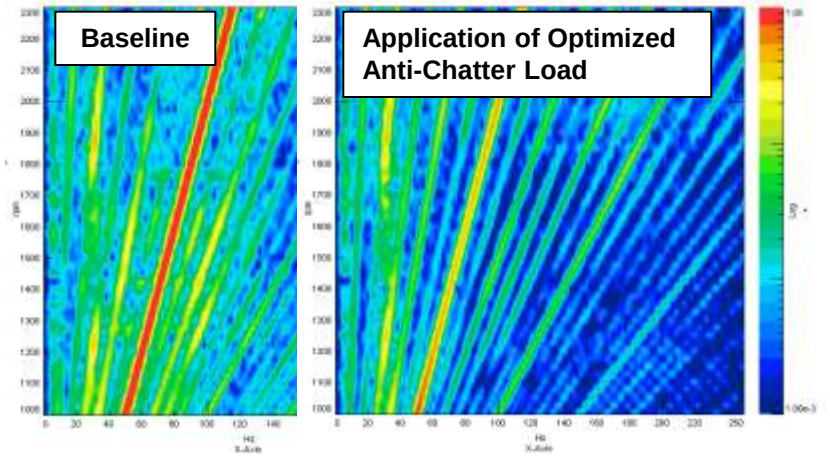
Results

GT-SUITE现在已经具备这种自动化流程并且已经与康明斯内部程序进行了验证。

Geartrain Modeling

Geartrain Chatter





Objectives

消除二阶平衡轴齿轮颤振（敲击）

Value Proposition

GT-SUITE提供快速的，系统级的齿轮建模，包括渐开线接触齿轮模型。模型可以很容易集成在曲轴和气门机构系统里，考察相互的作用

Approach

1 建立完整的齿轮副模型（包括齿轮间隙）

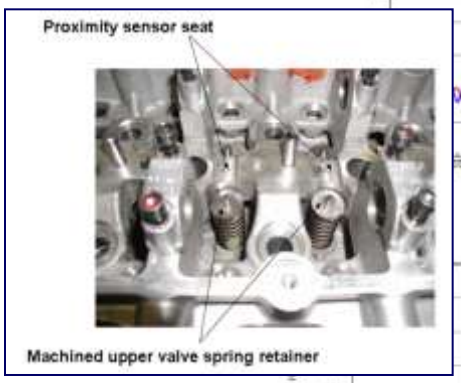
2模型与试验数据验证

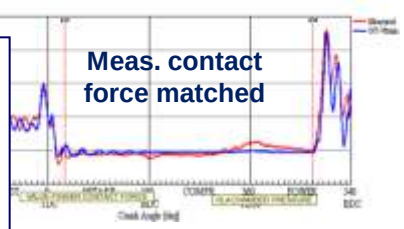
3优化真空泵的负荷要求（远离平衡轴）使齿轮的齿接触时可连续运行

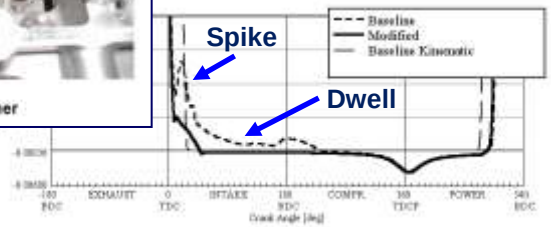
Results

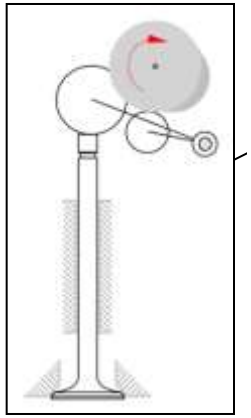
减少用于试验测试的时间及成本，节省时间用于评估及优化设计方案

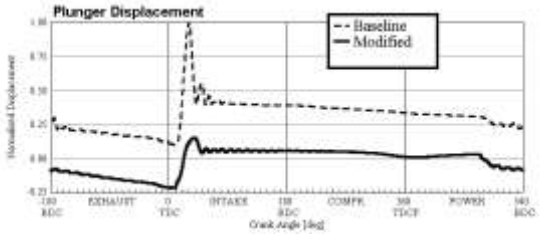
Exhaust Valve Behavior with a DPF

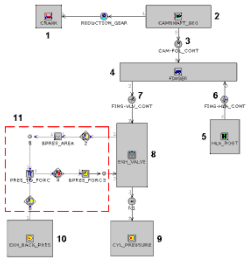


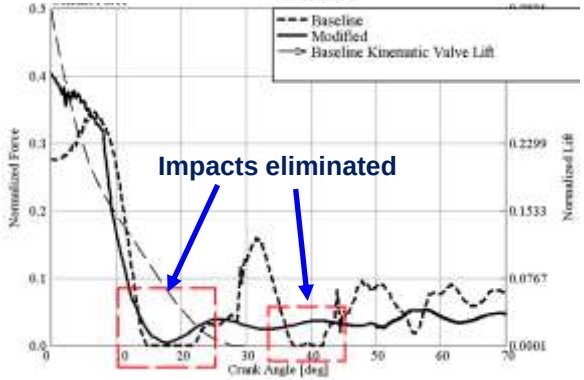












Objectives

高的DPF背压下进行仿真，理解和消除排气门关闭前的“Spike”和“Dwell”现象。

Value Proposition

GT-Vtrain非常适合于这种集成的研究，可以将一个” well tuned”的排气阀机构与DPF的集成。

Approach

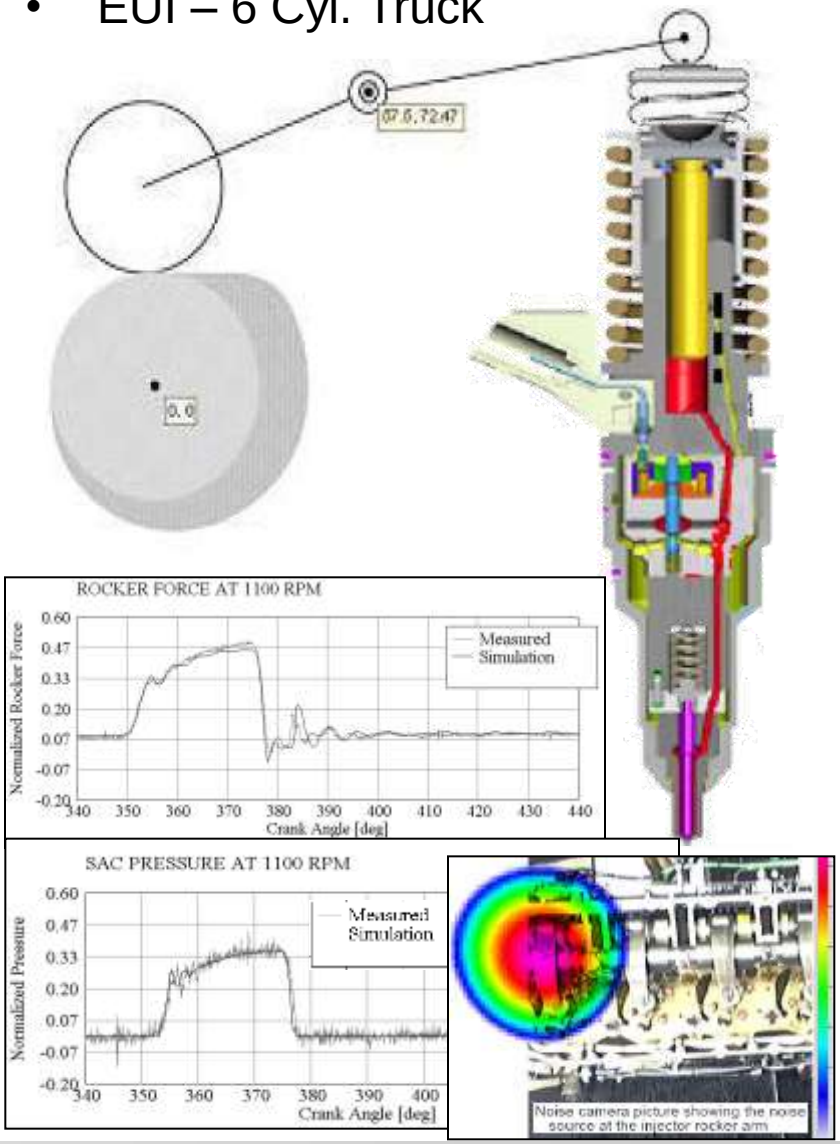
配气机构动力学，气道/气缸内气体压力，HLA液压系统的集成，可研究系统间相互作用，进行准确的预测。

Results

设计的改进被证明可以消除不良现象，并减少冲击力。

Cam-rocker Activated Unit Injector Noise

- Noise Analysis
- EUI – 6 Cyl. Truck



Objectives

新的排放标准和燃油经济性要求的6缸车用柴油机燃油喷射系统的修改。燃烧和排放的考虑－驱动导致机械振动增加的不良后果和相关的噪音水平。

Value Proposition

喷油器和凸轮轴驱动的机械系统内喷射系统液压和机械部件的动力学之间存在强相互作用。预测设计需要集成的流体-机械模型。

Approach

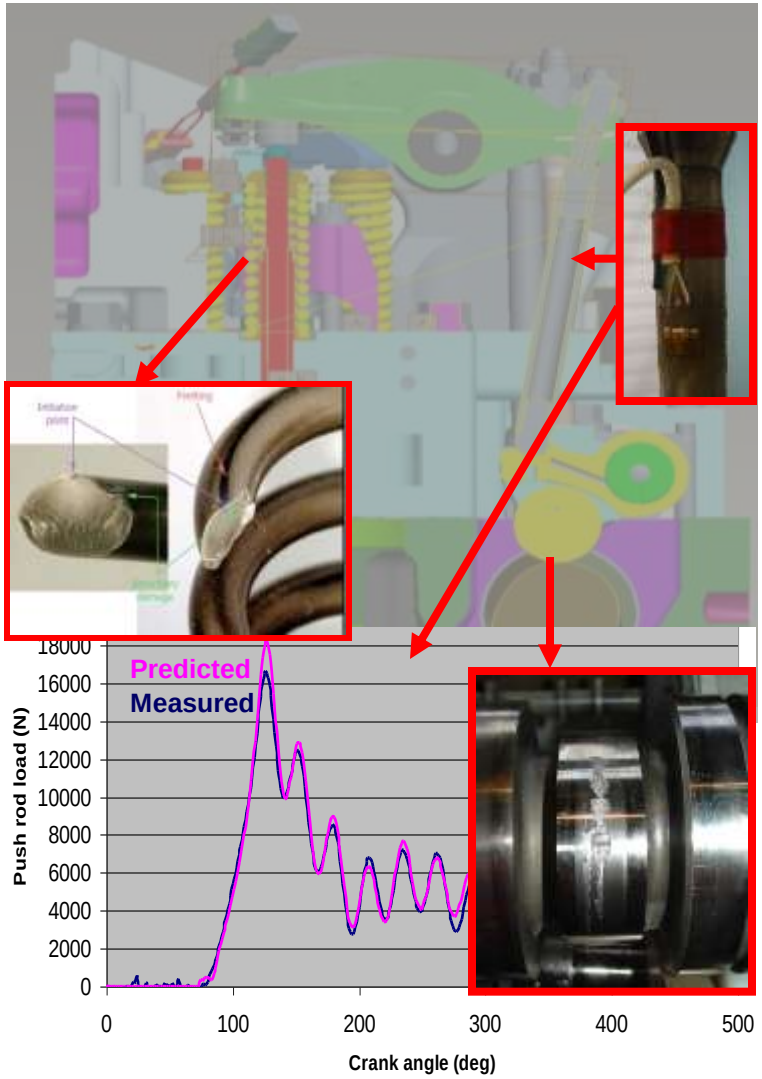
GT–Fuel的液压与机械模型使用相同的建模环境：它提供了设计的灵活性与高效性。

Results

完整的模型解释了实测振动增加的原因。模型用来在整体设计方案中寻找最优的解决方案。几个设计的更改进行验证和量化他们在降低振动水平的贡献

Valvetrain Failure Analysis

High Horsepower Engine



Objectives

- 评价设计方案来解决凸轮和滚轮磨损（点蚀）
- 评价设计方案避免阀线圈冲突

Value Proposition

- gt-vtrain提供了一个组合的赫兹接触和HD油膜的解决方案，可用于凸轮从动件界面预估接触应力和金属对金属的接触凸轮磨损。
- gt-vtrain提供了一个灵活的多质点弹簧模型，可以用来捕捉线圈冲突和计算各种线的几何形状和蜿蜒的方式接触应力。

Approach

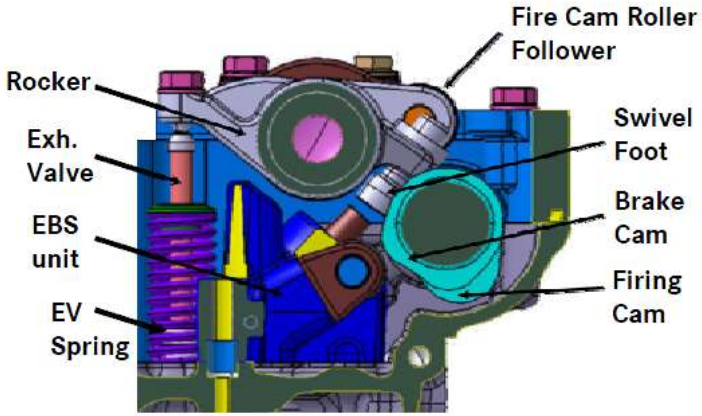
- 模型与试验结果进行验证
- 检查凸轮从动件和多质点弹簧质的结果来确定失效的根本原因。模拟可能的解决方案。

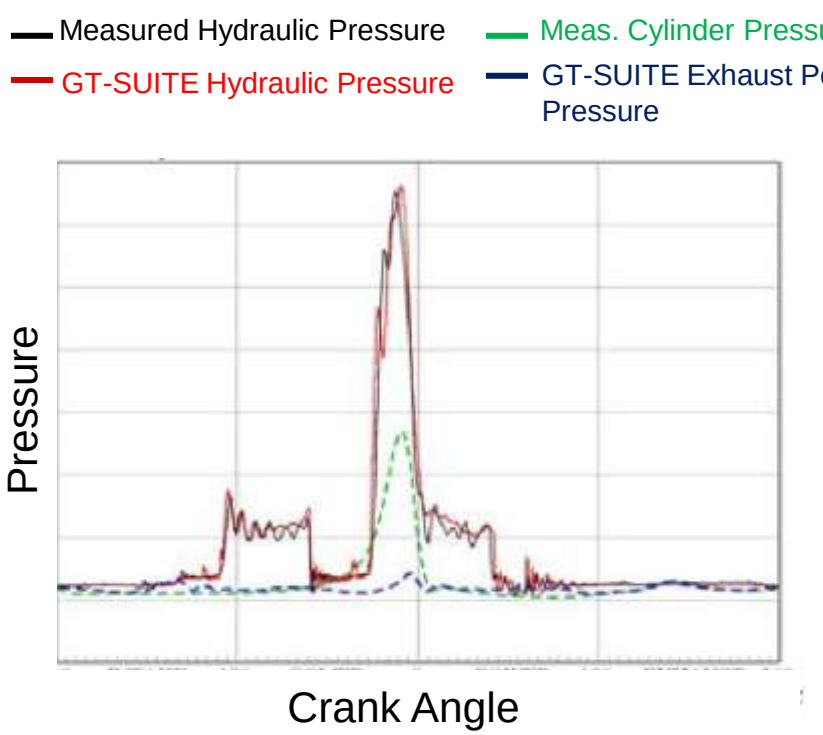
Results

模型的构建，验证和评估所有可能的设计方案在2周内完成。这有助于康明斯避免时间和外包等项目相关的成本。

Hydraulic Engine Brake

DAIMLER





Objectives

-模型的液压制动系统和相关的测量数据

-集成的液压模型与系统优化，详细的发动机模型的瞬态研究

Value Proposition

-GT-SUITE提供一个详细的和高精度的液压系统模型

-液压系统可以很容易地与一个详细的发动机（GT-POWER）模型集成来减少总的仿真时间和进行系统级的优化

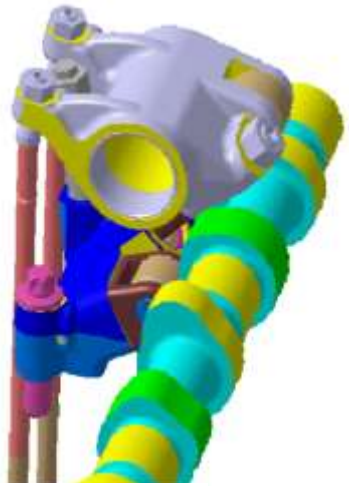
Results

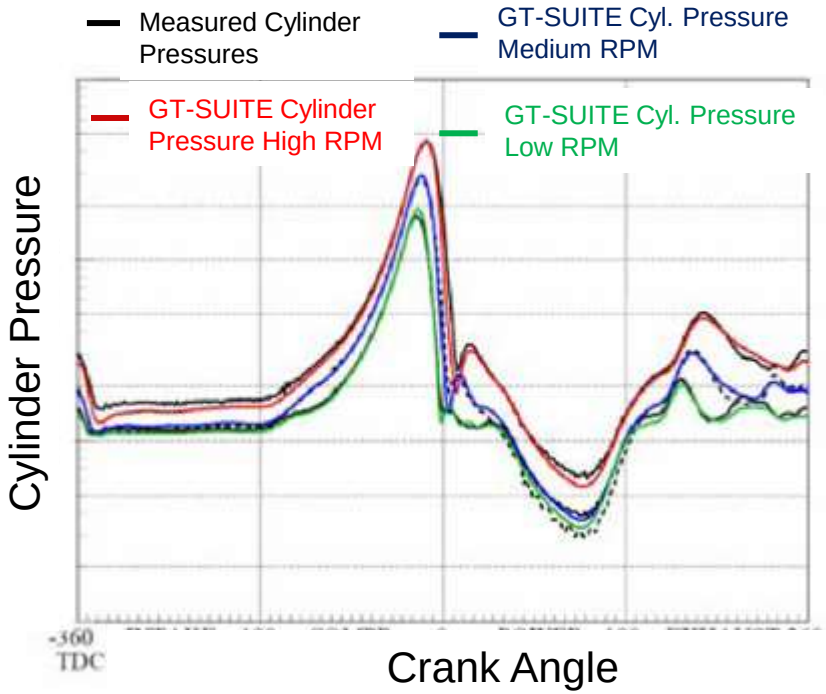
-液压制动模型准确地预测液压系统产生的压力，模型能够液压制动器的优化设计
-结果表明，2个系统的集成进行准确的系统预测是必要的，并能够减少模拟时间
-集成的模型可用于系统级优化

GT Gamma Technologies

Hydraulic Engine Brake

DAIMLER





Objectives

模型的液压制动系统，根相关的测量数据进行修正

集成的液压模型与系统优化，详细的发动机模型的瞬态研究

Value Proposition

-GT-SUITE提供一个详细的和高精度的液压系统模型

-液压系统可以很容易地与一个详细的发动机（GT-POWER）模型集成来减少总的仿真时间和进行系统级的优化

Results

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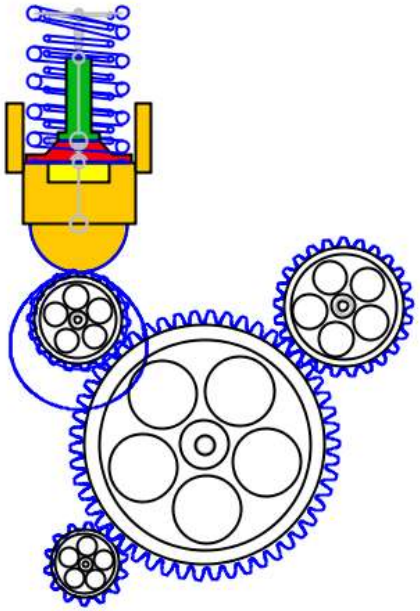
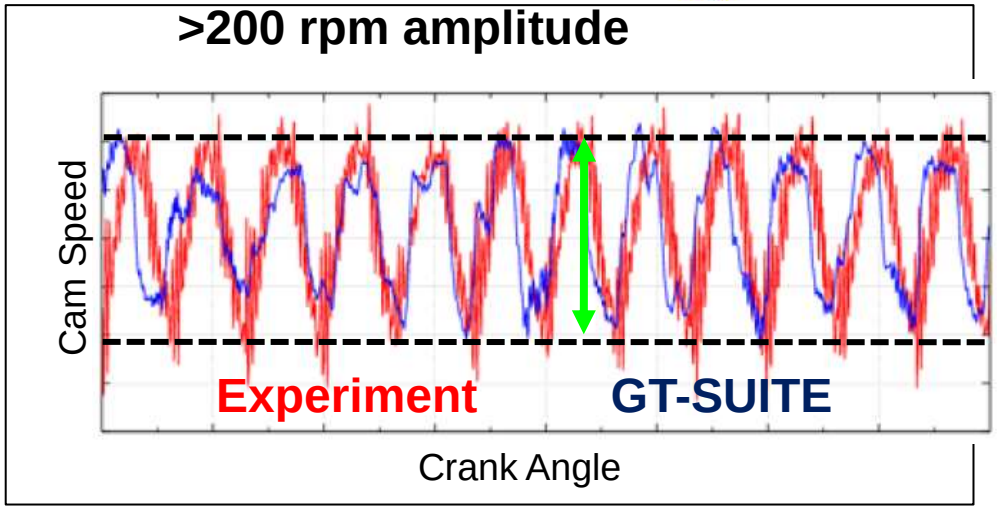
-结果表明，2个系统的集成进行准确的系统预测是必要的，并能够减少模拟时间
-集成的模型可用于系统级优化

GT Gamma Technologies

Geartrain Analysis for High Pressure Pump





Objectives

找出原因和消除齿轮驱动高压燃油泵凸轮的失效

Value Proposition

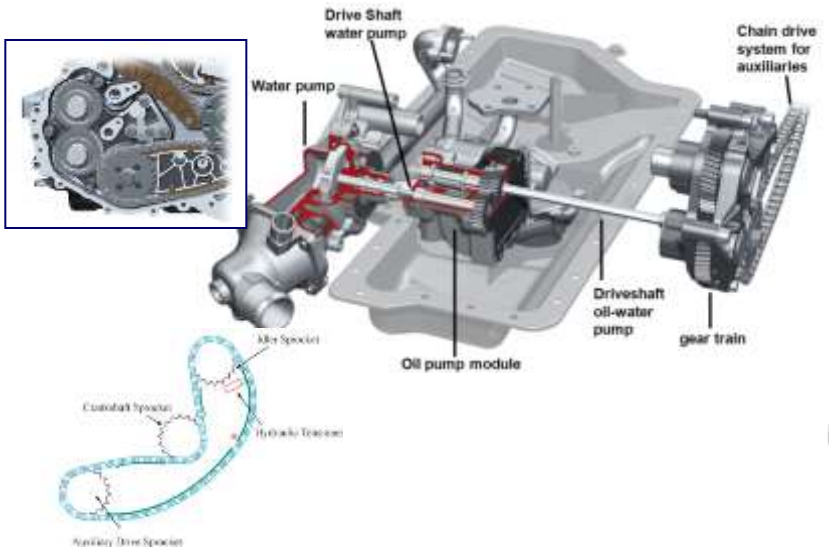
-GT-SUITE提供模型的液压能力（高低压系统），在凸轮从动件界面摩擦学全凸轮轴和齿轮系。

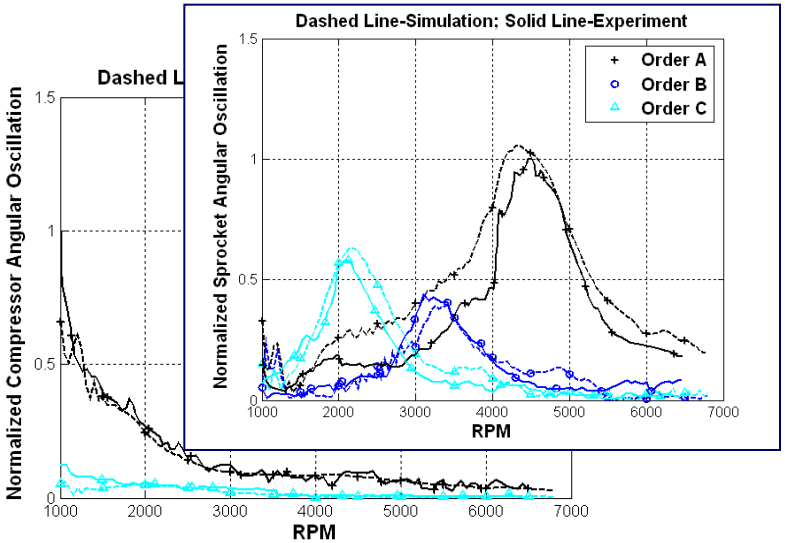
-详细的齿轮动态模型与齿轮啮合刚度的计算

Results

–喷油泵凸轮的速度出现在给定的标称测量凸轮振动速度模拟再现
–模拟用来选择解决问题的方案
–选择的解决方案进行测试实验，并与模拟预测的结果非常匹配

Combined Chain+Gear Drive Dynamics





Objectives

对驱动附件(油，冷却液，转向泵，空调压缩机）的齿轮-链传动系统动力学仿真（在发动机的转速范围内)

Value Proposition

集成GT-SUITE的模型，分析复杂齿轮-链驱动模型

Approach

在GT-SUITE中很容易建立一个完整的传动系统模型

Results

预测的角振荡谐波在发动机速度测量范围内与测试值吻合。即使简化的齿轮接触模型也能达到很好的匹配。