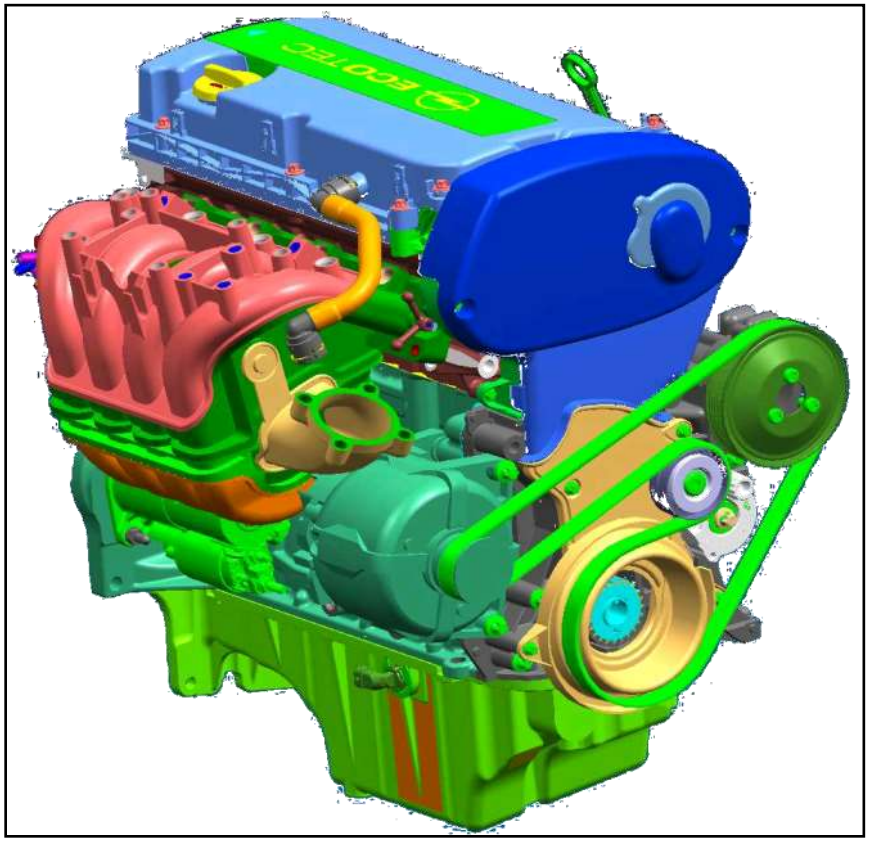
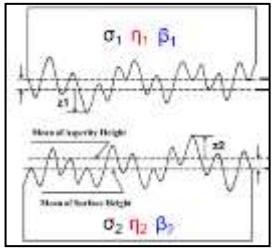
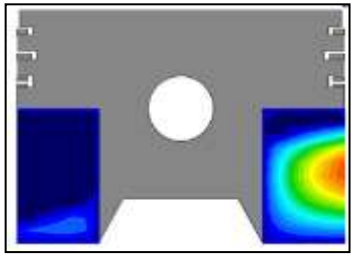
GT-SUITE
在发动机摩擦中的分析应用







2013.12.20

Gamma Technologies

主要内容

1 GT-SUITE在发动机摩擦中的预测分析与模拟
- 动机、原因和需求
- GT-SUITE能提供的关键技术
- 发动机摩擦模拟的关键模板
- 校核

2 摩擦和润滑;

3 应用分析

4 Q&A, 讨论

应用“前瞻”

- 对于发动机的轴承，什么样的间隙是合适的？什么样的入口润滑油温度是合适的?
- 在“strip-down”的测试中相关参数， 怎么关联到运行中的发动机摩擦?
- 在发动机的停-起过程中，发动机的摩擦副是什么样的运行状态?

主要内容

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4 Q&A, 讨论

发动机摩擦的预测模拟: 动机

工业界的应用和需求:

1 在概念设计阶段预测设计和运行的条件的影响，在各运行条件下减少摩擦，考虑设计的最优化，使得发动机的摩擦最小

2 在GT-SUITE 发动机动力学模型中，仿真瞬态的缸内摩擦，对于瞬态或停-起状态中的混合动力车来说非常重要 (starting, HEV)

3 对于VTM来说，评估摩擦副的热产生状态

发动机摩擦的预测模拟: 动机

预测 vs. 关联或经验

1　物理模型, 与基本的摩擦原理一致

2　单独模拟发动机的每一个摩擦副

3　瞬态模拟 (与曲轴转角相关)

4　相对于表面、摩擦系数和润滑参数的敏感性分析

困难: 模型必须有以下特点:

- 高精度, 预测必须准确
- 运算快速、使用简便, 适合日常应用

主要内容

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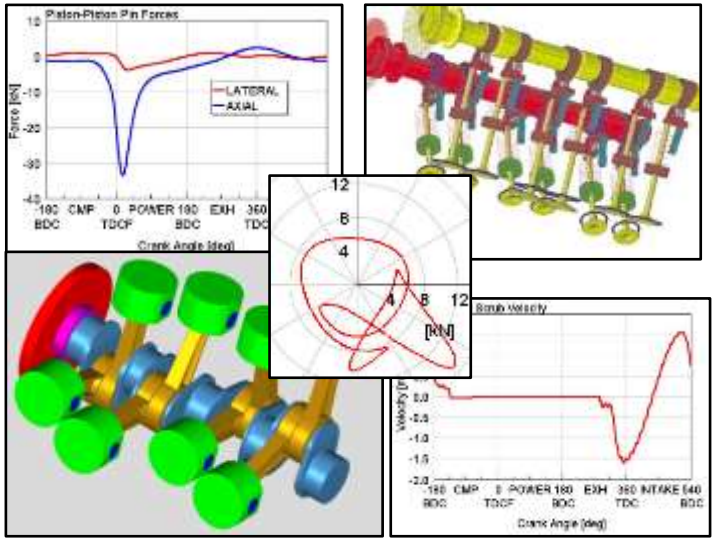
GT-SUITE提供的关键技术 1

Mechanics

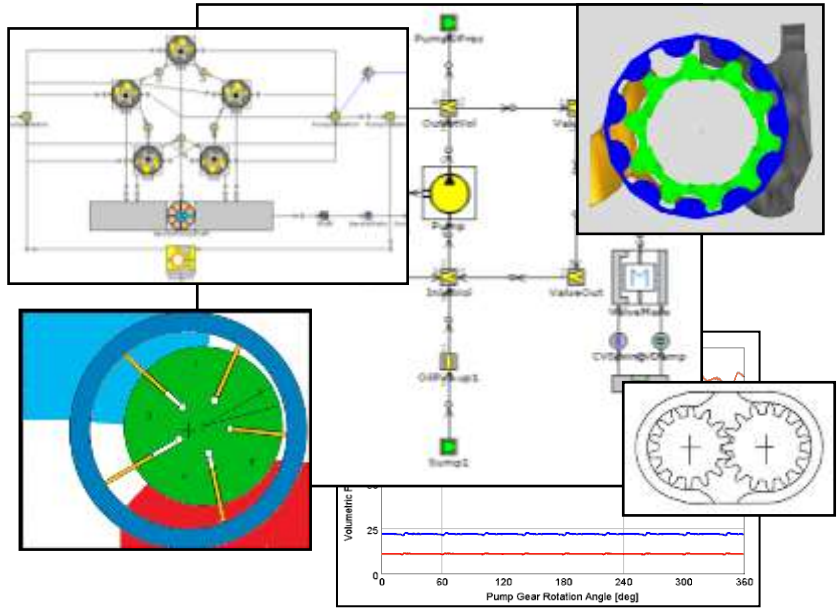
Mechanical Modeling/MBD: Speeds/Loads



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

ThermoFluids

Modeling of Thermal and Fluid Systems, Pressures & Pumping Losses

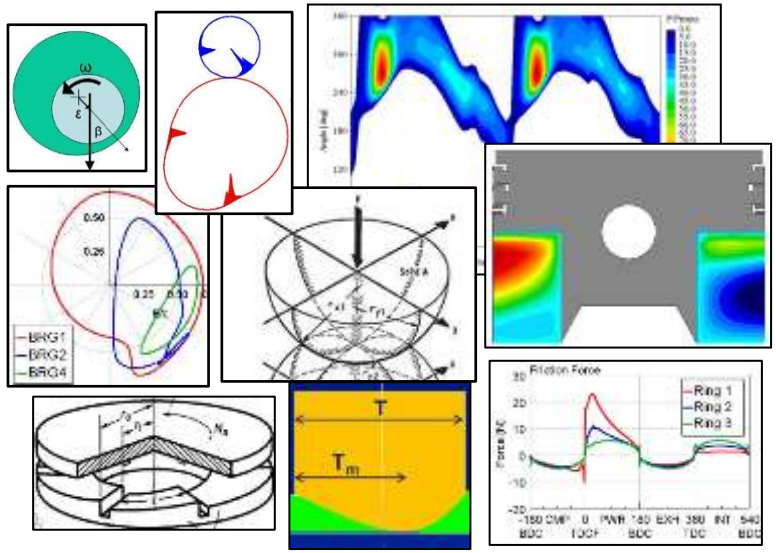


- ✓ Coolant, oil, gas pressures, flow rates, component temperatures
- ✓ Pump PdV work, leakage, friction etc. losses
- ✓ Fluid pressure BCs

GT-SUITE提供的关键技术 2

Tribology: Models

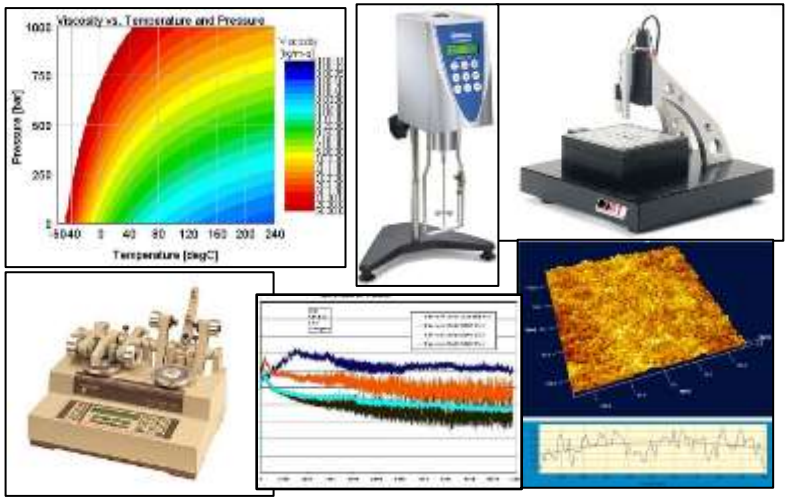
Modeling of Oil Film HD, Surface Roughness Interactions



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

Tribology: Properties

Inputs for/Sensitivity to Laboratory Measurements: Oil, Surface, Friction

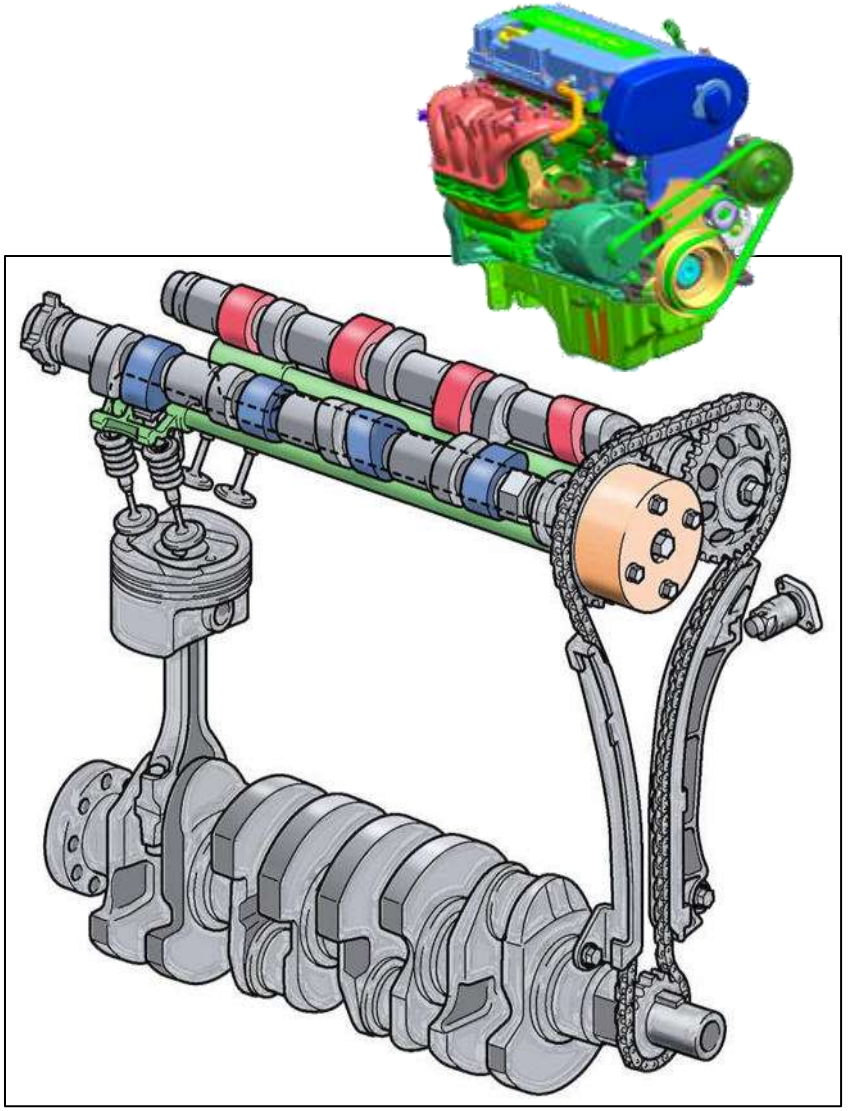


- ✓ Oil viscosity vs. T,P, shear rate
- ✓ Surface roughness
- ✓ Friction and wear coeff. for friction surface matl. pairs

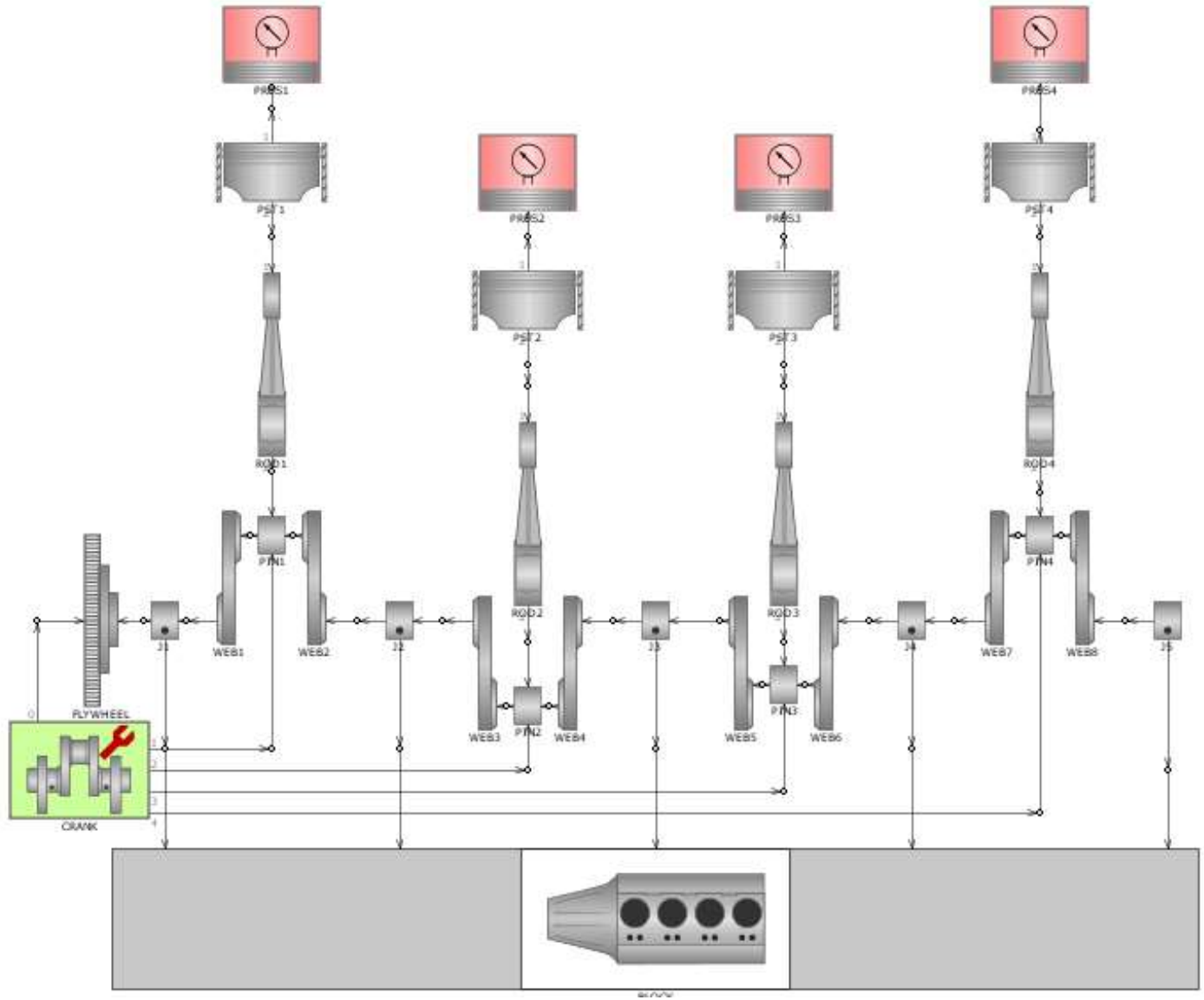
关键的仿真技术- 机械/MBD

速度, 负荷

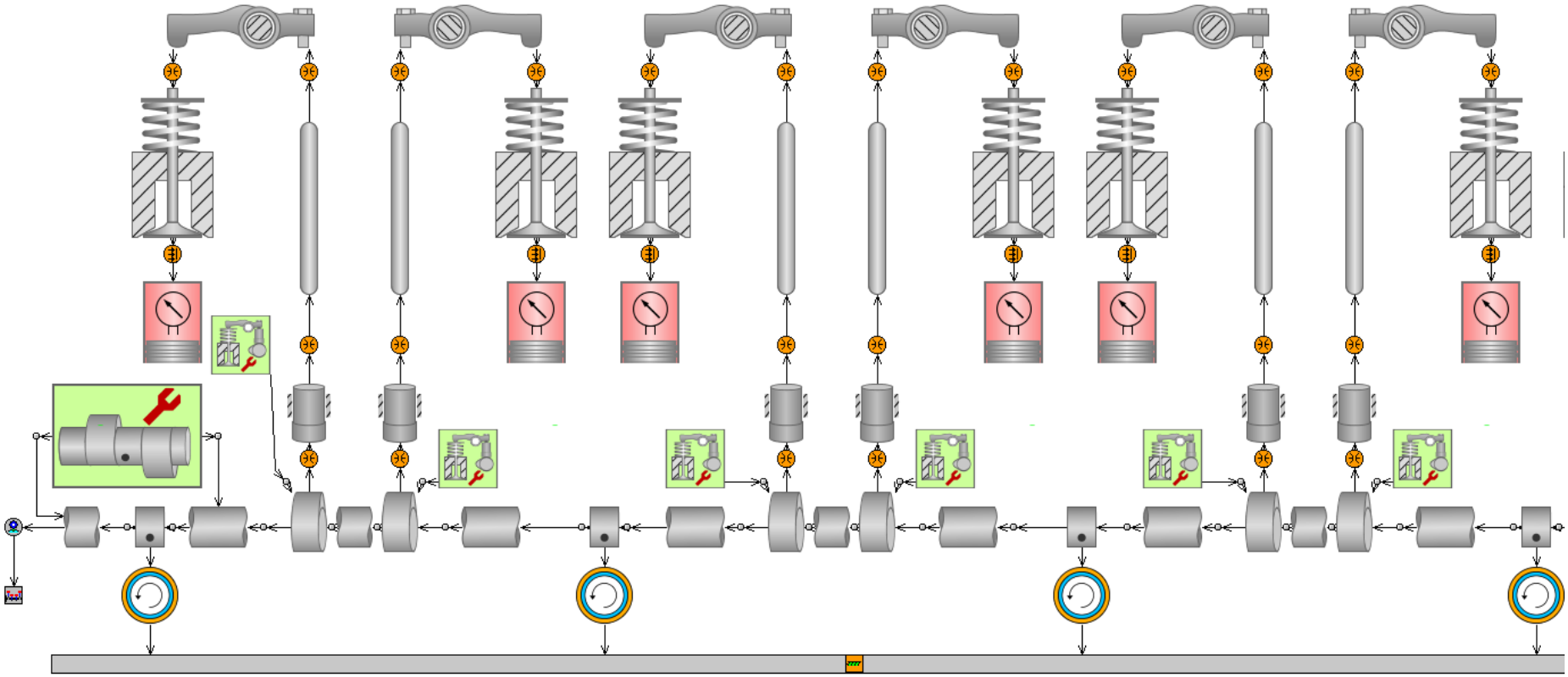
- 曲柄连杆机构,平衡轴
- 配气机构,凸轮轴
- 齿轮、链条、和带传动
- 增压器和各种泵
- 基于最通用的2-D/3-D (rigid/flex) MBD
- 通过高水平的部件系统联合仿真完整的发动机的机械系统
- 与发动机（GT-POWER）和/或润滑系统无缝的耦合



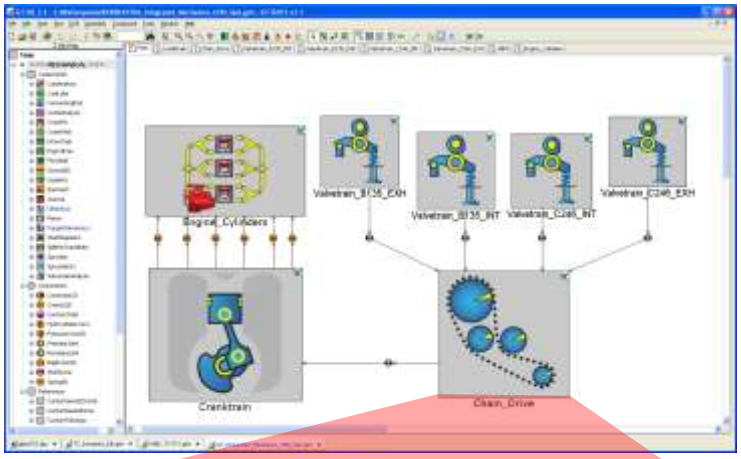
GT-SUITE 发动机机械仿真(Cranktrain)

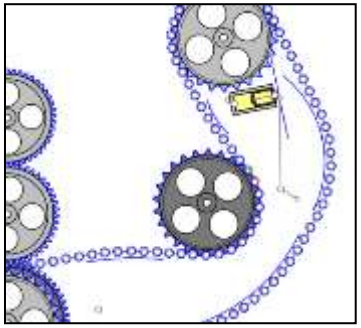


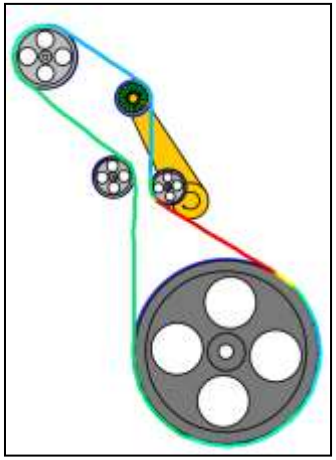
GT-SUITE 发动机机械仿真(Valvetrain)

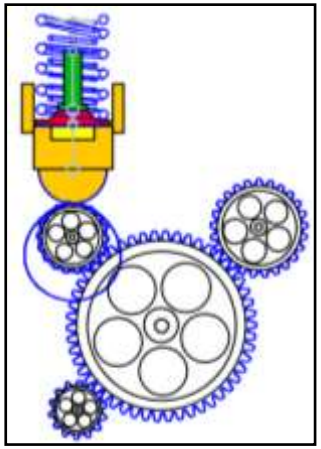


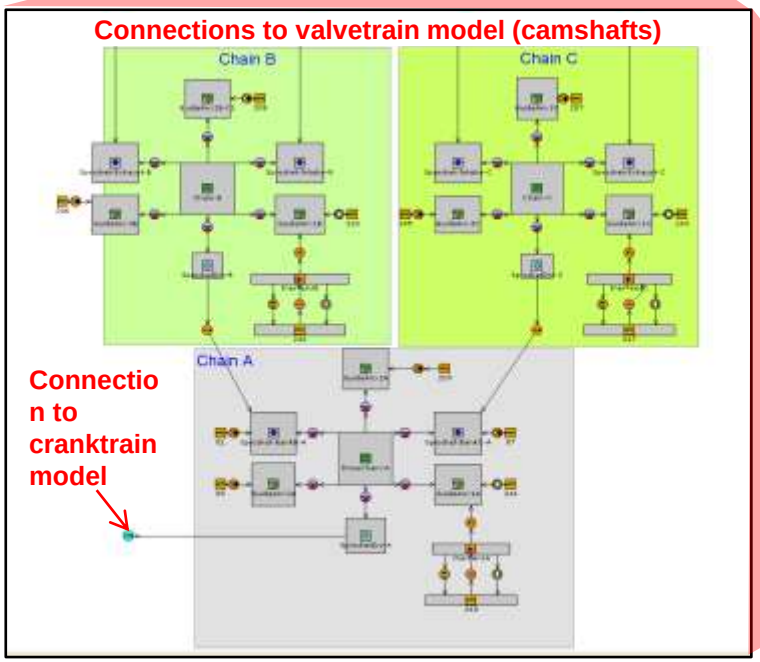
GT-SUITE 发动机机械仿真(Timing Drives)

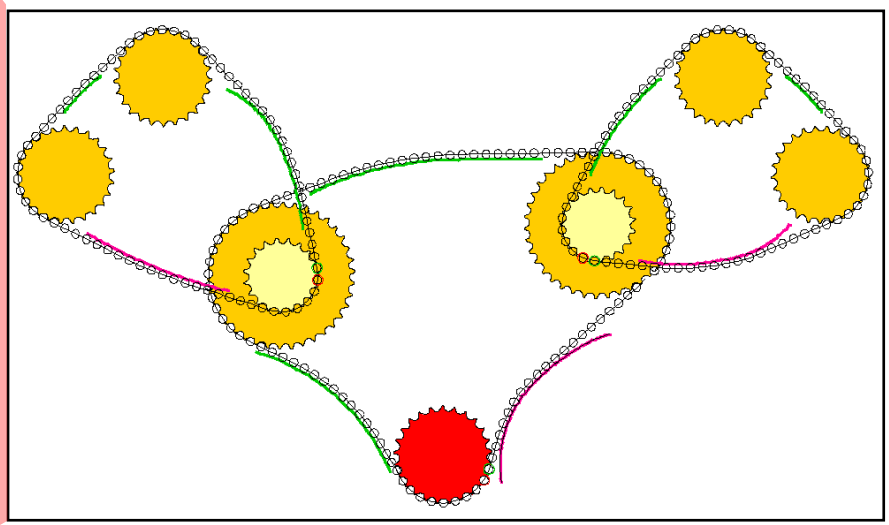






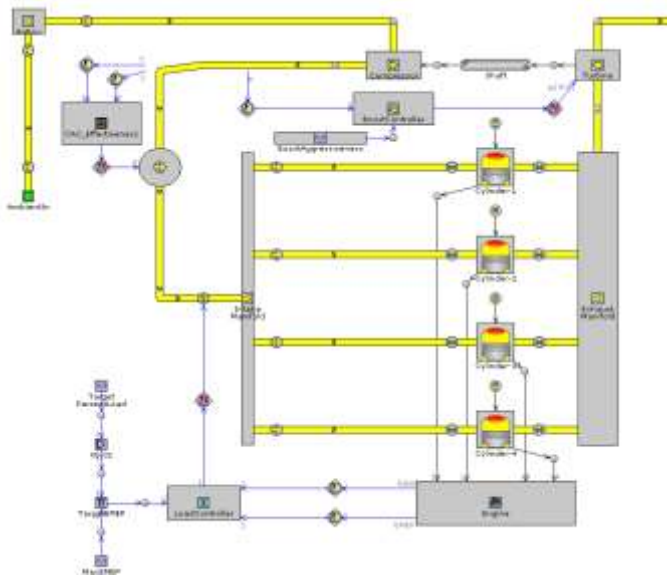




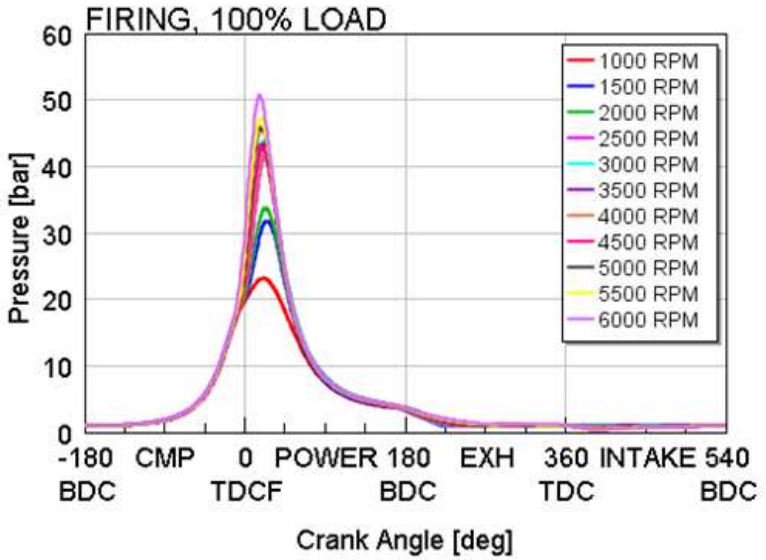


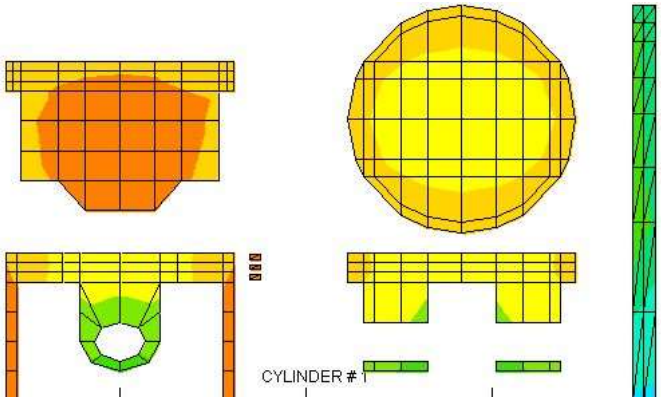
关键的仿真技术- 热流体技术

GT-POWER model

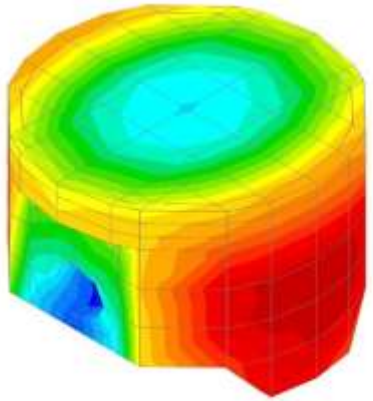


Cylinder Pressures





Piston, ring, liner Temperatures

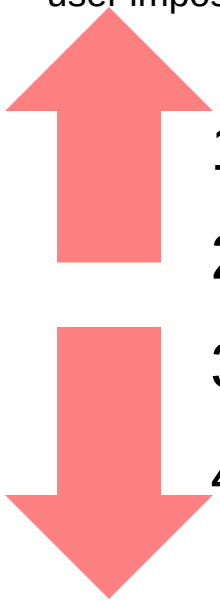


RPM	ΔT
250	0.2
500	0.6
750	1.1
1000	2.0
1250	2.5
1500	3.5

摩擦模拟在GT-SUITE中的应用

在机构中的的摩擦模拟**连接**:

less predictive:
basic geom
user imposed



1 机械连接(运动学的限制1D,2D,3D)

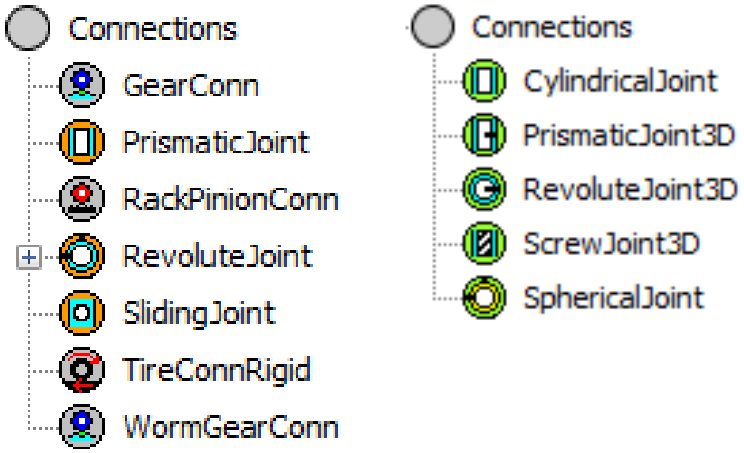
2 滑移摩擦连接(typically 1D)

3 接触副 (between 2D, 3D bodies)

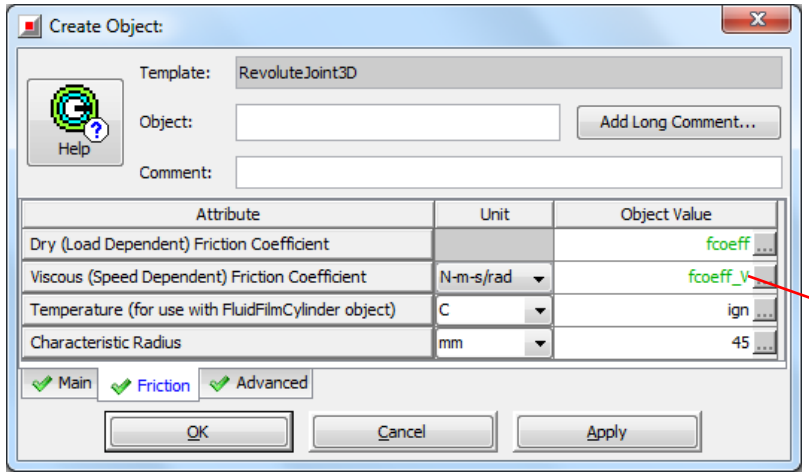
4 HD的油膜连接, 与润滑系统相互作用(1D,2D,3D)

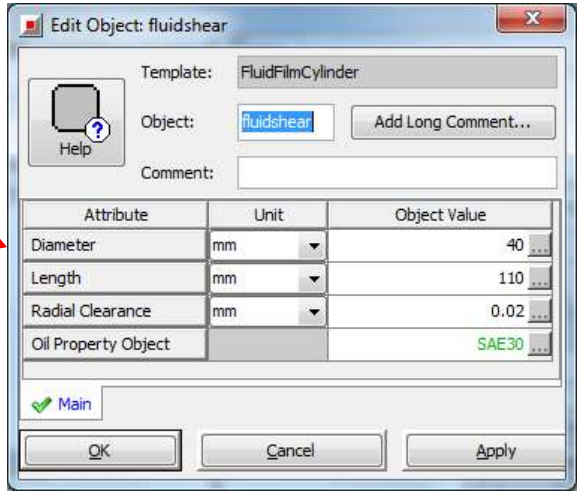
more predictive:
detailed geom
physical model

机械连接中的摩擦

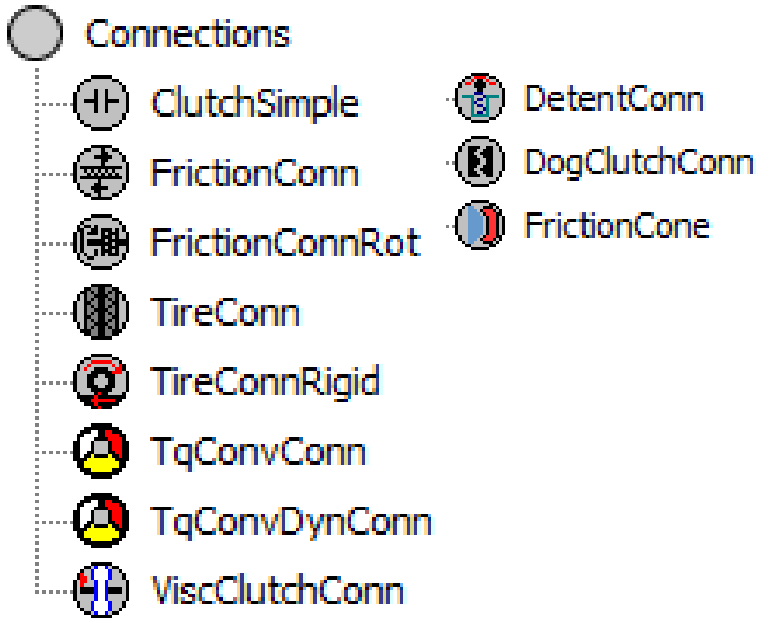


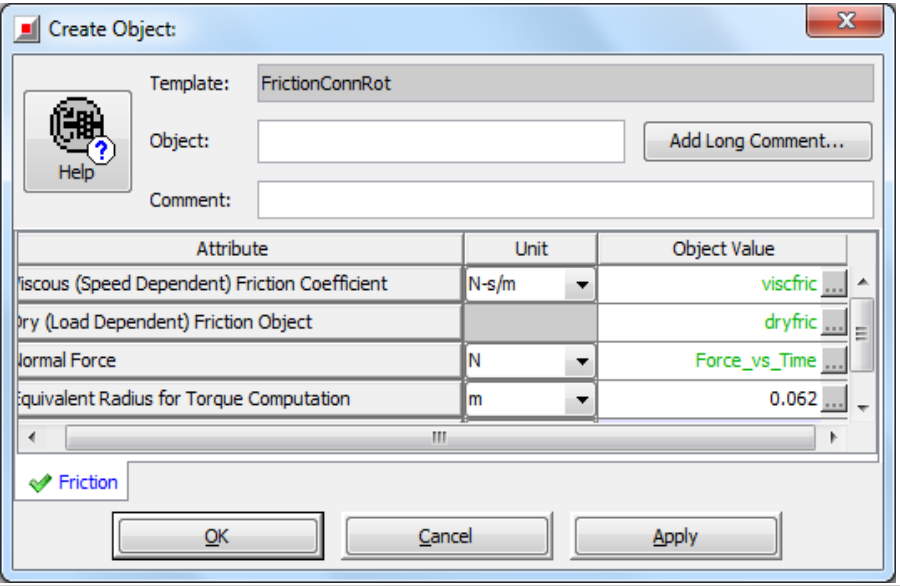
- 2D 或 3D的基本元件
- 运动学或动力学的连接，提供速度、载荷
- 摩擦系数（效率）与速度和载荷相关
- 一定程度上的准物理现象： 基于油粘性剪力,油的属性





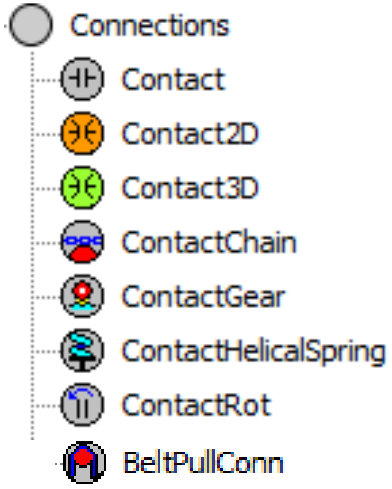
在滑动连接中的摩擦

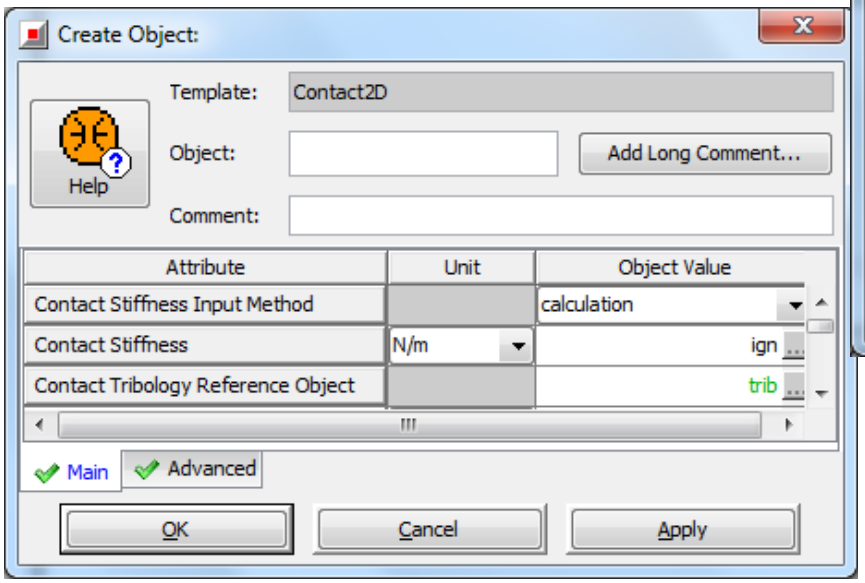


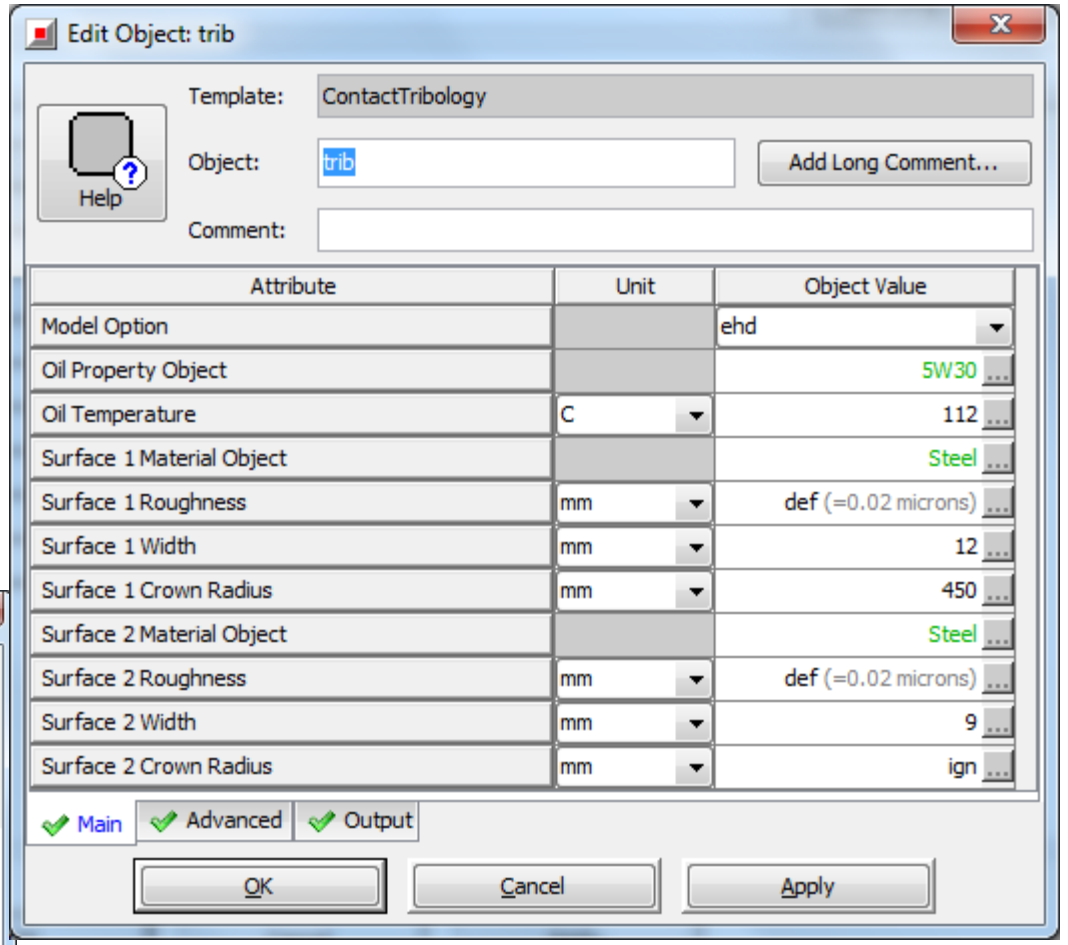


- 1D/1D基本旋转元件
- 正交的负载: 用记定义或外部输入 (离合器的执行力，轮胎负载等.)
- 滑移速度: 根据模型的状态(发动机、变速箱、增压器轴转速、同步器等)
- 图或表的摩擦系数. vs. speed, load
- 特定的准物理模型: 基于粘性剪切应力, 润滑油的属性, LuGre 模型, 液力变有矩器MAP图，等.

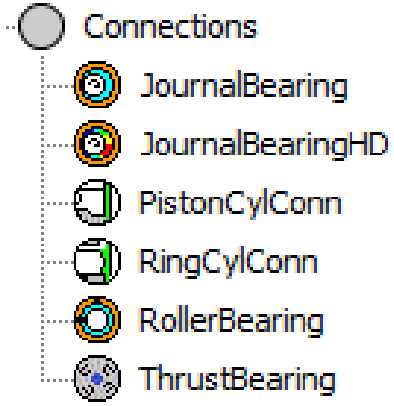
接触摩擦

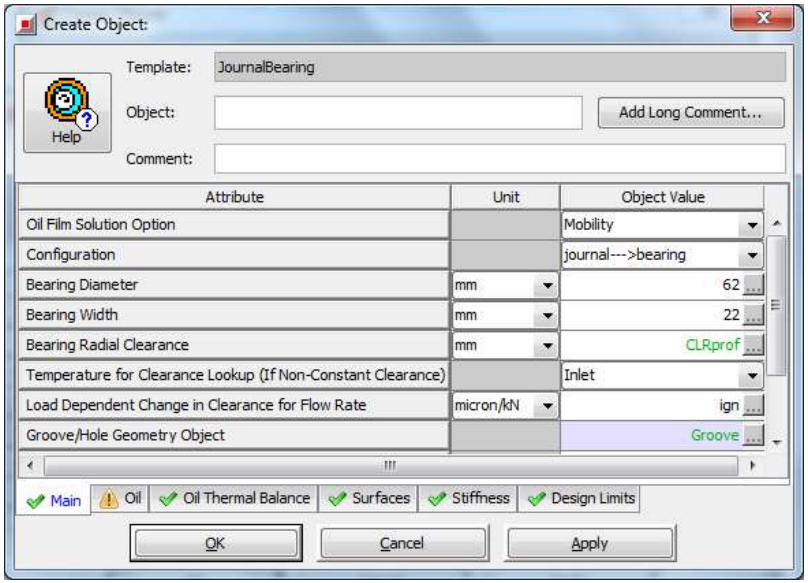






油膜连接的摩擦模拟

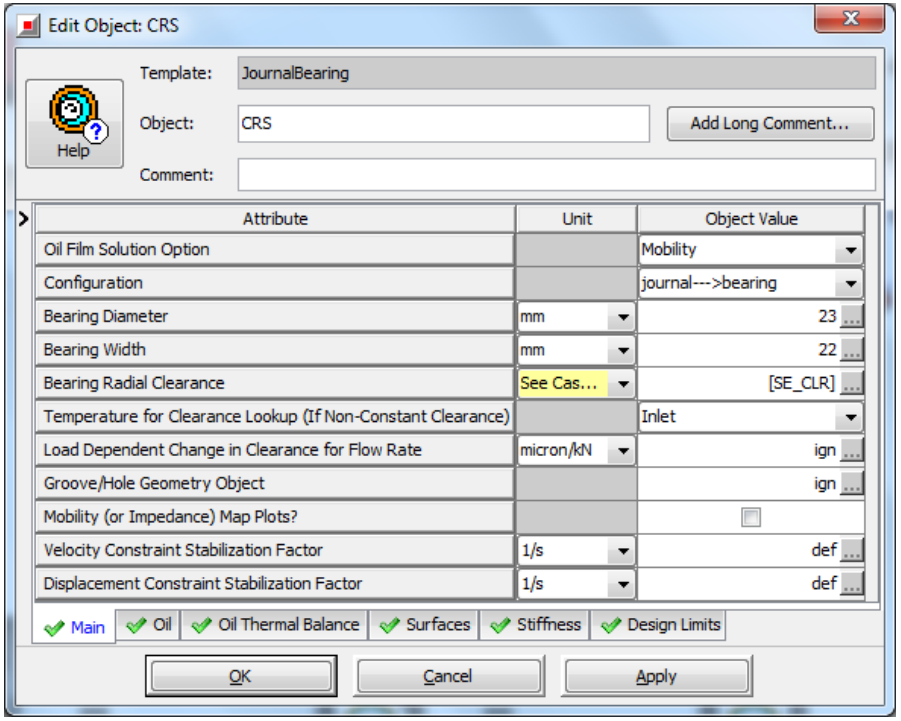


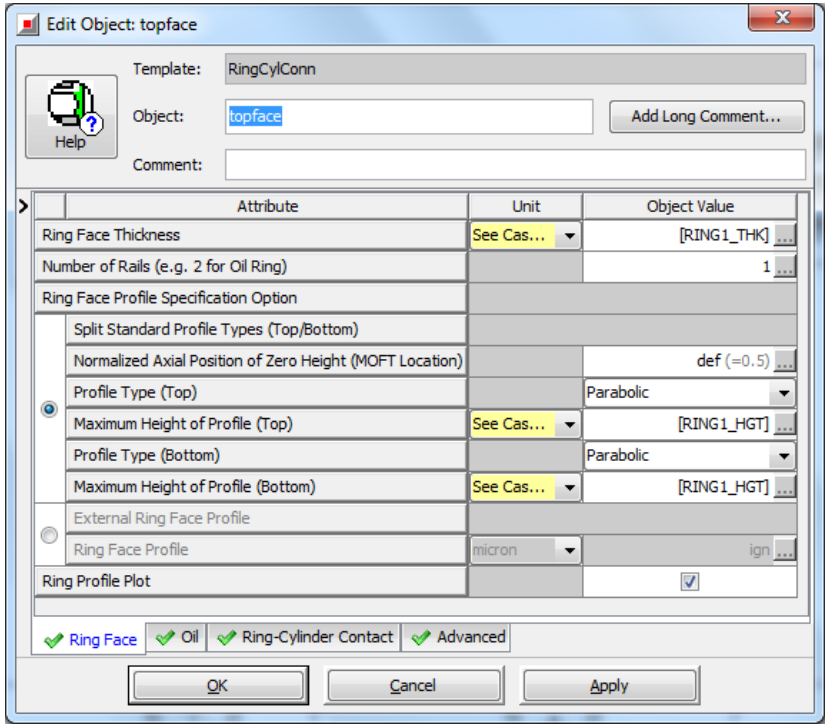


- 适形的润滑界面
- 1D,2D, 3D 机械部件 (2+ dofs)
- 专业化的 拓扑几何/运动, 如： 平面, 圆柱形油膜, 旋转和/或平移的二阶运动
- 表面粗糙度 (粗糙度) 交界面, 混合润滑
- 模型进行HD和接触摩擦混合计算, 而非输入
- 真实的物理现象， 预测

油膜连接– 常规输入

- 不同的几何参数, 用到以下参数:
  - 油压和温度等边界条件 (或者通过计算得到温度边界)
  - 润滑油的属性: OilPropData*, FluidLiq*
  - 表面粗糙度的数据: SurfaceRoughness
  - 表面材料属性: MaterialMechanical



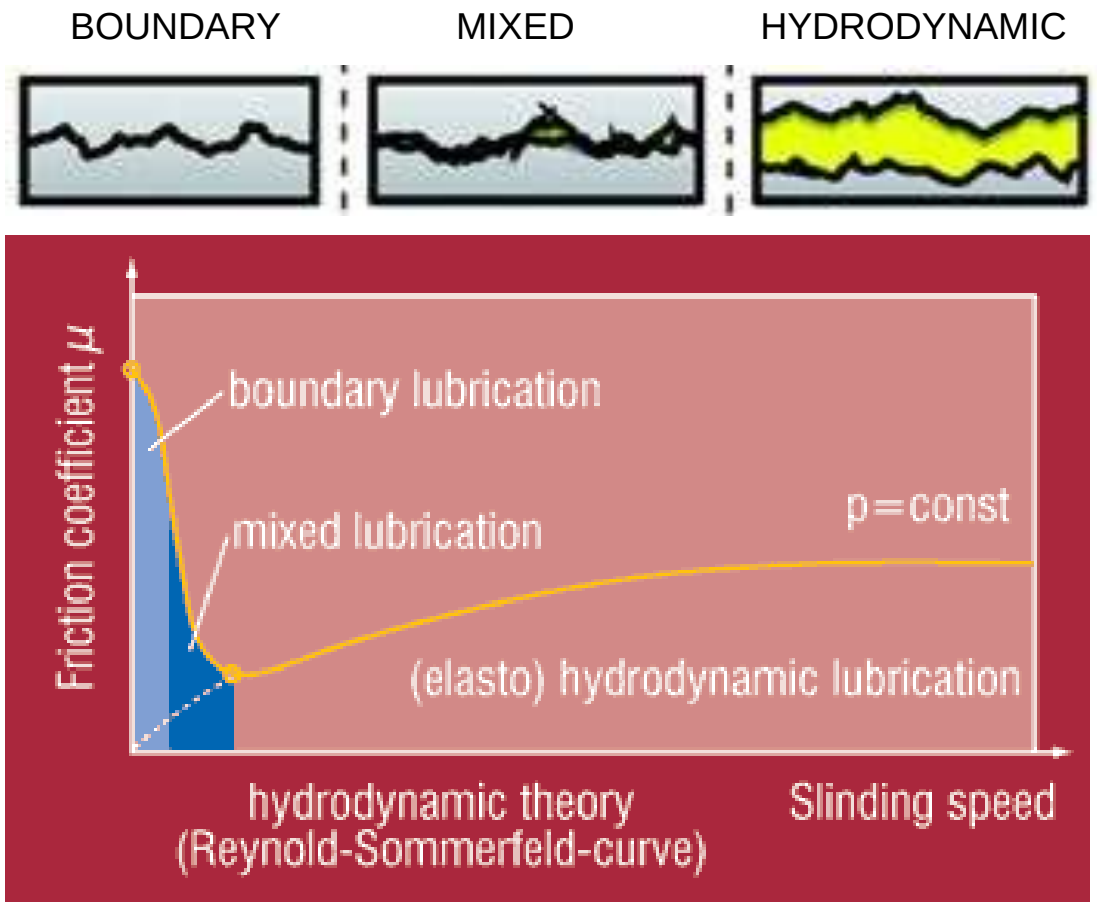


关键的仿真技术– 摩擦学

关键目标:

准确预测：摩擦交界面的状态,是流体润滑、,边界润滑和混合润滑, 必须与以下一致:

- Speeds
- Load
- Geometry
- Lubricant properties
- Surface material properties
- Surface roughness
- Component temperatures



关键的仿真技术– 摩擦学

1 油膜的 HD求解 (Reynolds Eq.) 求解(FD)
- 气缸几何(journal bearings, piston skirt)
- 平面几何(slider bearing, e.g. rings)
- 圆盘/圆环向何(止推轴承)

2 通用的油膜拓扑HD 求解 (FE, mass-conserving, v74)

3 Greenwood-Tripp 粗糙度 (asperity) 接触模型

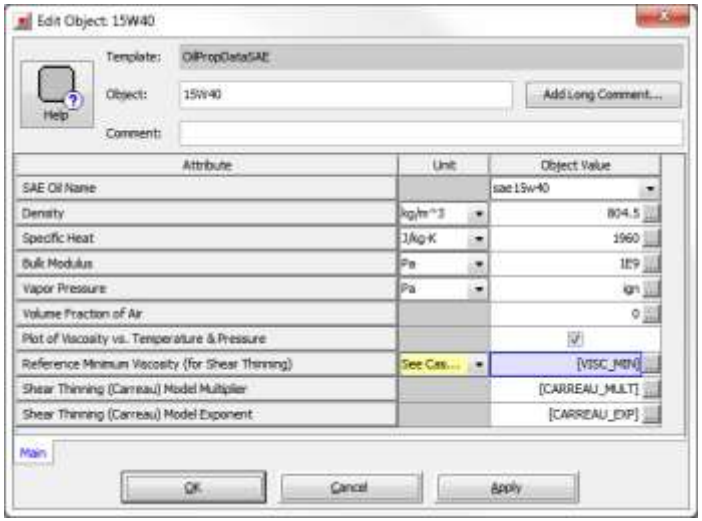
4 Patir-Cheng corrections for roughness effect on film HD

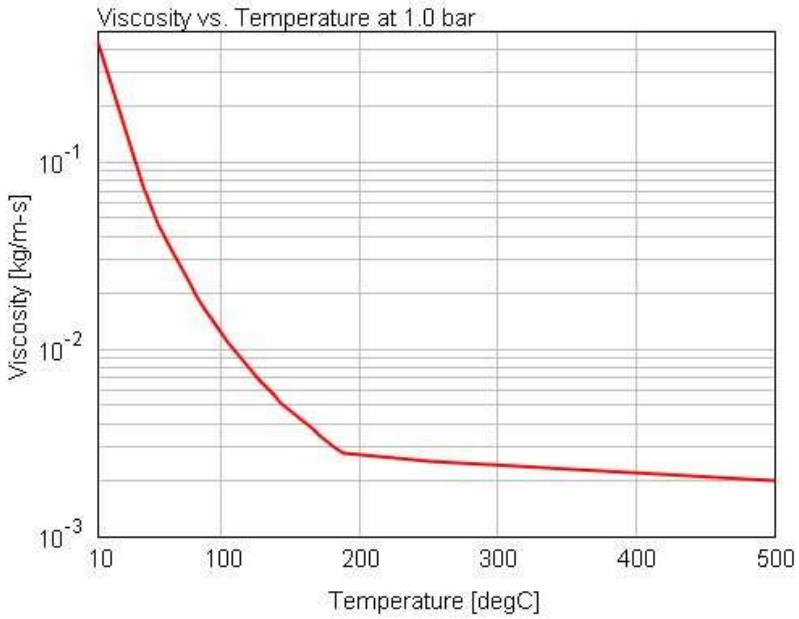
5 Dawson-Hamrock EHD 模型或线/点的接触
-- Valvetrain contacts, ball/needle bearings

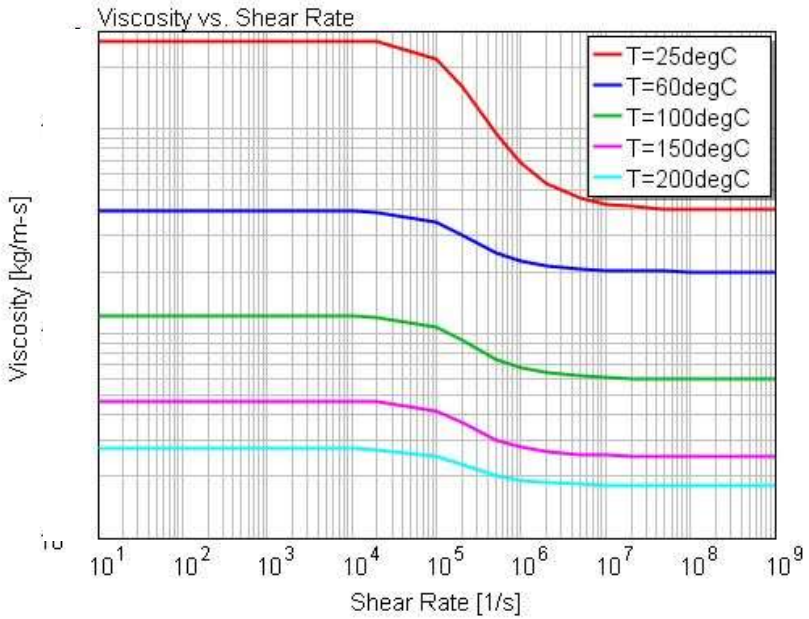
6 油膜的热模拟

关键的摩擦学数据– 油的属性

- 油度的粘度, 影响因子:
  - 温度
  - 压力
  - 剪切速率 (Carreau Eq.)
- 油的密度,比热等

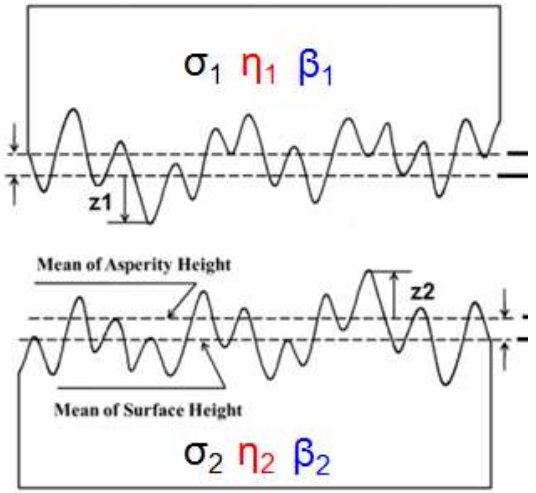


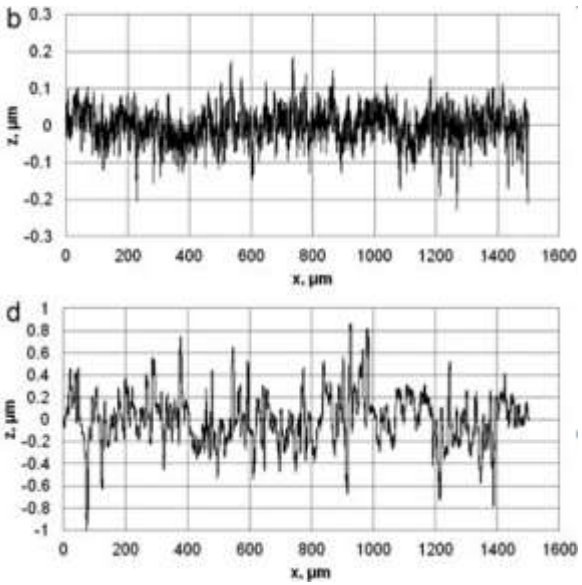




关键的摩擦学数据– 表面粗糙度

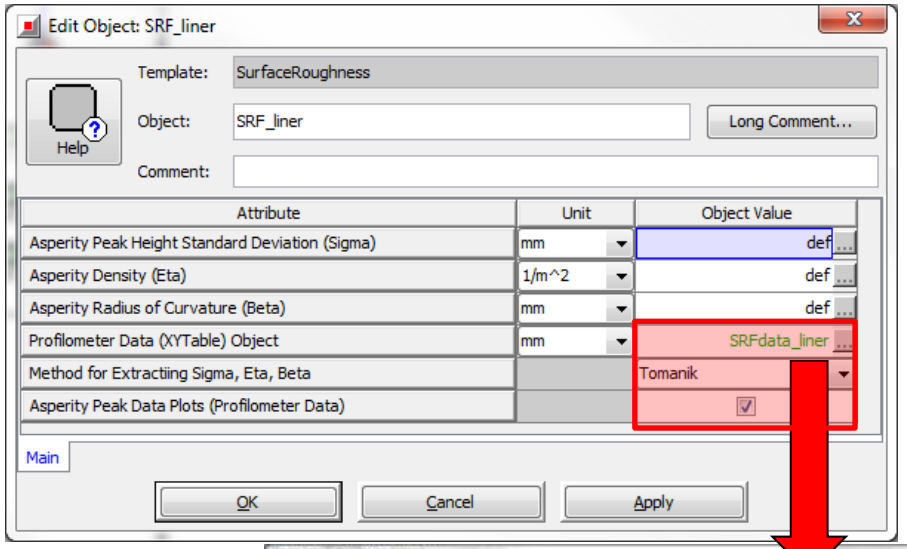
- Greenwood 模型参数
  - σ asperity height standard deviation
  - β asperity peak radius of curvature
  - η asperity density (area^{-1})
- Data available:
  - Raw profilometer measurements
  - Rq, Δq etc.
- σ,β,η have to be calculated from this data



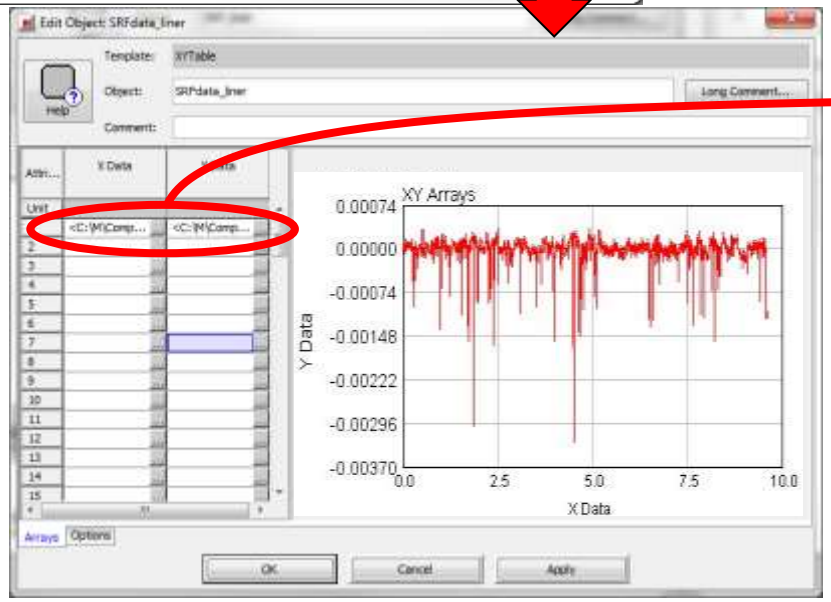


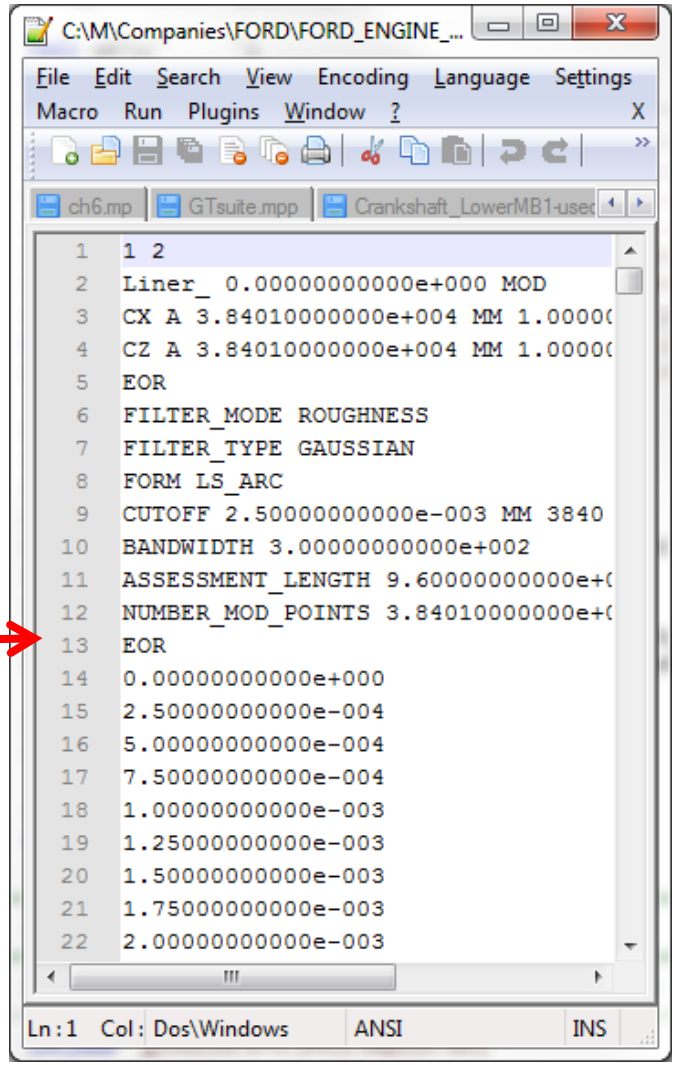
自动抽取粗糙度参数 σ,β,η

SurfaceRoughness object



XYTable object





GT Gamma Technologies

主要内容

1 GT-SUITE在发动机摩擦中的预测分析与模拟

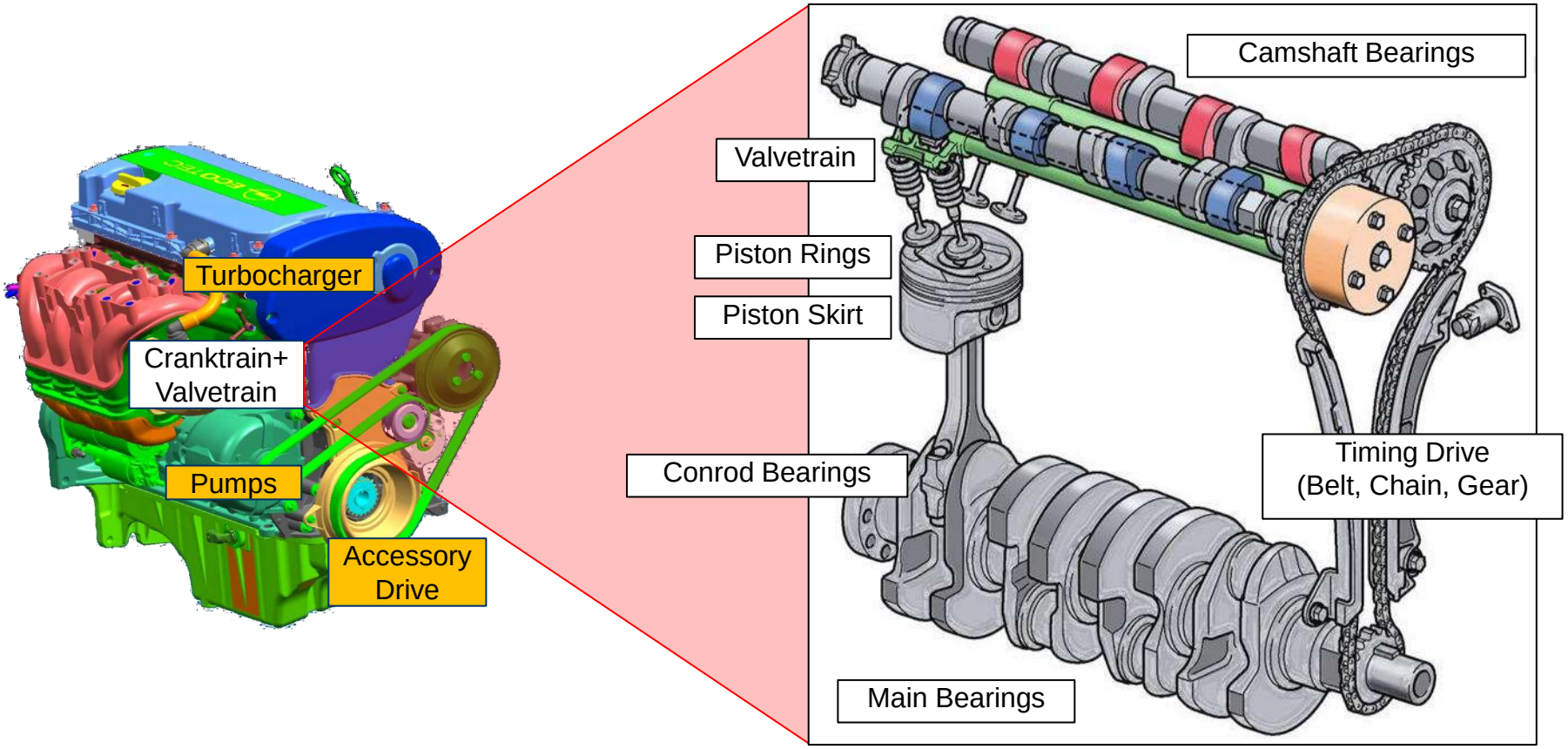
- 动机、原因和需求
- GT-SUITE能提供的关键技术
- 发动机摩擦模拟的关键模板
- 校核

2 摩擦和润滑; v7.5新功能和开发进展

3 应用分析

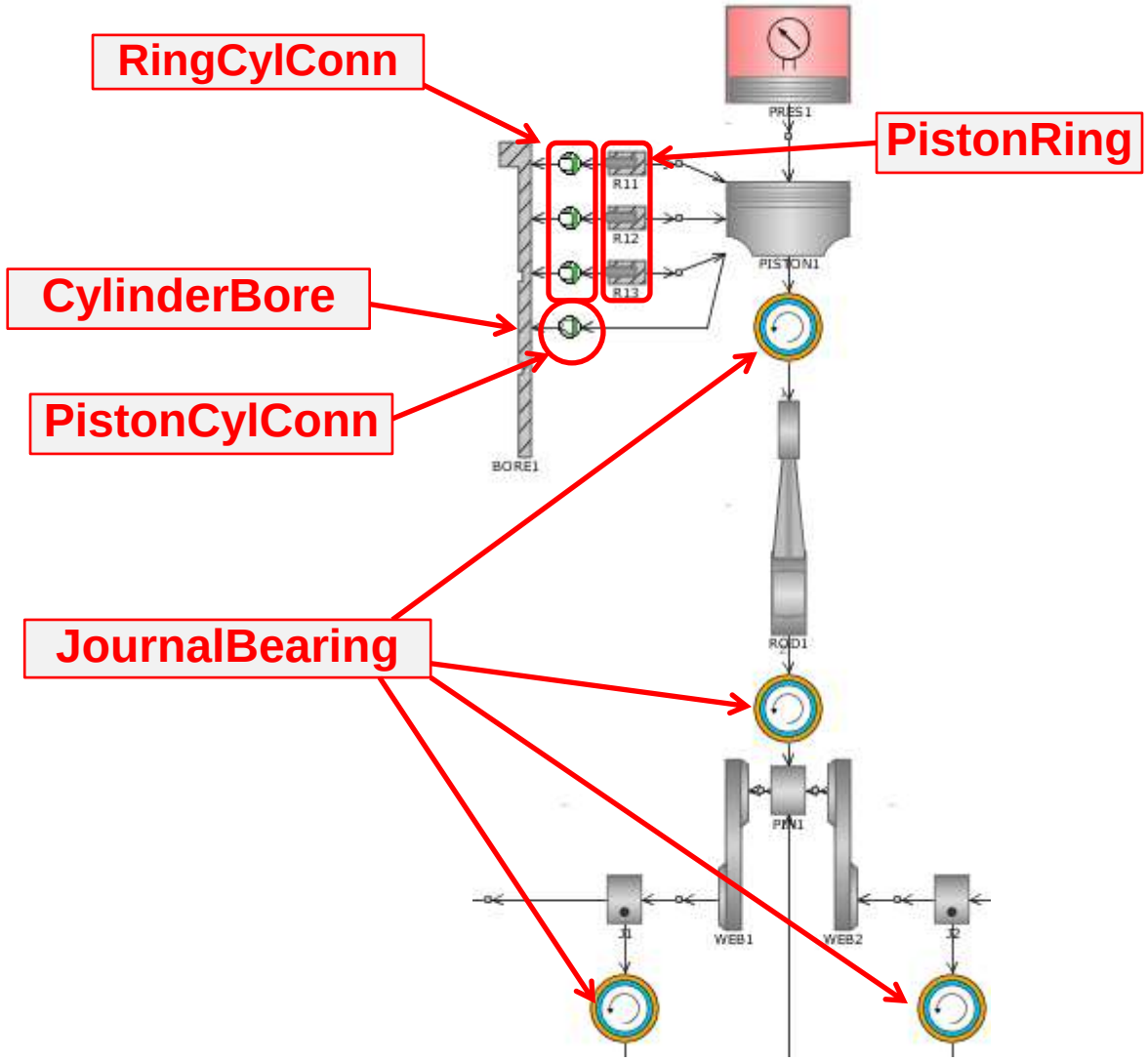
4 Q&A, 讨论

GT-SUITE 中关于发动机的摩擦部件



发动机曲柄连杆机构中关键的油膜 HD模板

BASIC CRANKTRAIN SEGMENT



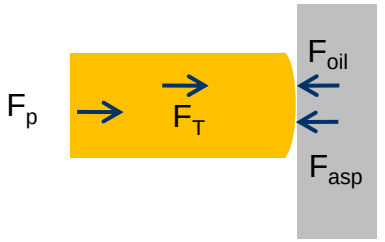
WITH FRICTION MODELS

活塞环摩擦RingCylConn: 物理,方程式

Ring Radial Force, Twist Moment Balances

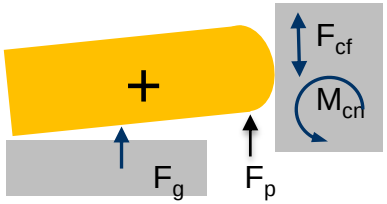
(ring radial position r, toroidal tilt θ)

$$Md^2r/dt^2 \sim 0^* = F_p + F_t - F_{crb}\{F_{oil}\,(dh/dt) + F_{asp}\}$$



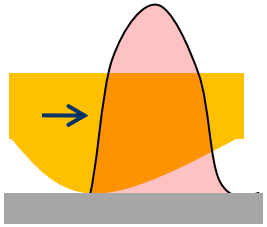
$$I_{ring}\, d^2\theta/dt \approx 0 =$$

$$F_g(R_g-R_r)+F_p(R_p-R_r)+ F_{crb}\{ F_{cf}(R_c-R_r)+M_{cn}\} - K_T\theta$$



Ring Oil Film Hydrodynamics Oil Film Pressure P(y)

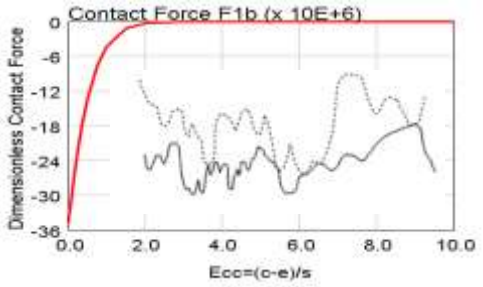
$$\partial/\partial x(\Phi_p h_T^3 \partial P/\partial x) = 6U\mu(\partial h_T/\partial x+\sigma\partial\Phi_s/\partial x)+12\mu\partial h_T/\partial t$$



Ring-Bore Asperity Contact (Greenwood-Tripp)

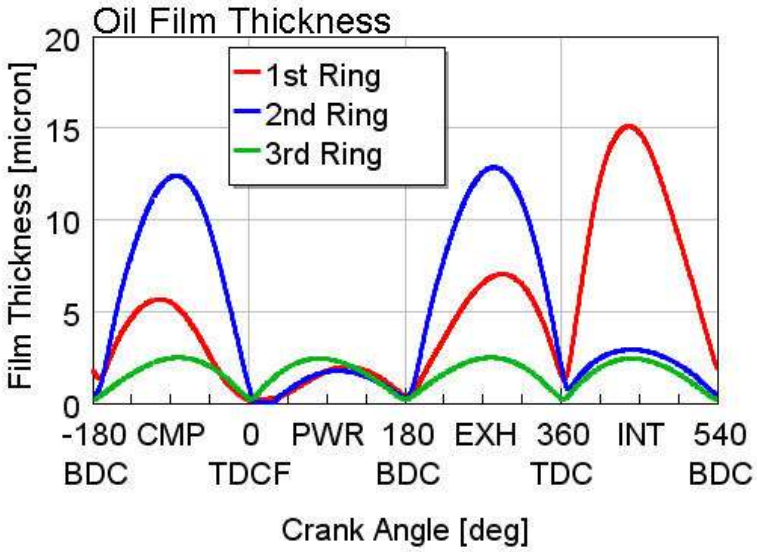
(asp. Contact pressure $P_{asp}(y)$)

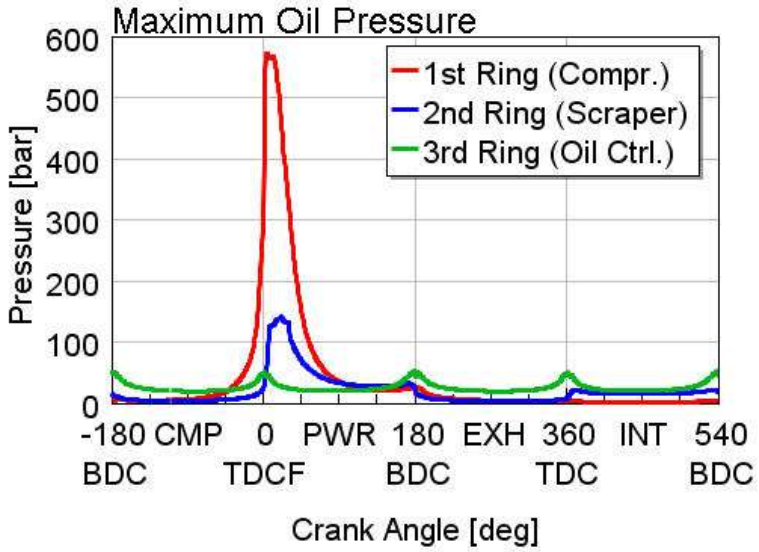
$$P_{asp} = (16\sqrt{2}/15)\,\pi\,(\sigma\beta\eta)^2\, E\,\sqrt{\sigma/\beta}\, F_2(h/\sigma)$$

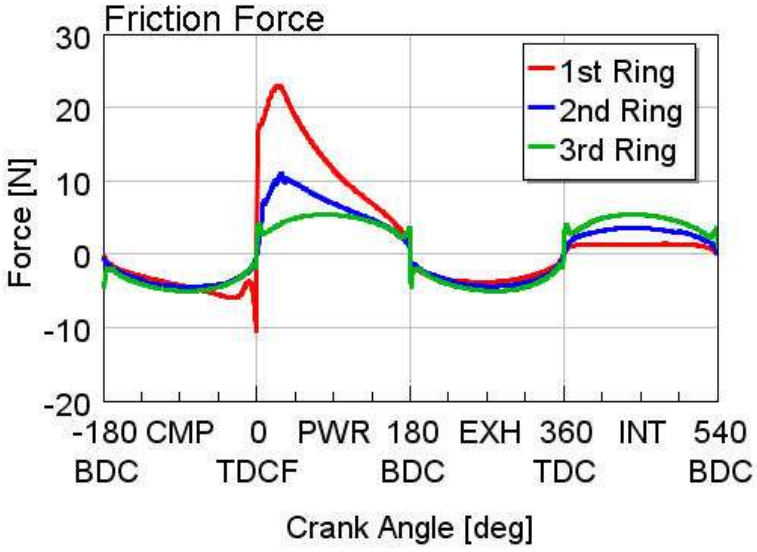


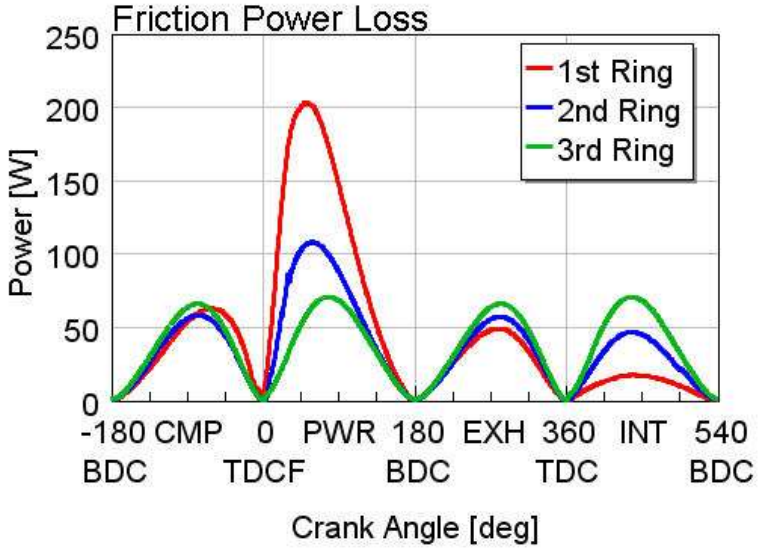
*Inertia may be ignored for a quasi-static force balance solved with little or no loss of accuracy, gain in CPU speed

RingCylConn模板：预测三个活塞环 - 3000 RPM









活塞裙部摩擦 PistonCylConn – 物理学,方程式

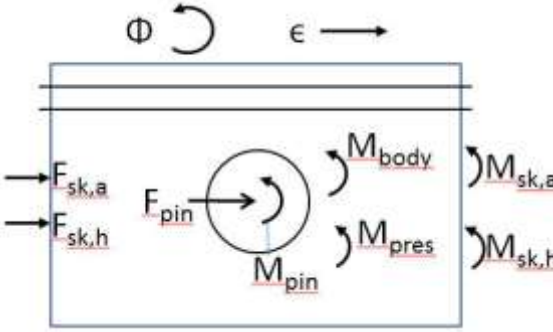
Lateral Force and Moment Balances (eccentricity ε and tilt angle Φ)

$$M_p d^2\epsilon/dt^2 \sim 0^* = F_{pin} + F_{sk,h} + F_{sk,a}$$

$$I_p d^2\Phi/dt^2 \sim 0^* = M_{body}+M_{pres}+M_{pin}+M_{sk,h}+M_{sk,a}$$

$$F_{sk,h},\ F_{sk,a}\ ,M_{sk,h},\ M_{sk,a} = f\ (V_p,\varepsilon,\Phi,d\epsilon/dt,d\Phi/dt)$$

(F, M values from by HD/asperity models)



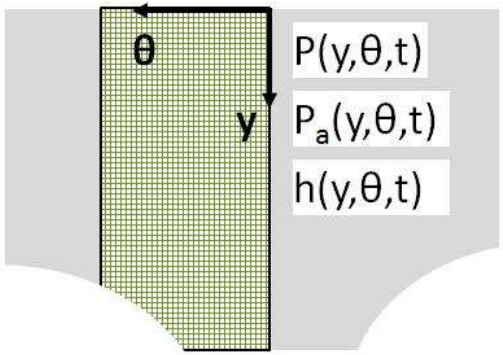
Skirt Oil Film Hydrodynamics (Reynolds Eq. -oil film pressure P(y,θ,t))

$$\partial/\partial y(\Phi_p h_T^3 \partial P/\partial y) + (1/R^2)\partial/\partial\theta(\Phi_p h_T^3 \partial P/\partial\theta)$$
$$= 6V_p\mu(\partial h_T/\partial y+\sigma\partial\Phi_s/\partial y)+12\mu\partial h_T/\partial t$$

Skirt-Bore Asperity Contact (Greenwood-Tripp)

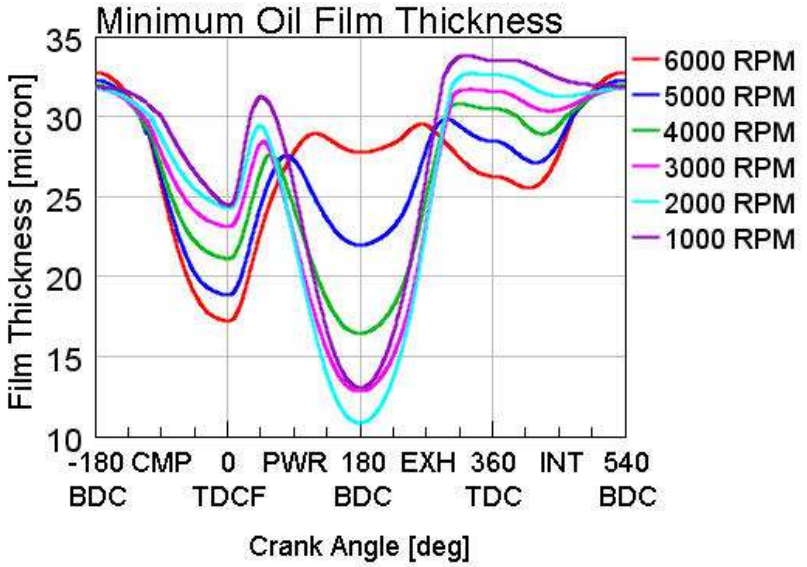
(Asperity contact pressure $P_{asp}(y,\theta,t)$)

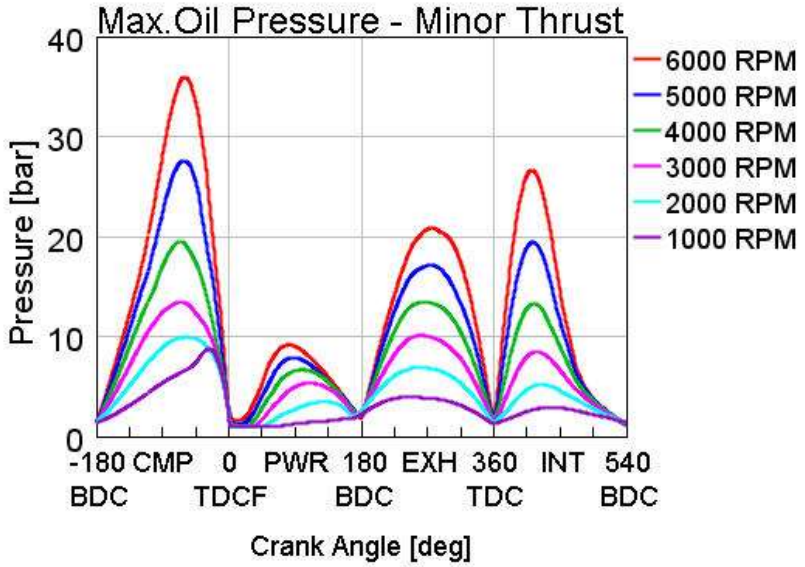
$$P_{asp} = (16\sqrt{2}/15)\ \pi\ (\sigma\beta\eta)^2\ E\ \sqrt{\sigma/\beta}\ F_2(h/\sigma)$$

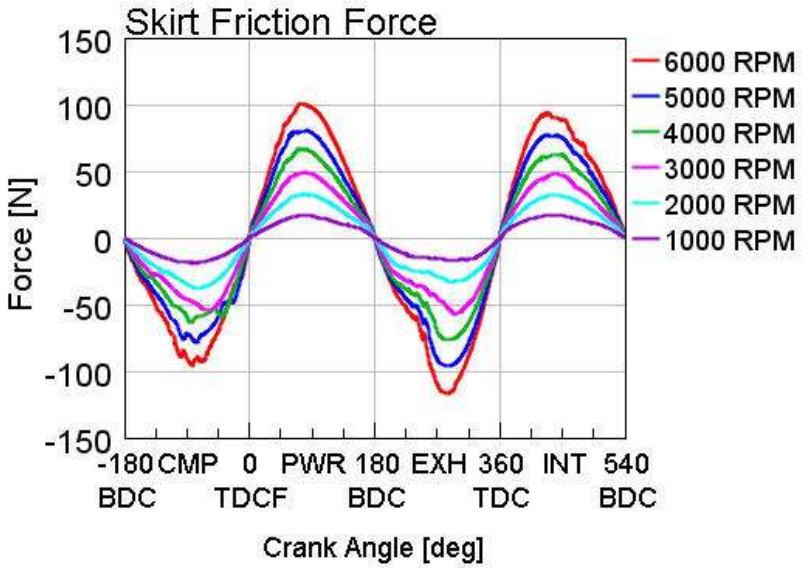


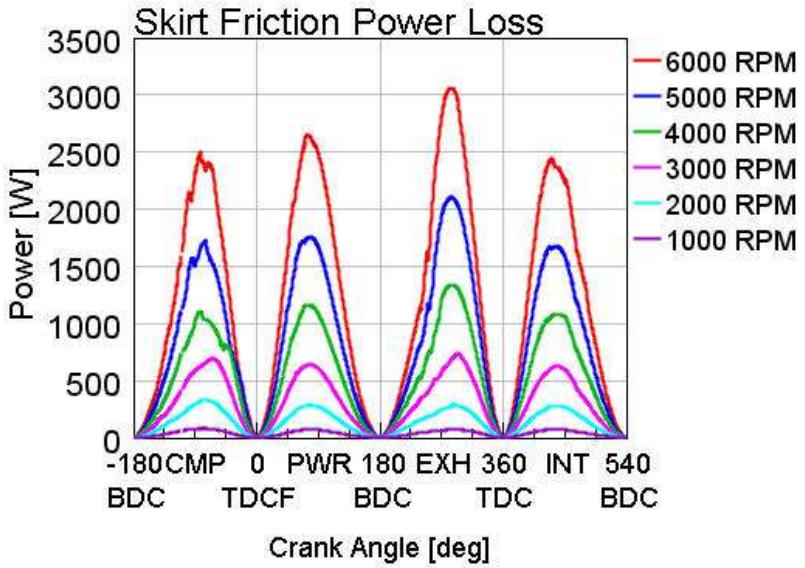
*Inertia may be ignored for a quasi-static force balance solved for (i), with little or no loss of accuracy, gain in CPU speed

PistonCylCnn: 活塞裙部摩擦分析



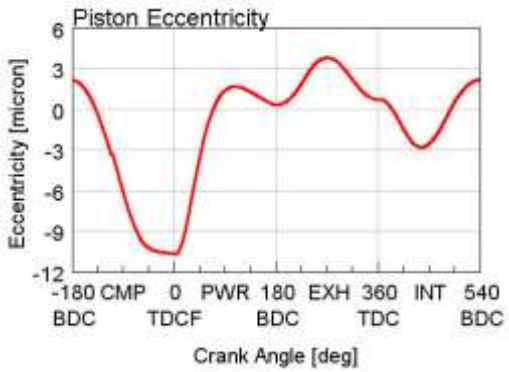


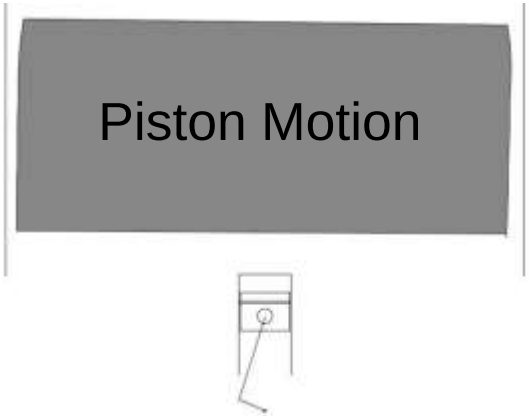


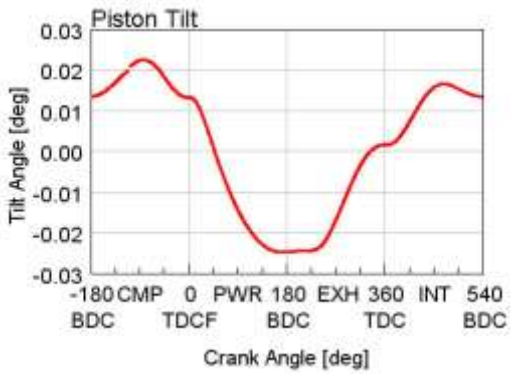


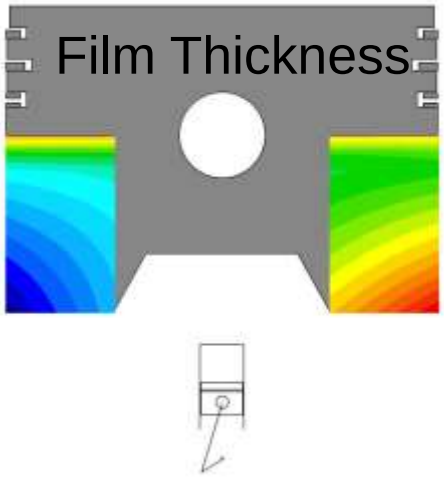
活塞裙部摩擦 关联输出

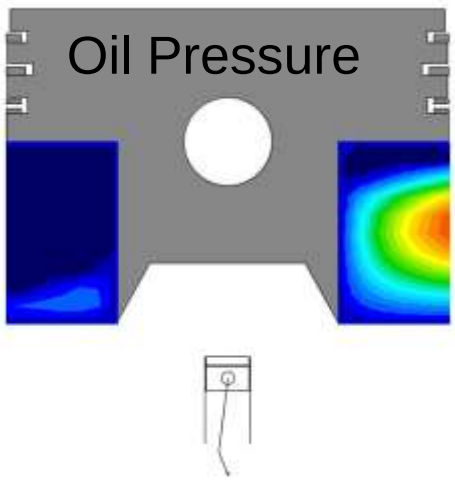
活塞运动和裙部油膜动画

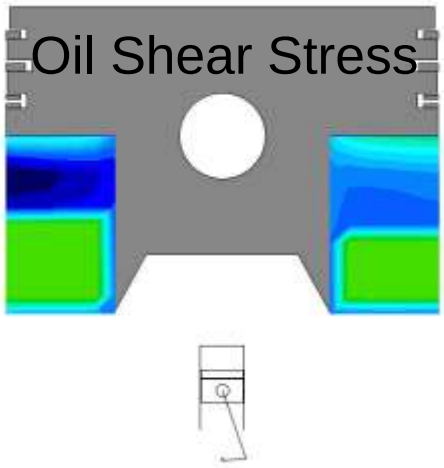










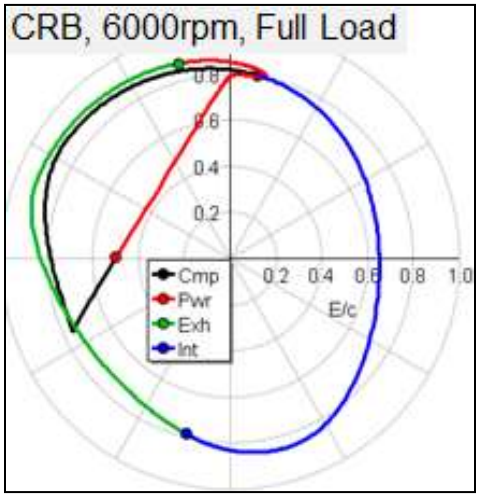


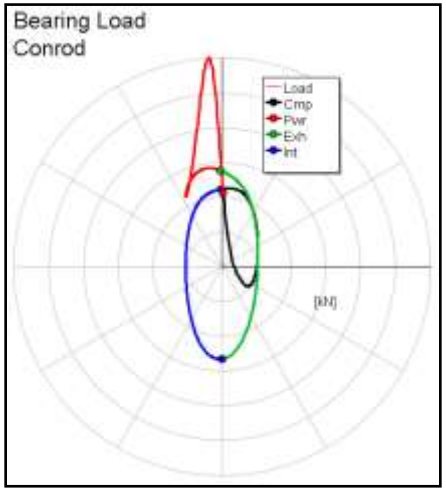
轴承油膜HD,摩擦: JournalBearing

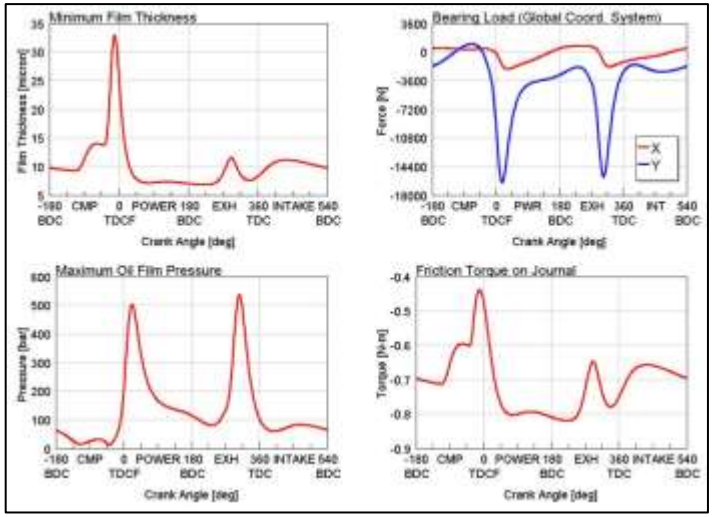
- Hydrodynamic (HD) 油膜求解
- 采用预处理: MAP图/拟合fits of relationship between force and motion used, for fast orbit/MOFT, soln.
- 预测运行过程中：摩擦力矩，功率损失，油膜的延展性, 最大油膜压力等
- 油温上升预测
- Greenwood-Tripp粗糙面接触模型
- 油槽/油孔压力感受模型;
- 与GT-SUITE的润滑系统联合仿真

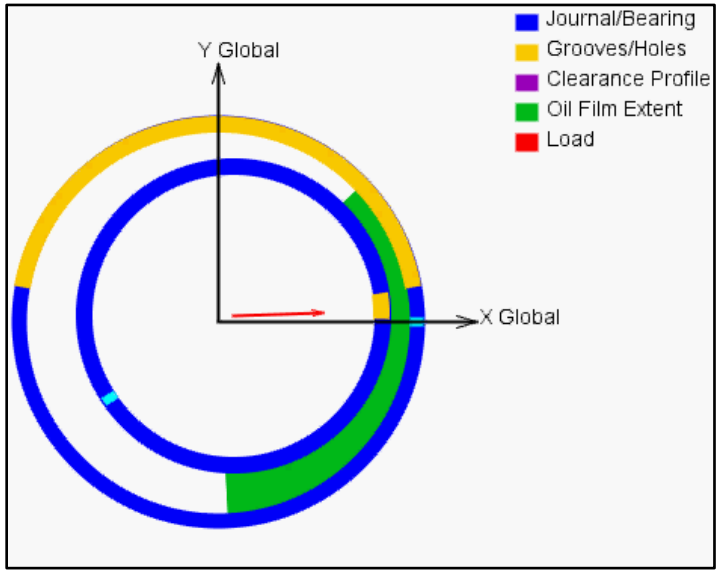
轴承油膜&摩擦模型

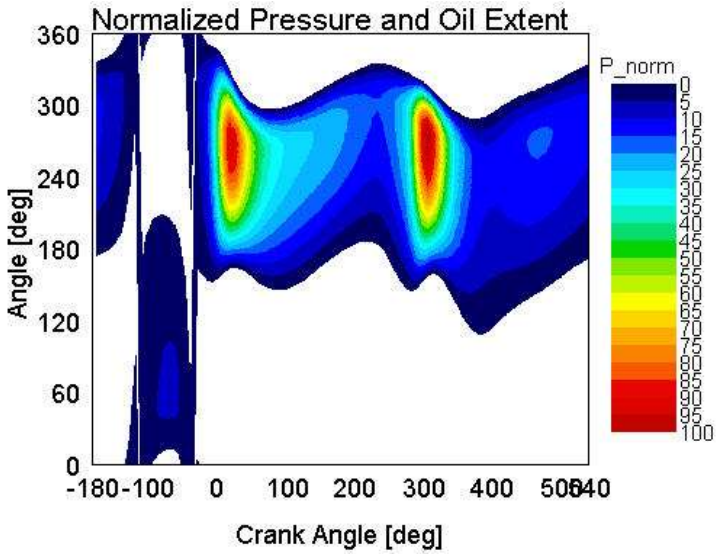
输出:轴心轨迹，负荷，动动，油膜的延展性, MOFT,摩擦等



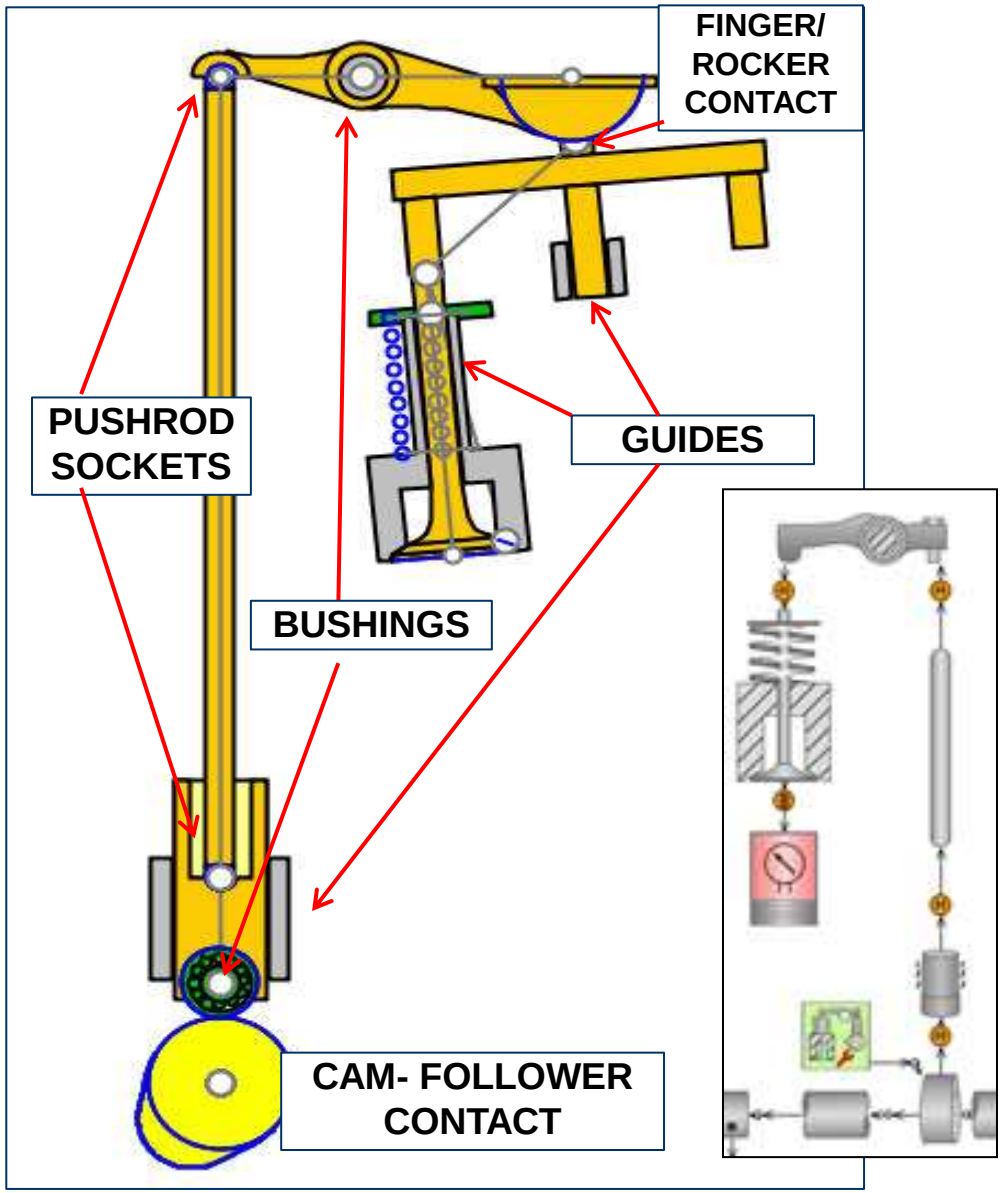






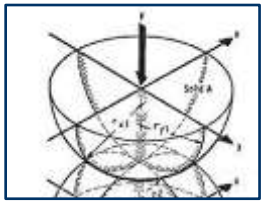


配气机构摩擦- Contact2D, 各种铰接



接触副, 摇臂等:

- EHD油膜压力 (Dawson-Hamrock EHD)
- 粗糙度的接触压力 (Greenwood-Tripp)
- 热模拟 (间隙、温度)

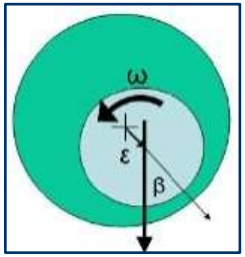


导管,推杆:

- 油膜的剪切力
- 与负载相关的摩擦系数 (fric. coeffs. for load, moment

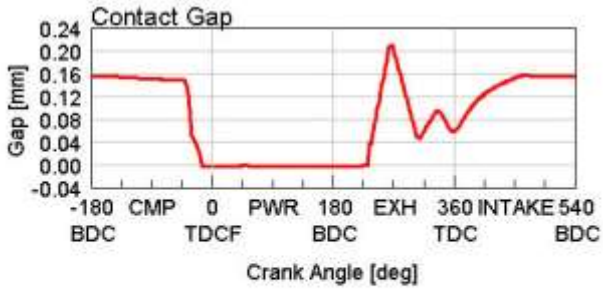
凸轮轴的轴承

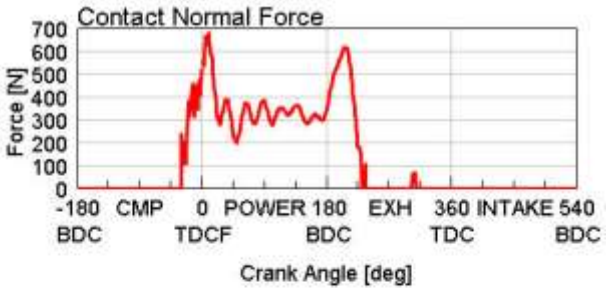
- HD轴承

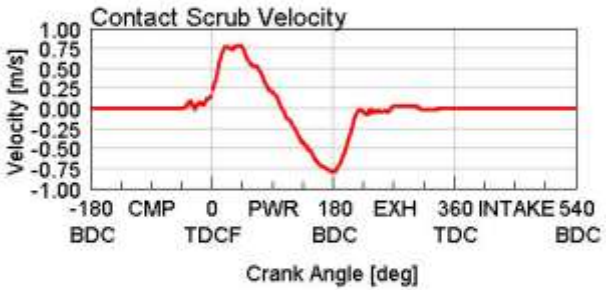


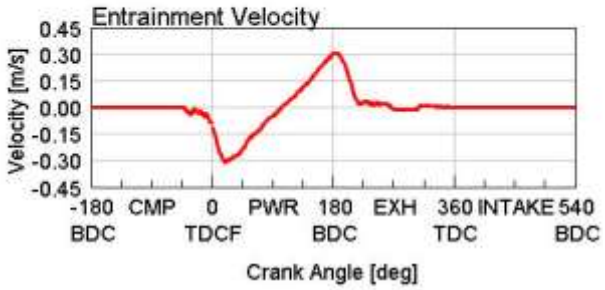
可选择性的选择配气机构摩擦模型及相应输出

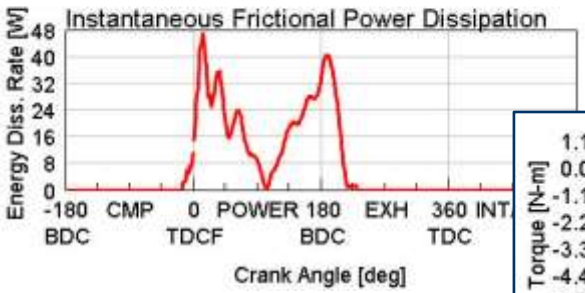
Contact physics, friction/wear, valvetrain torque

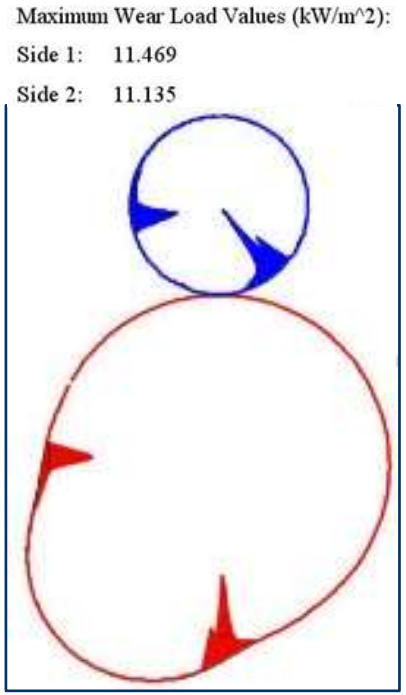


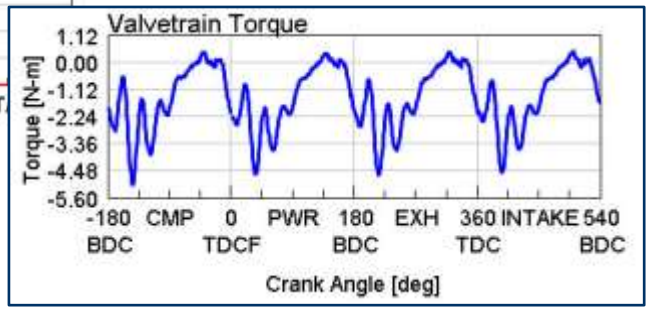








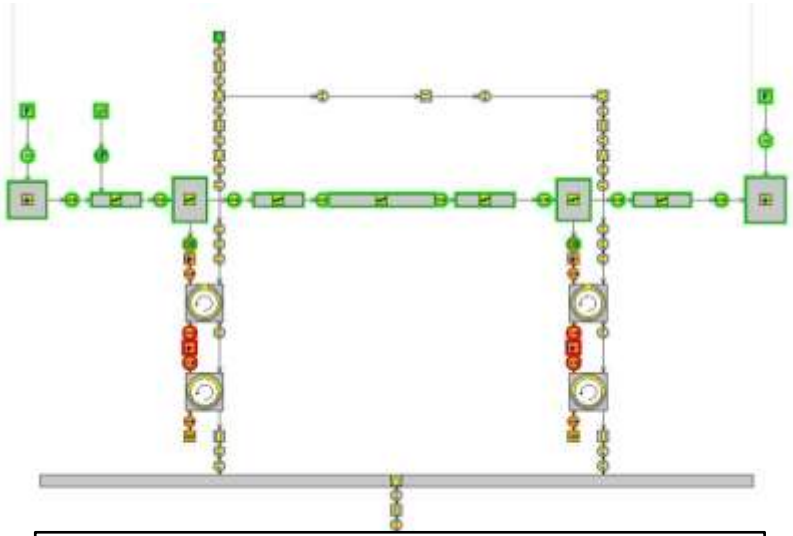


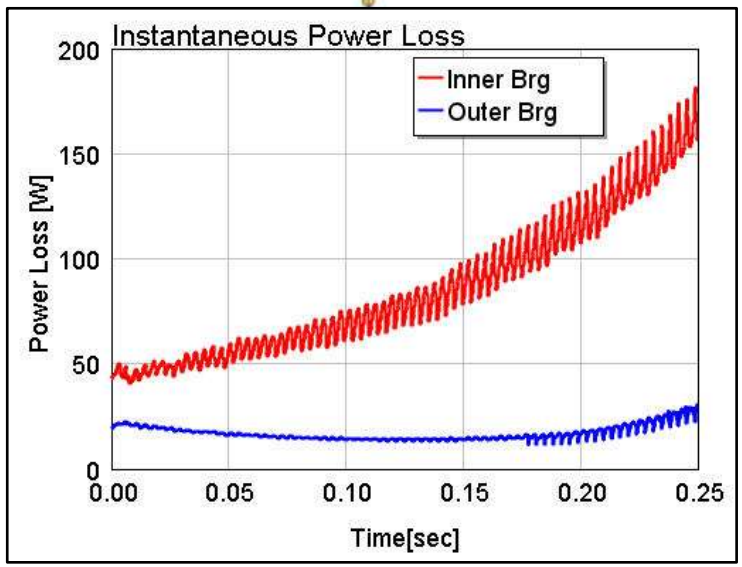


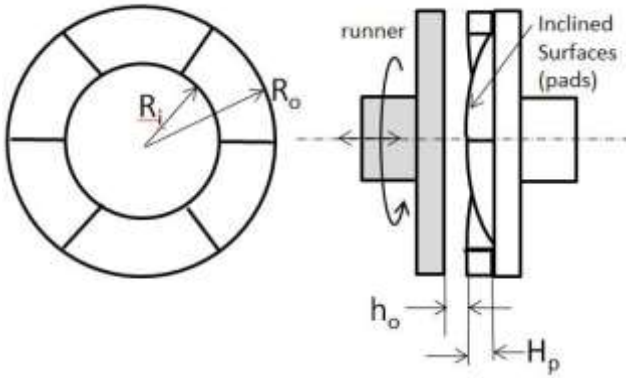
增压器摩擦 JournalBearing, ThrustBearing

- 增压器的机械动力学
- 浮动式轴承 (double JB)
- 倾斜平面的止推轴承
  - HD求解
  - Greenwood-Tripp粗糙度接触
- 摩擦力矩、功率损失和流量预测

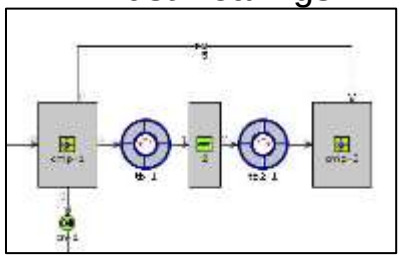
T/C Lubrication Circuit and Bearings





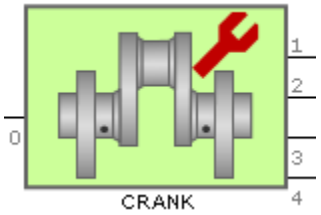


Thrust Bearings



全局性发动机摩擦输出

- 很方便的实现：可视化、扫掠/MAP输出
- 所有的摩擦RLT可以作为优化对象来考虑



Example: Cranktrain friction global output in **CrankAnalysis** part– speed

Part Information

Part: Cranktrain

Template: CrankAnalysis

Print ...

Data View Options

Show Multiple Case

Show Template Group

Show Time RLT vars

Case 1

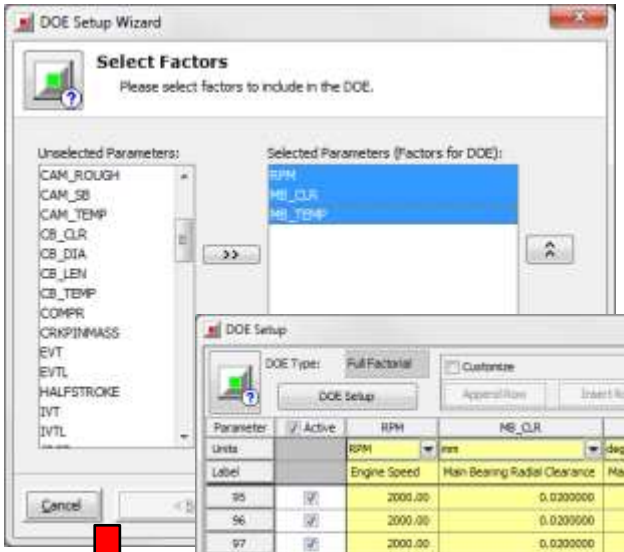
Attribute Value	Unit	Short Name	6000 RPM Case# 1	5000 RPM Case# 2	4000 RPM Case# 3	3000 RPM Case# 4	2000 RPM Case# 5	1000 RPM Case# 6
Favorites								
Main								
Balance								
Friction								
Frictional Power Loss	kW	fricpwr	5.46799	3.34959	1.98363	1.07566	0.48189	0.135076
Fric. Power - Main Bearings	kW	fricpwrmn	2.79335	1.56889	0.855521	0.429549	0.179564	0.0464012
Fric. Power - Lrge.End Bearings	kW	fricpwrle	1.09958	0.662613	0.382233	0.19946	0.0864562	0.0231415
Fric. Power - Sml.End Bearings	kW	fricpwrse	0.0309701	0.0220705	0.0153922	0.0100955	0.00573824	0.00222297
Fric. Power - Piston Rings	kW	fricpwrcyr	0.318027	0.24496	0.178533	0.119303	0.0674888	0.0256736
Fric. Power - Piston Skirts	kW	fricpwrcys	1.22607	0.851051	0.551954	0.317249	0.142643	0.0376371
Fric. Power - Other Cylinder	kW	fricpwrcy	0.0	0.0	0.0	0.0	0.0	0.0
Working Stresses (Rigid/Torsion)								
Safety Factors								
Stress_Recombination								

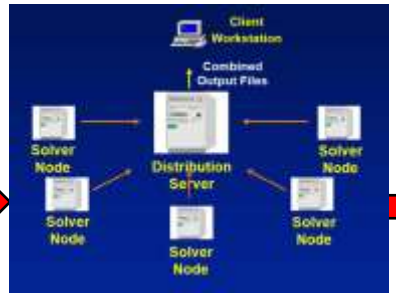
Done

GT-SUITE DoE/Optimization 工具

- 必不可少的设计拓展, ‘tradeoffs’ 和限制的优化, 获得最小的摩擦损失
- 对于获得未知参数 (如：粗糙度)去与尽可能的与试验数据相匹配也是很有用的

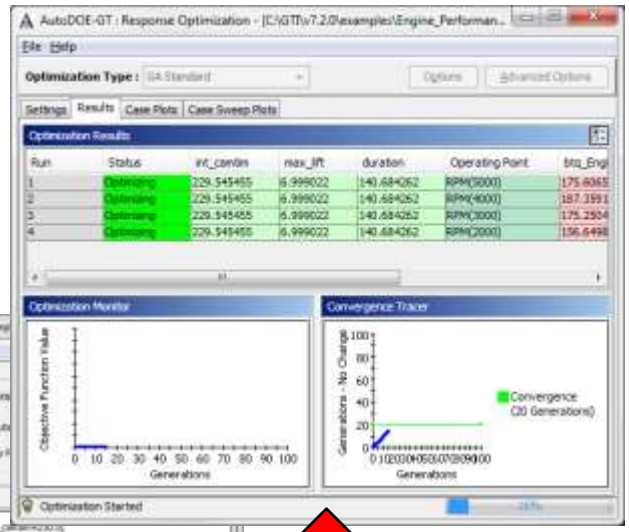
SELECT PARAMETERS

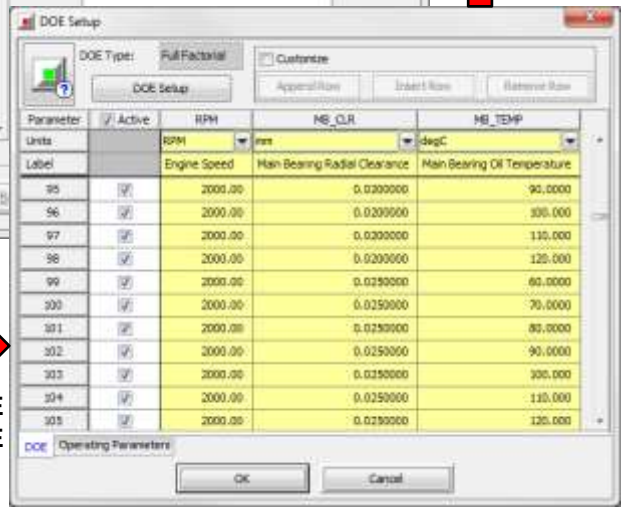




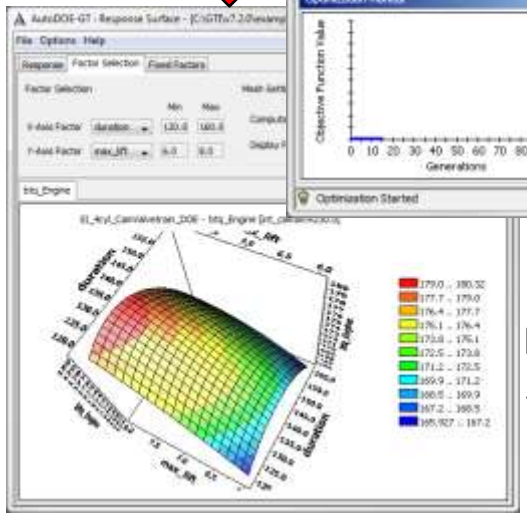
DISTRIBUTED PROCESSING

OPTIMIZE WITH DESIGN CONSTRAINTS





GENERATE DOE



VIEW &ANALYZE RESPONSE

GT Gamma Technologies

主要内容

1 GT-SUITE在发动机摩擦中的预测分析与模拟
- 动机、原因和需求
- GT-SUITE能提供的关键技术
- 发动机摩擦模拟的关键模板
- 校核

2 摩擦和润滑; v7.5新功能和开发进展

3 应用分析

4 Q&A, 讨论

用来进行对比的测试数据 (V6 SI Engine)

典型的测量数据

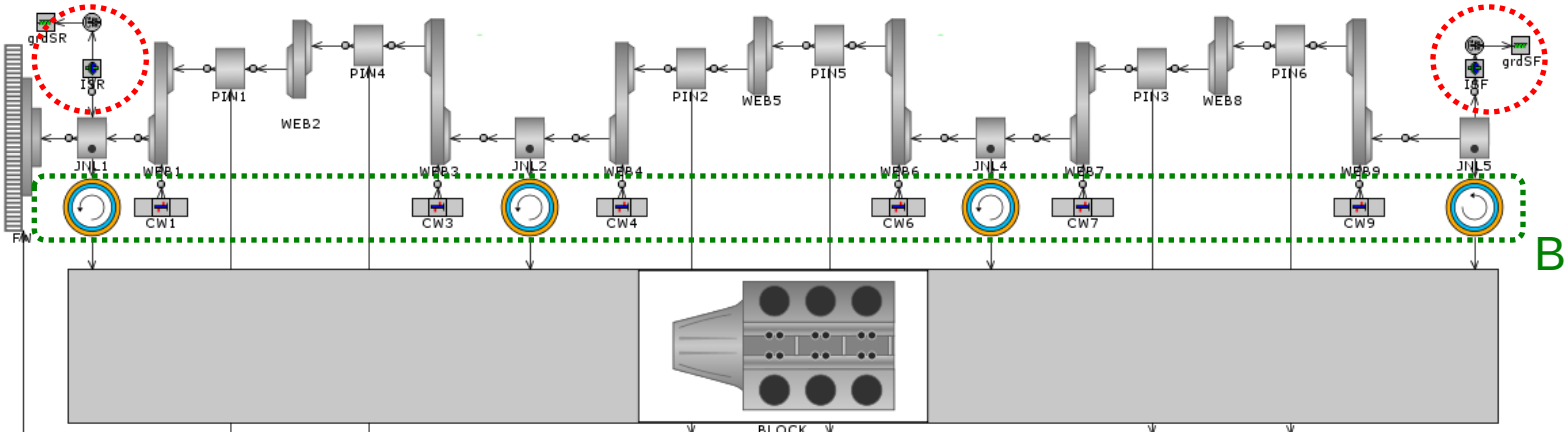
- 发动机拆解试验数据
- 单缸发动机 浮云衬套驱动力矩
- 配气机构驱动力矩

测试参数

- 润滑
- 油温 (供油温度)
- 发动机转速
- 表面抛光
- 表面材料 (coatings)

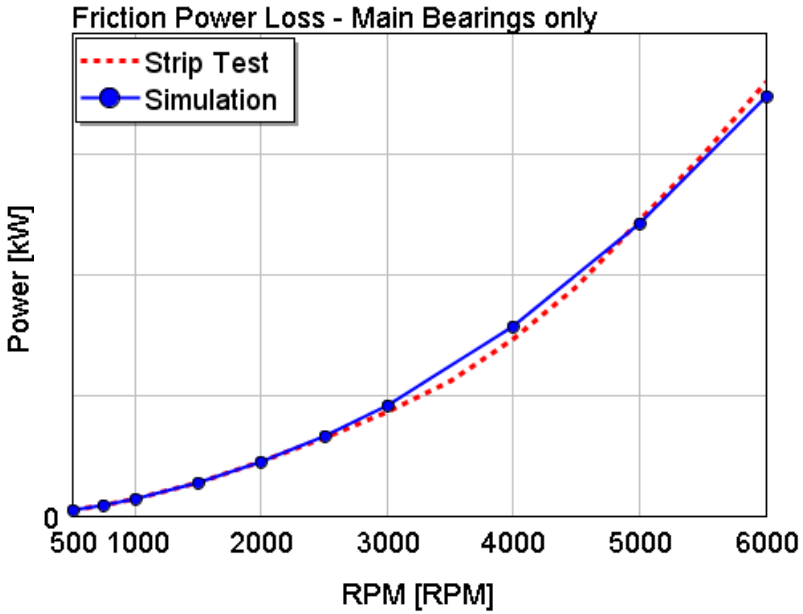
对发动机Strip-down的测试数据对比

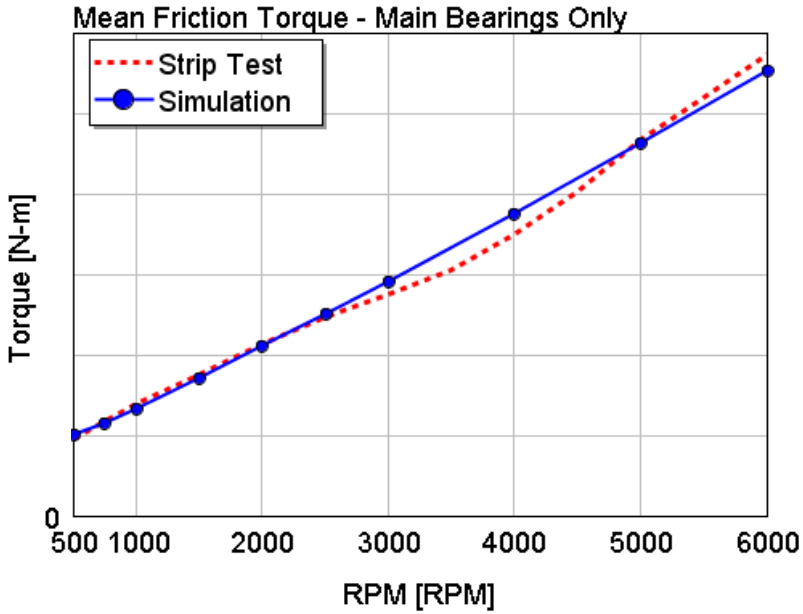
主轴承+ 油封的 FMEP (只有曲轴)



FRONT & REAR SEALS

MAIN BEARINGS





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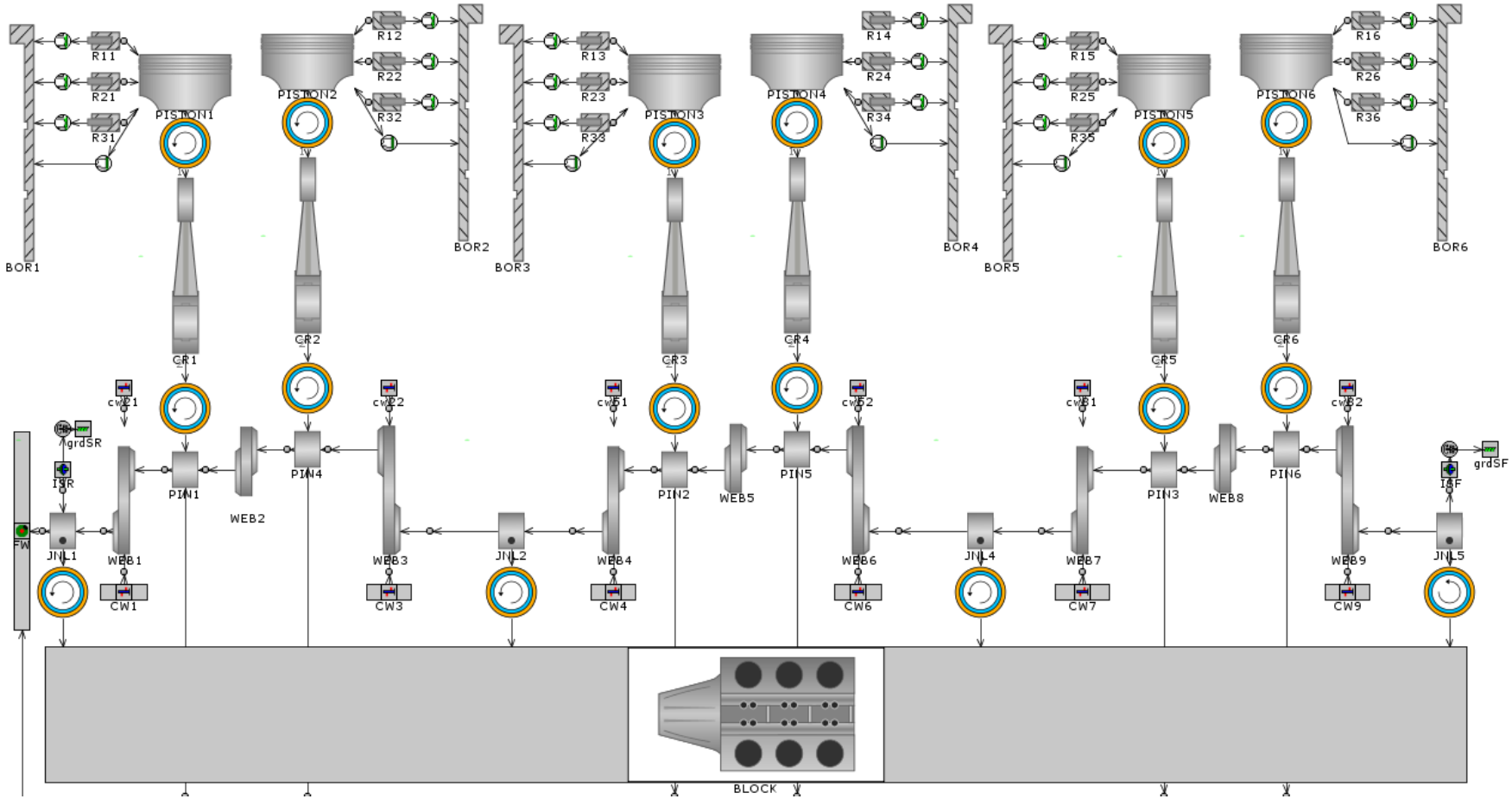
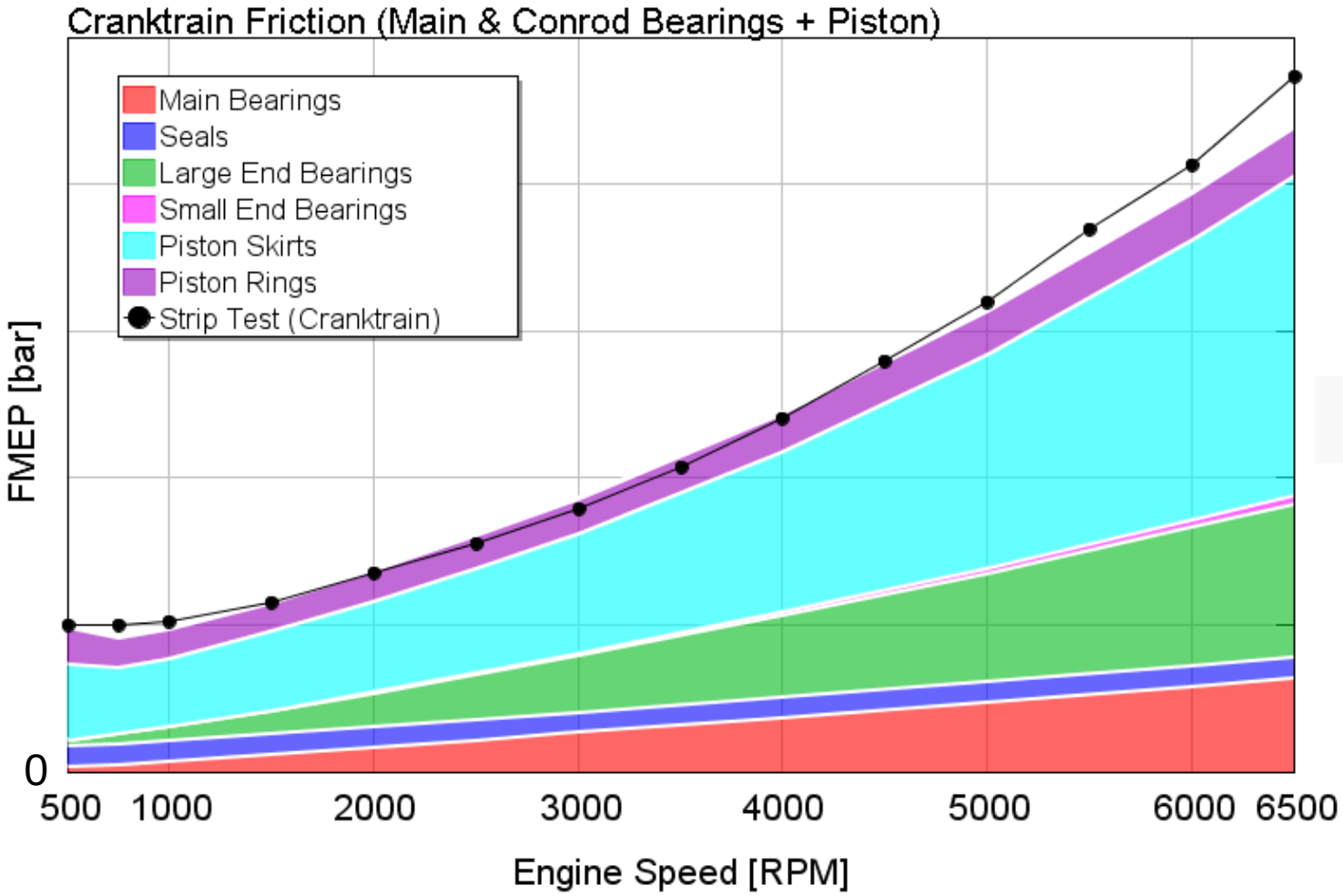
与发动机的Strip-down测试数据对比

完整的曲柄连杆机构模型，带有轴承、活塞和活塞环油膜/摩擦子模型 (没有缸太远, “开”的发动机)



与发动机的Strip-down测试数据对比

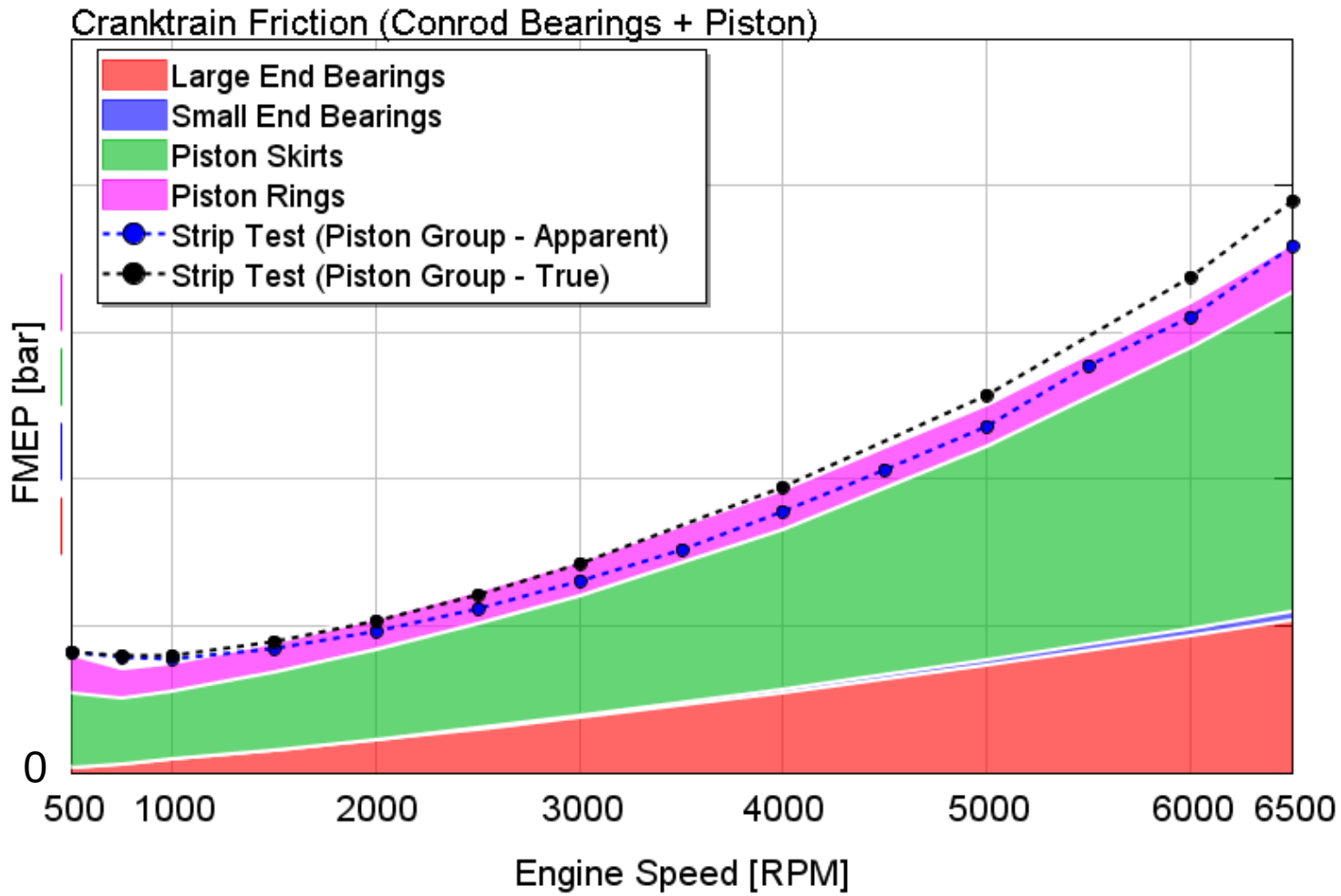
完整体的曲柄连杆机构的FMEP



与发动机的Strip-down测试数据对比

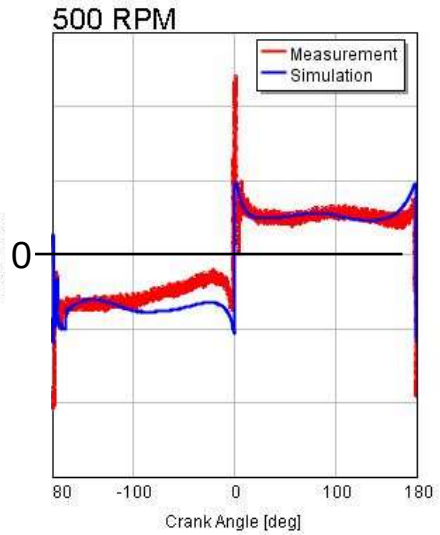
活塞组 (活塞环、活塞裙部、连杆轴承) FMEP

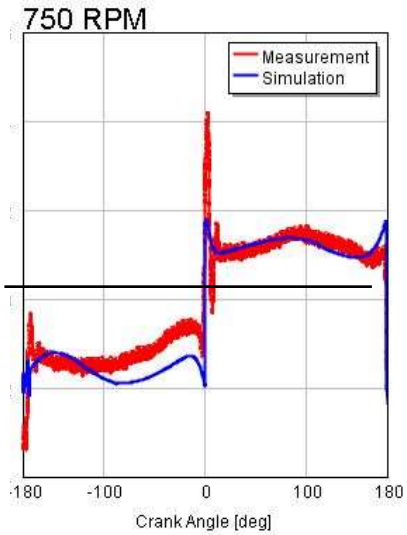
$$FMEP_{test} = FMEP_{cranktrain} - FMEP_{main\ bearings}$$

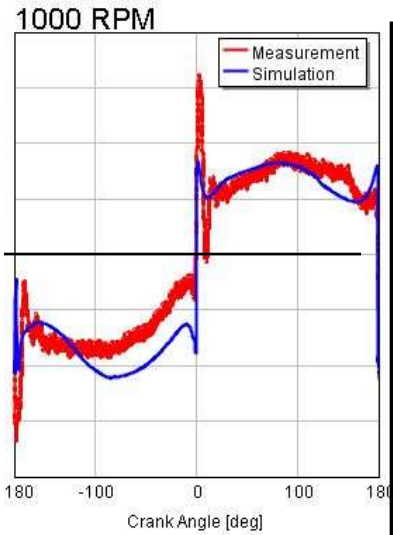


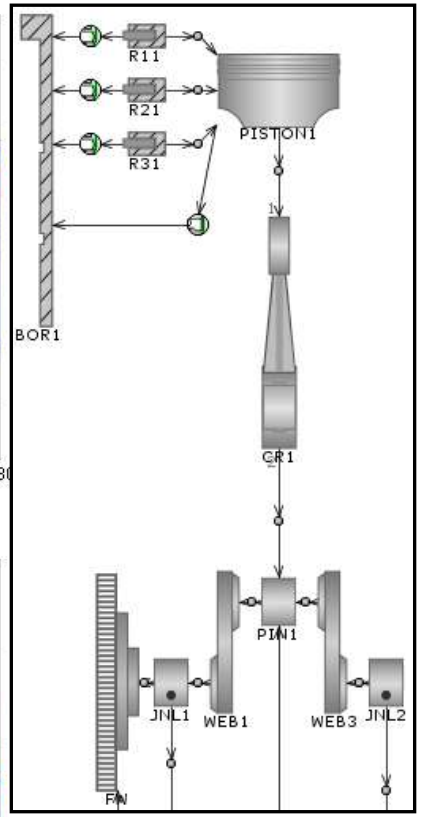
与浮动测试数据对比 A

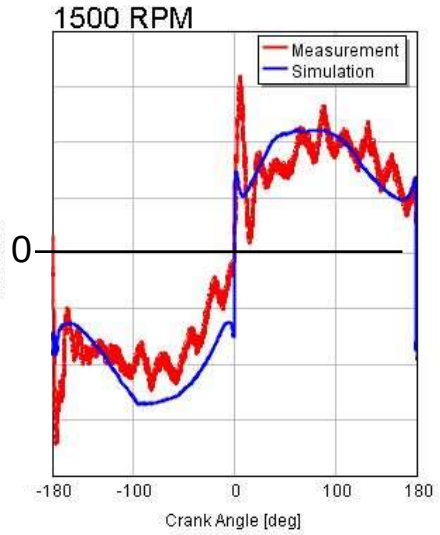
活塞 +活塞环的摩擦力

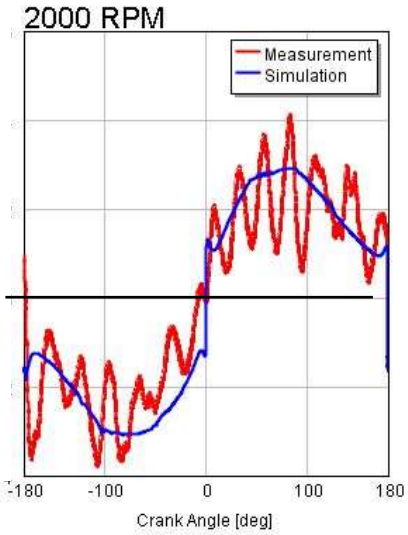


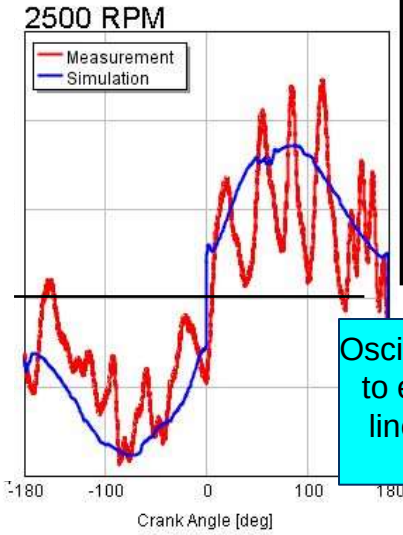








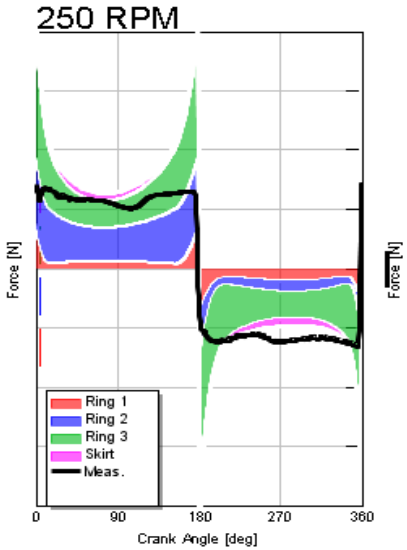


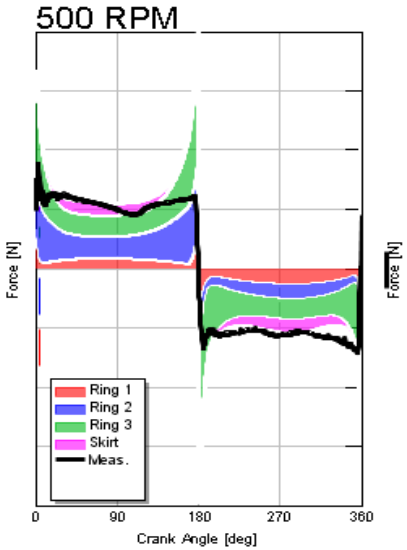


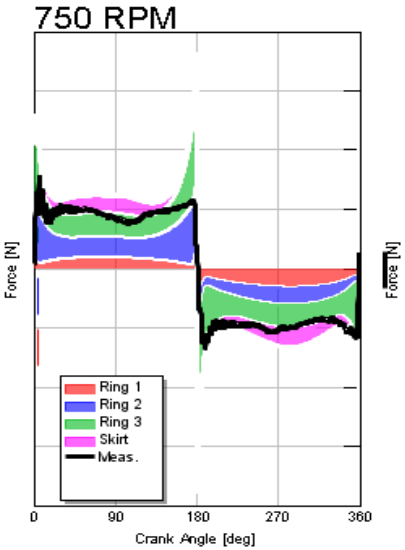
Oscillations: vibration due to excitation of floating liner system at higher speeds.

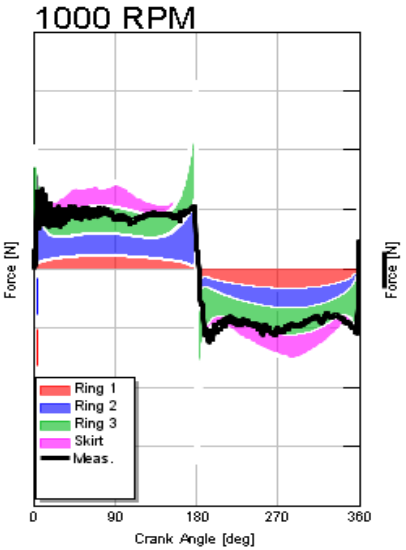
与浮动测试数据对比 B

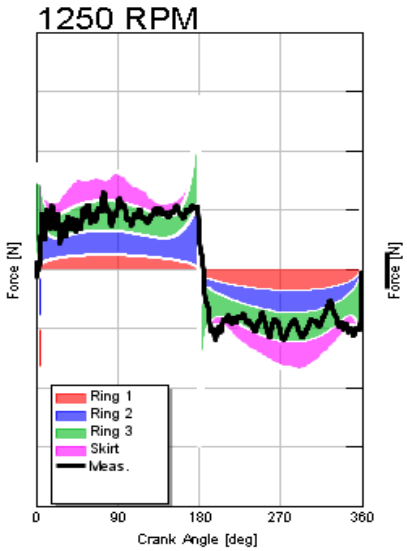
Piston + Ring Friction – 100degC

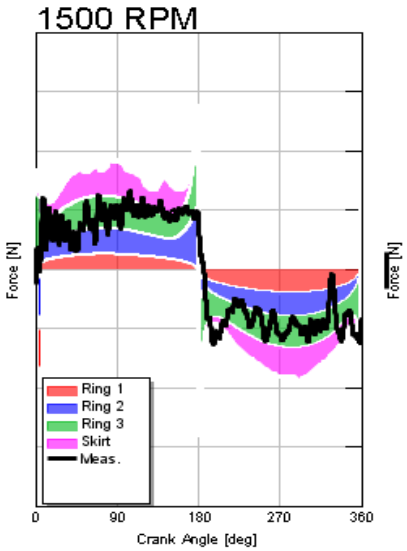


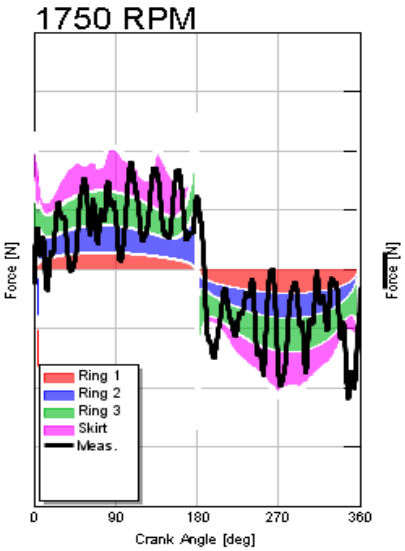


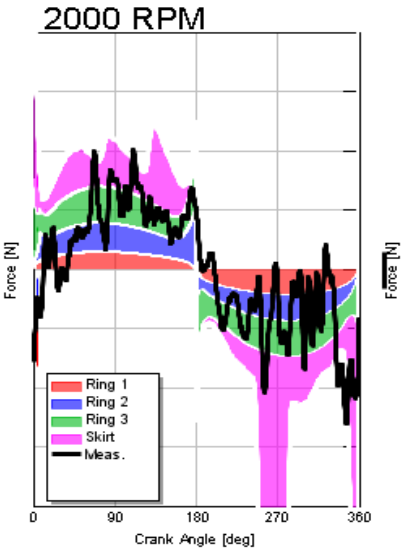






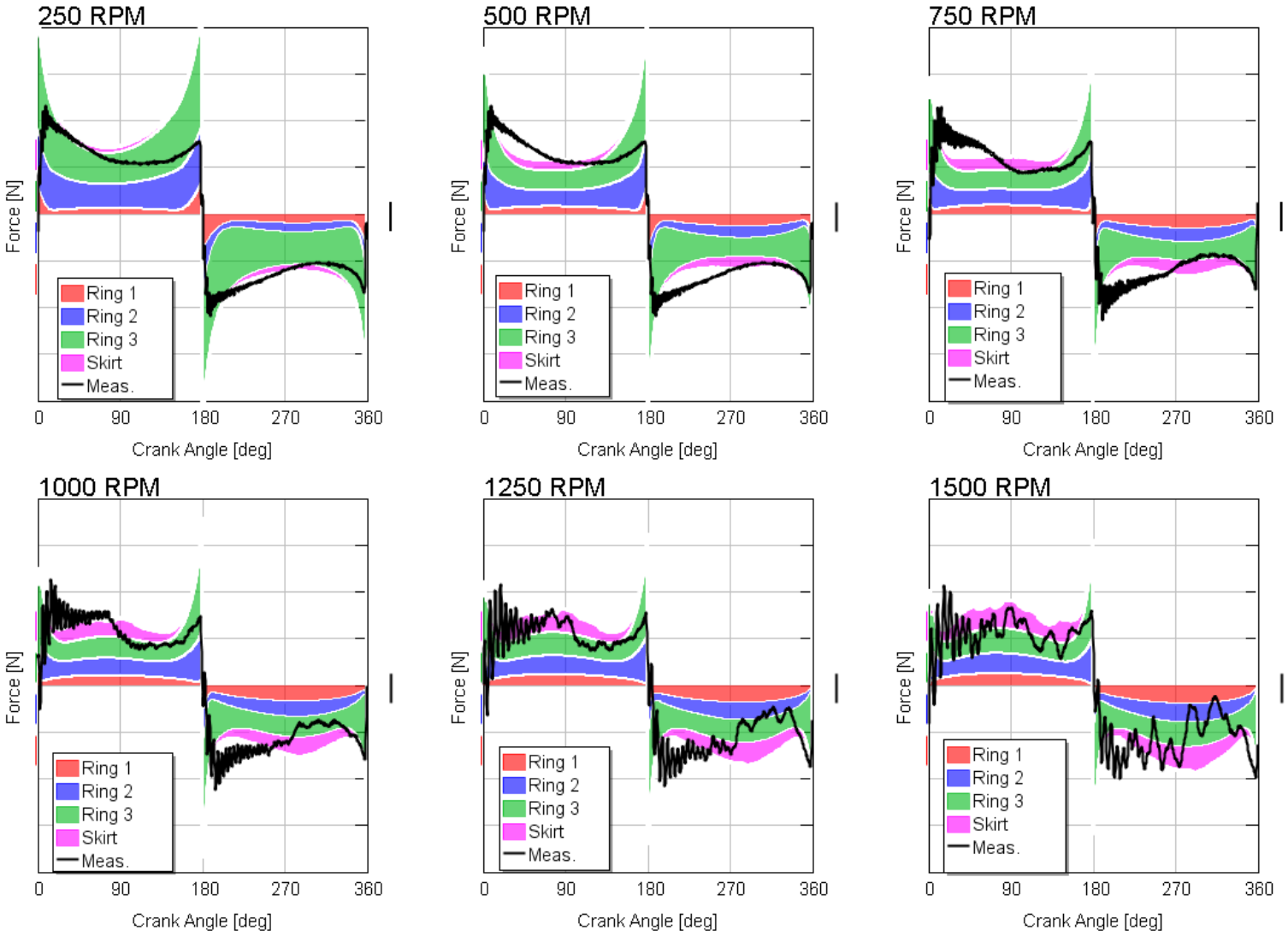






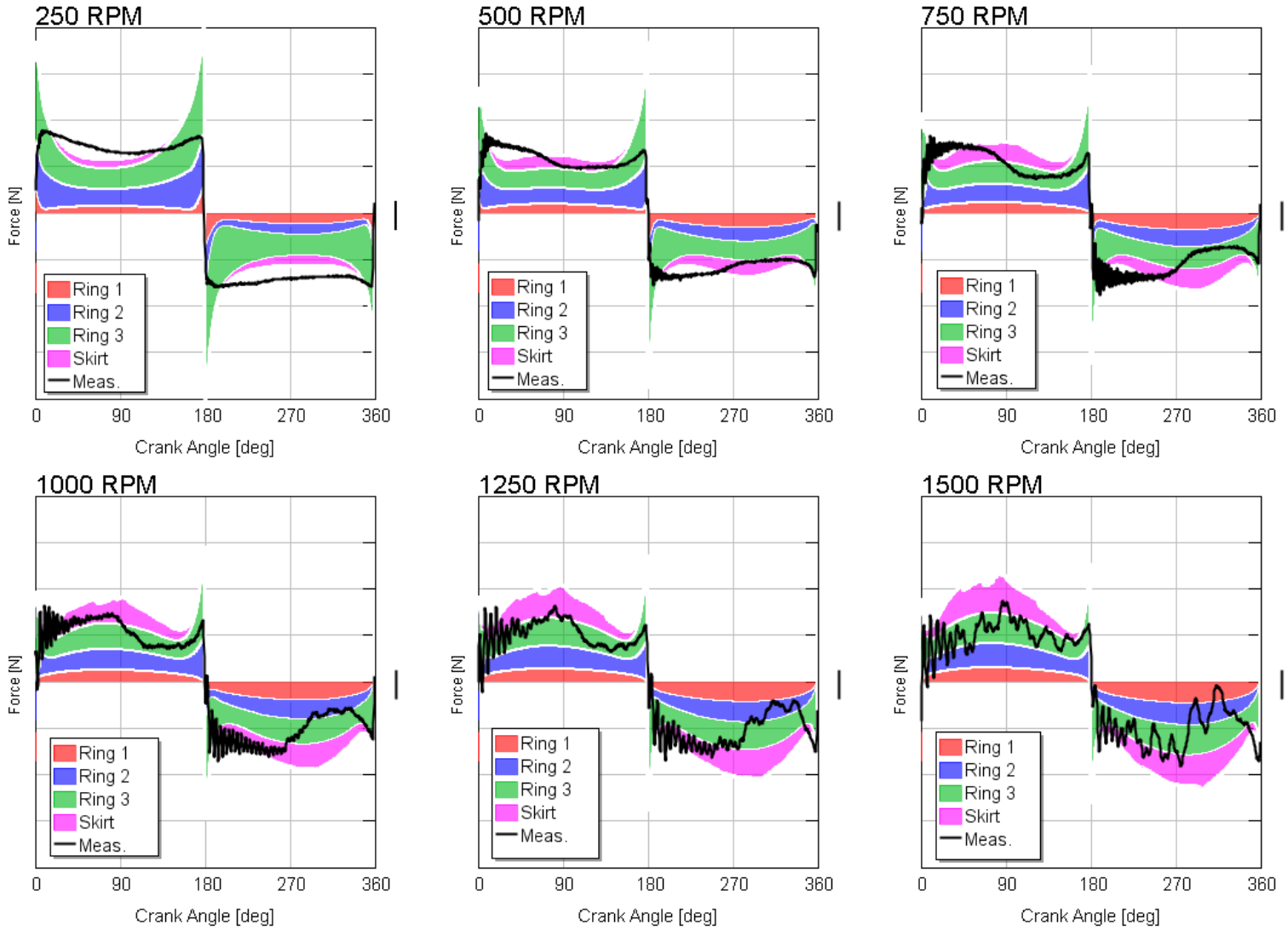
与浮动测试数据对比

Piston + Ring Friction – 100degC



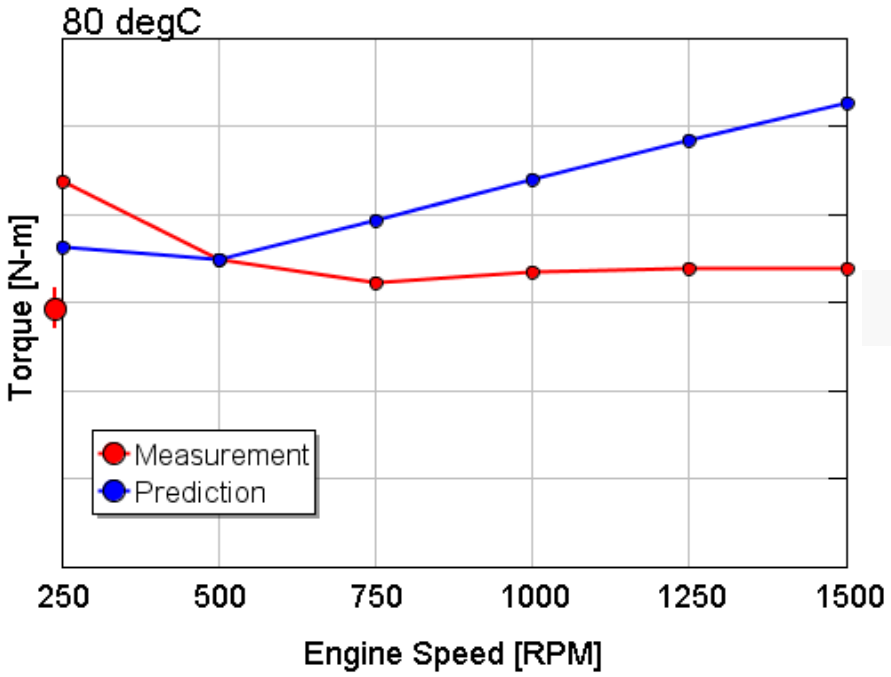
与浮动测试数据对比 C

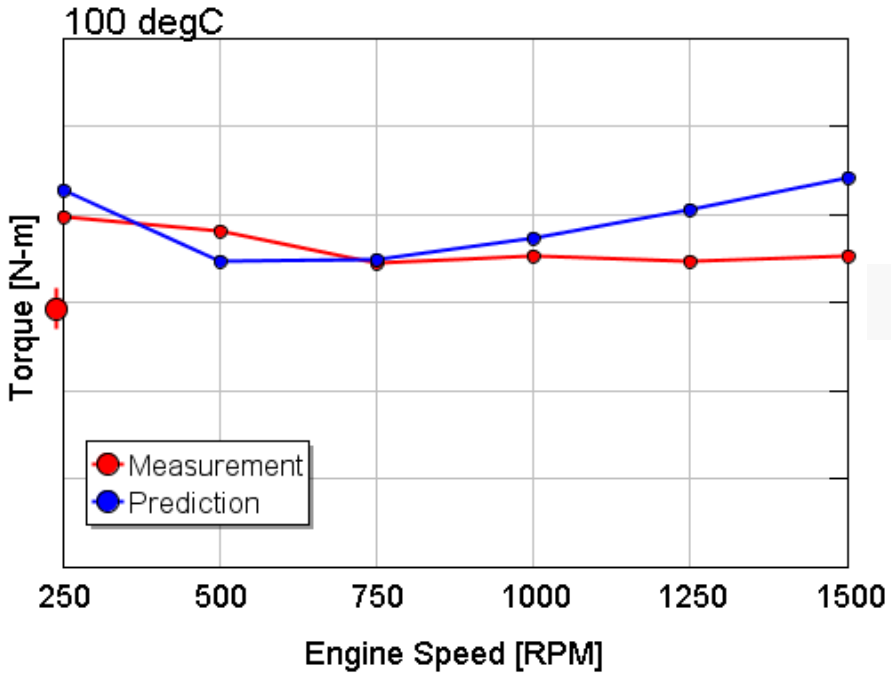
Piston + Ring Friction – 80degC



与浮动测试数据对比 C

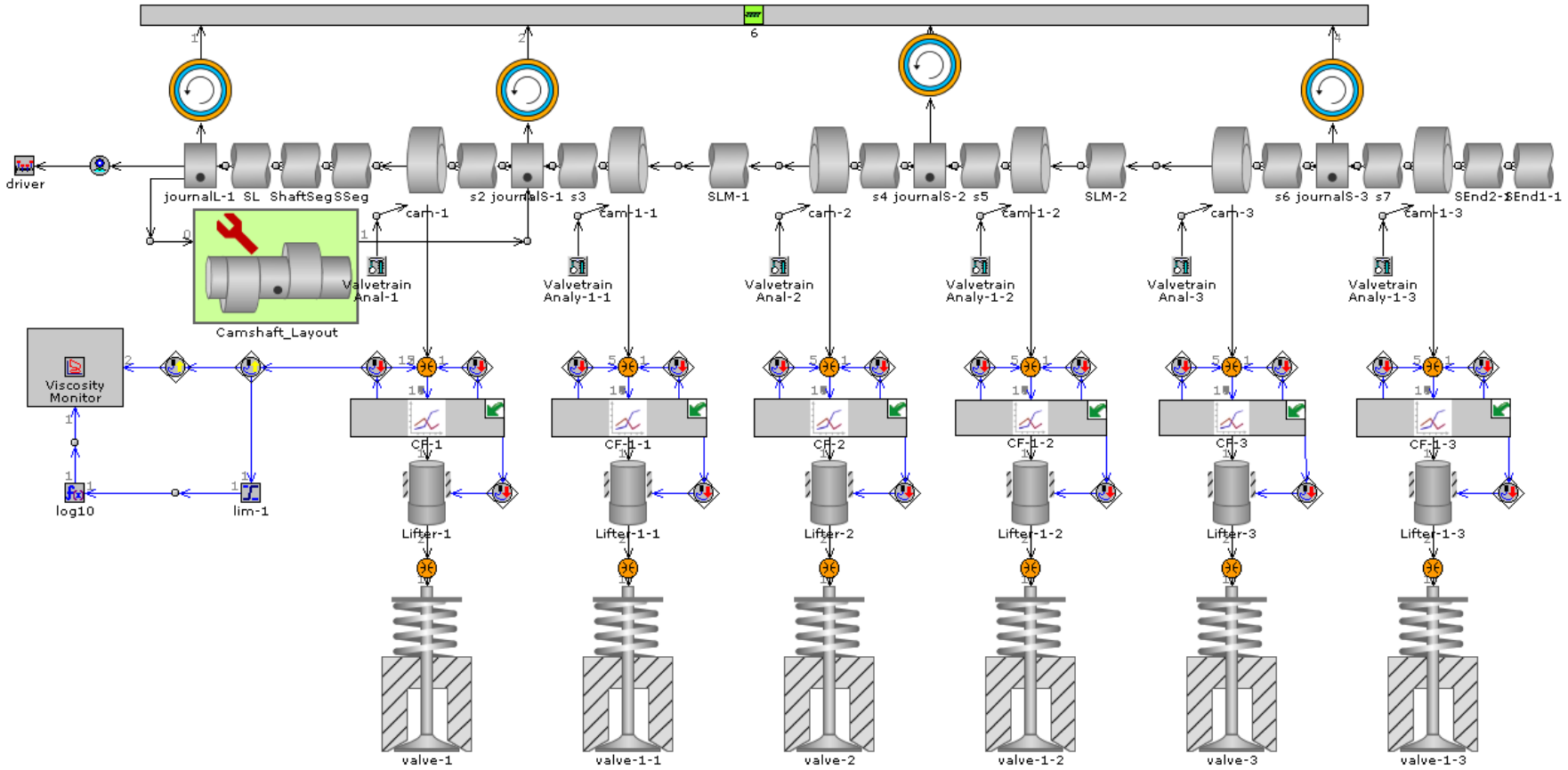
Mean Torque of Piston+Ring Friction





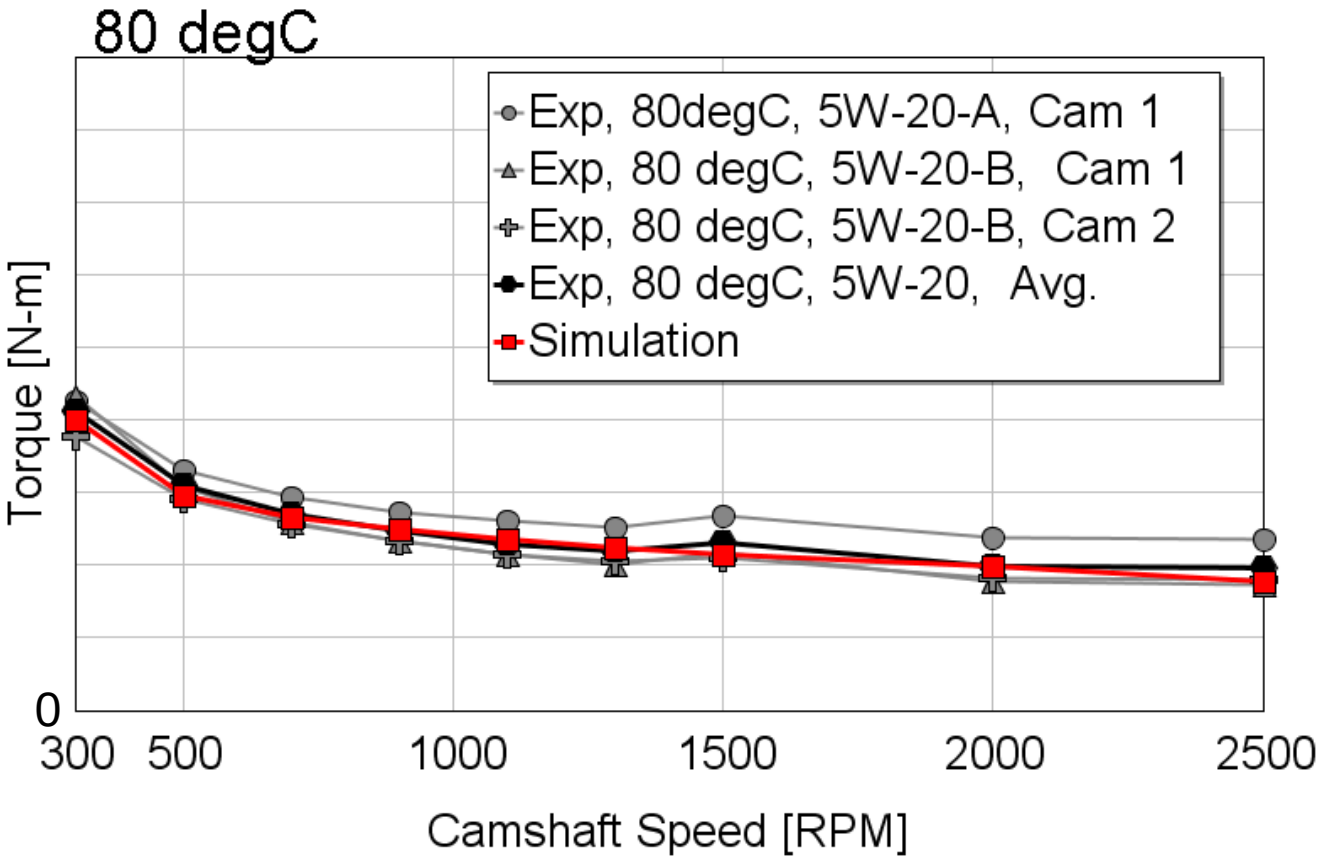
配气机构摩擦测试数据

Model of motored camshaft and valvetrain (direct-acting, flat-tappet)



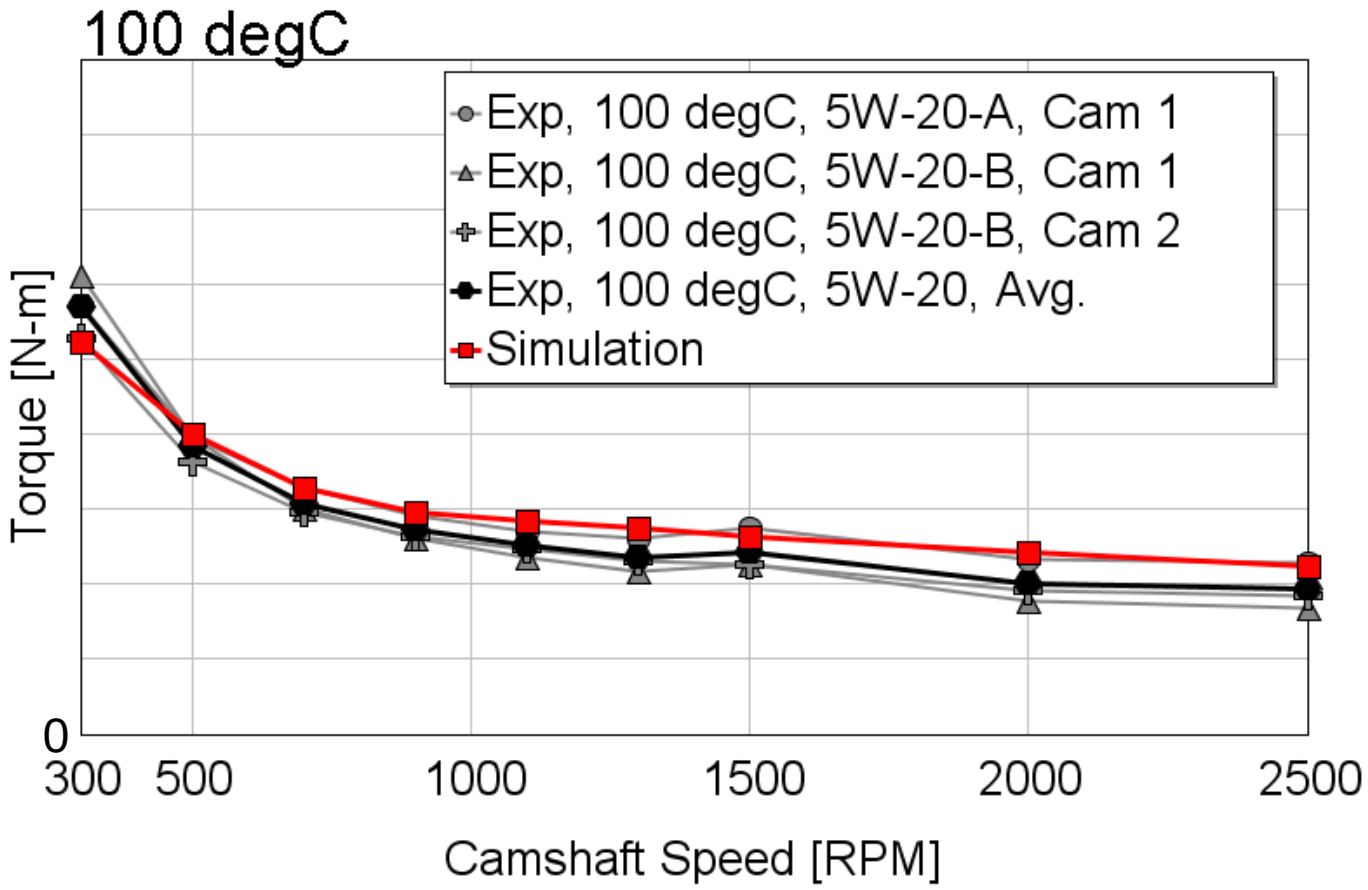
配气机构摩擦数据(Direct-acting, Flat-tappet VT)

Comparison to motored valvetrain (camshaft) torque



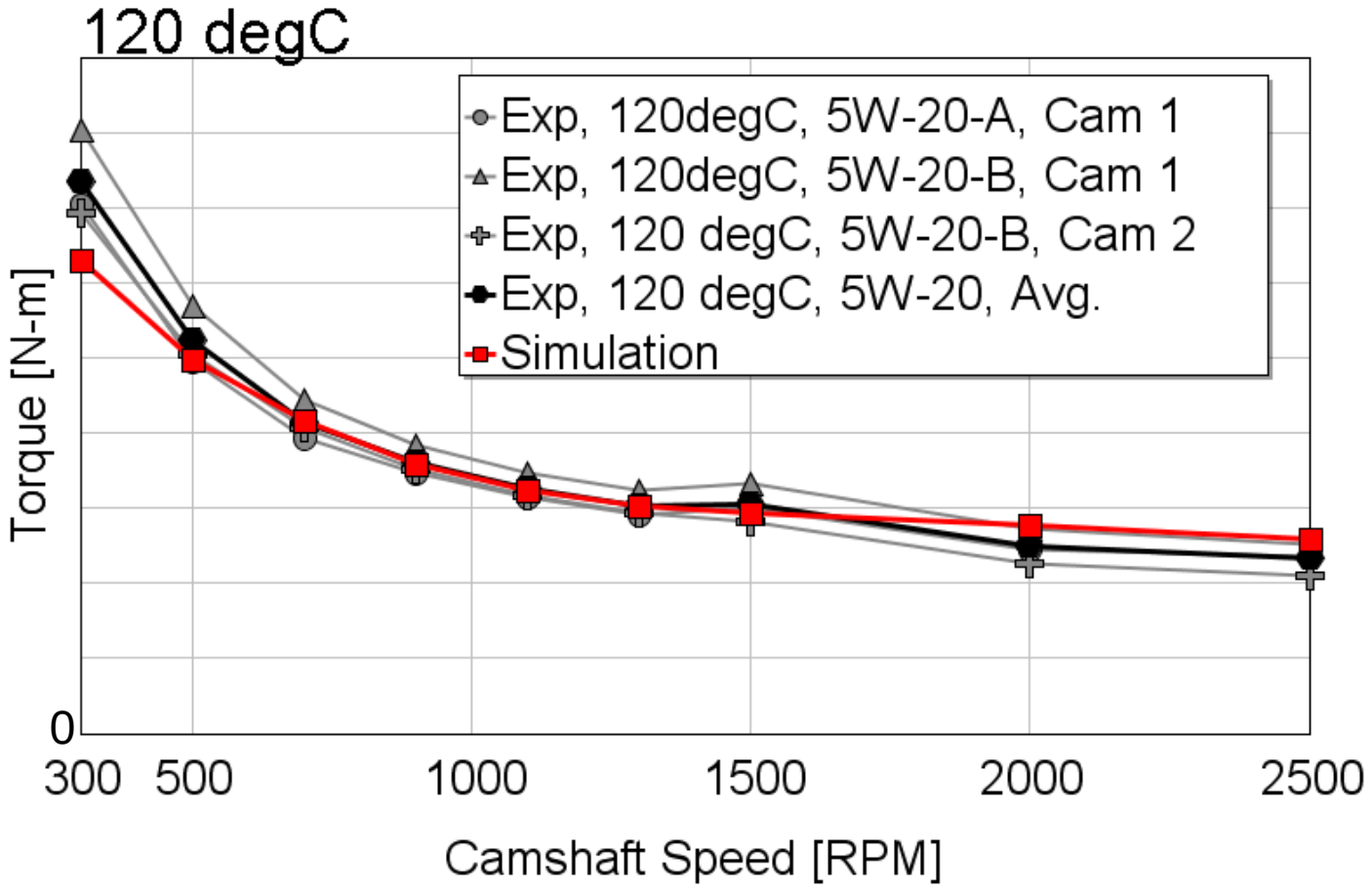
配气机构摩擦数据(Direct-acting, Flat-tappet VT)

Comparison to motored valvetrain (camshaft) torque



配气机构摩擦数据(Direct-acting, Flat-tappet VT)

Comparison to motored valvetrain (camshaft) torque



总结

- GT-SUITE平台已经提供了预测发动机摩擦损失所需要完全的模板，包括机械, 流体/液压和摩擦等多种部件
- 发动机摩擦（EF）部件有足够的灵活性可以单独模拟, 而且它们的计算效率适应于概念设计和优化设计时的相对优化处理
- GT 可以适当的展开进行发动机的摩擦研究的专门输出
- 灵活程度更高的关于HD/EHD油膜仿真技术v75有新的扩展，可用来进行更详细的仿真