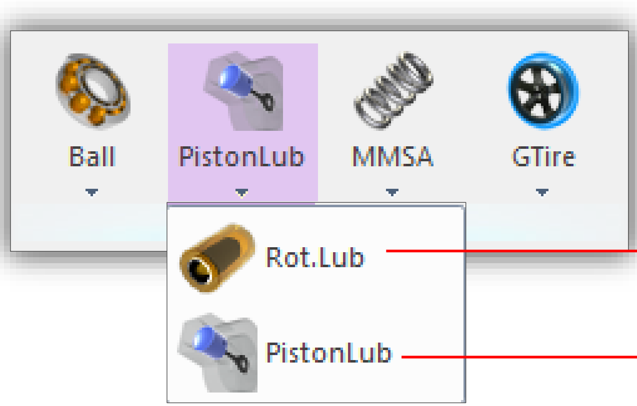
EHD (Piston Lubrication)

Index

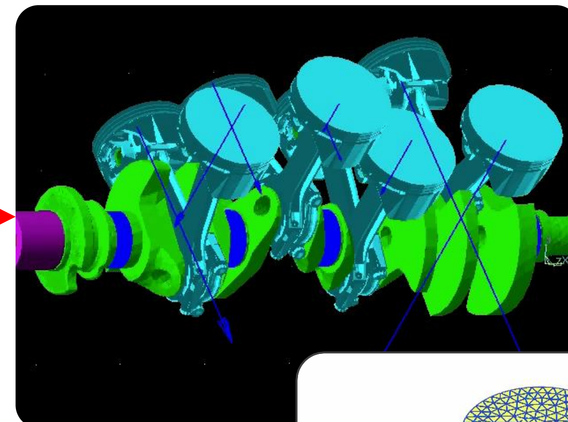
Background

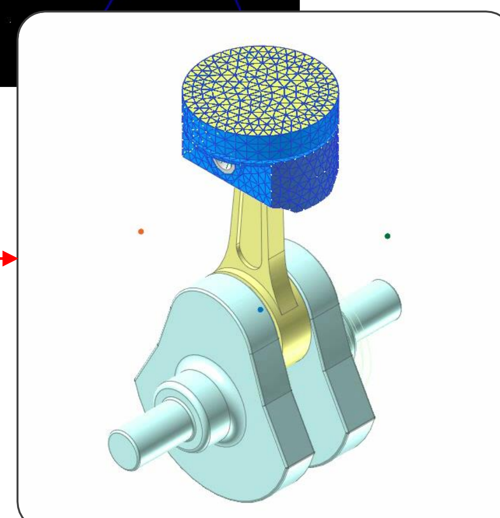
EHD Toolkit

- ❖ The EHD (Elasto-Hydro Dynamic) Toolkit is released in V9R1.
- ❖ The EHD bearing entity
- ❖ The new piston lubrication entity



● **Rotational Lubrication**





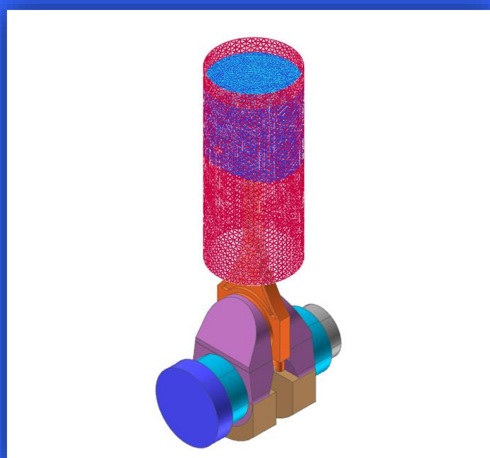
● **Piston Lubrication**

❖ Features

- ✓ Elastic Hydrodynamic Force
- ✓ Asperity Contact Force
- ✓ Consider Viscosity
- ✓ Consider Roughness
- ✓ EHD Force Contour Display
- ✓ Export Result Data

Interactions between MFBD and EHD

MFBD Solver



Thickness

Position
Velocity

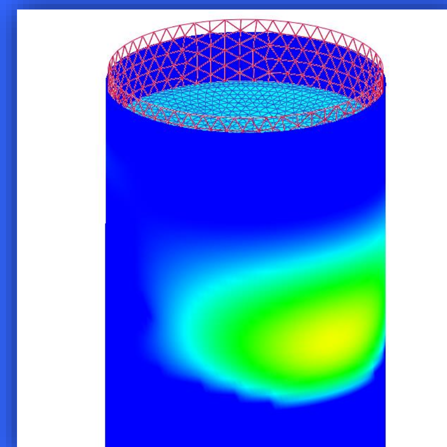
→

←

Force
Torque

Pressure
Thickness

EHD Solver

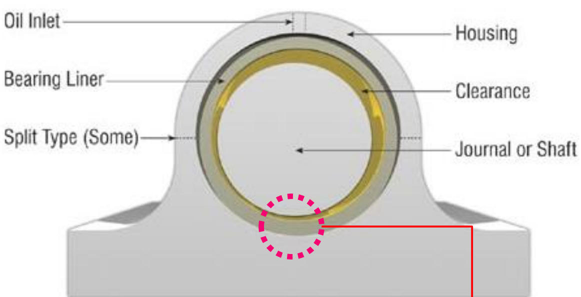


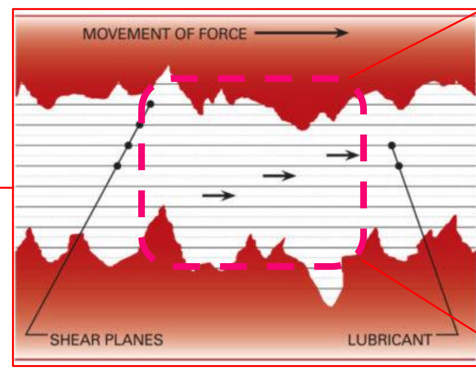
What is EHD?

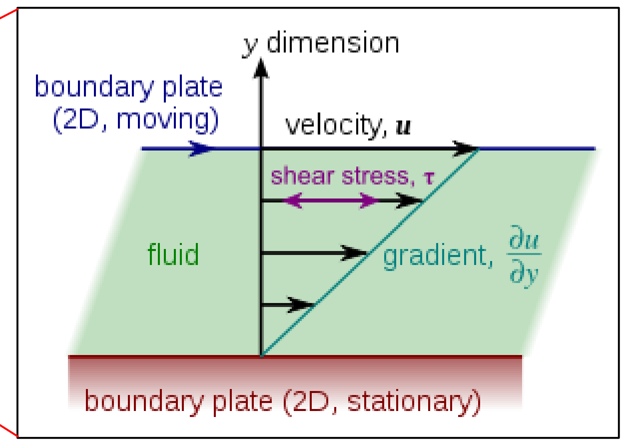
http://www.tribonet.org/wiki/hydrodynamic-lubrication/

- The goal of hydrodynamic lubrication is to add a proper lubricant, so that it penetrates into the contact zone between rubbing solids and creates a thin liquid film. This film separates the surfaces from direct contact. In general, this reduces friction and can consequently reduce wear, since friction within the lubricant is less than between the directly contacting solids.
- History of lubrication theory goes back to 1886 when O. Reynolds published famous equation of the fluid film flow in the narrow gap between two solids. This equation carries his name and forms a foundation of the lubrication theory.

< Journal Bearing >

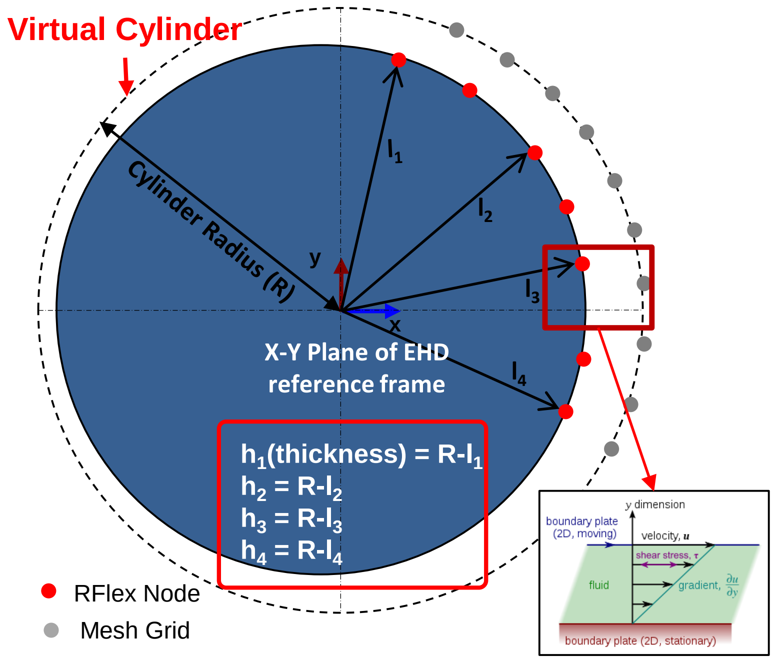






< Piston Lubrication>

Fluid Lubrication Region: Governing Equation



Navier-Stokes Equations

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \rho=const.$$

Boundary Conditions

$$u=U_1,\ v=V_1,\ w=W_1\ \ for\ y=0$$

$$u=U_2,\ v=V_2,\ w=W_2\ \ for\ y=H$$

Assumptions

$$\left(\frac{C_r}{R}\right)^2 \ll 1 \quad R_e\frac{C_r}{R} \ll 1 \quad \left(Re\frac{C_r}{R}\approx O(0.001)\right)$$

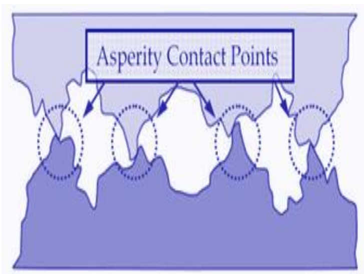
$$U_1=V_1=W_1=0$$

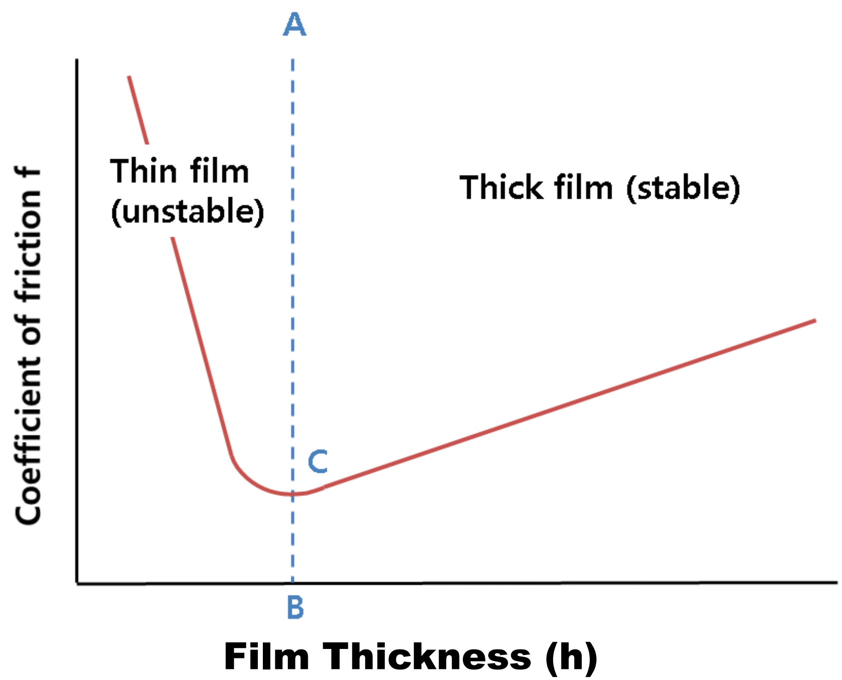
$$U_2,\ W_2=const.$$

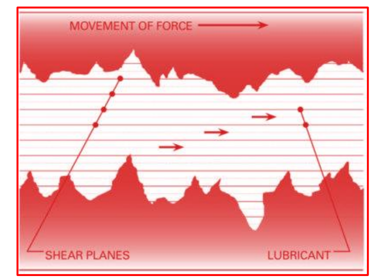
Reynolds Equation

$$\frac{\partial}{\partial x}\left(\Gamma\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\Gamma\frac{\partial p}{\partial z}\right)=12V_2+6U_2\frac{\partial H}{\partial x}+6W_2\frac{\partial H}{\partial z} \qquad \Gamma=\frac{H^3}{\mu}$$

Lubrication Region and Contact Region







Thin Film	Thick Film
Height / Roughness < 4	Height / Roughness ≥ 4
Metal-to-metal Contact Region	EHD Lubrication Region

Contact Region: Governing Equations

➢ Asperity Contact

- In the case of a mixed lubrication region, the asperity contact force is added in the fluid pressure. The equation for the asperity contact force is as follows:

Contact Pressure at the Point of the Surface

$$p_a(h) = KE'F_{5/2}(h/\sigma_s)$$

$$F_{5/2}(h/\sigma_s) = 4.4086 \times 10^{-5}(4 - h/\sigma_s)^{6.804}$$

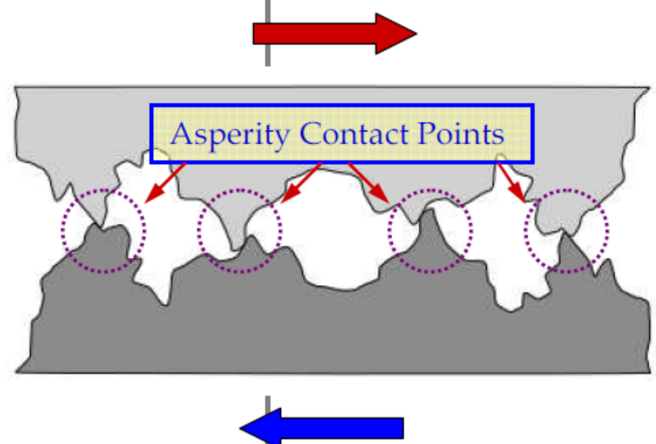
p_a is the asperity contact pressure [F/L^2].

h is the film thickness [L].

σ_s is the roughness[L].

K is the elastic factor.

E' is the composite elastic modulus [F/L^2]



Piston Lubrication Modeling Process

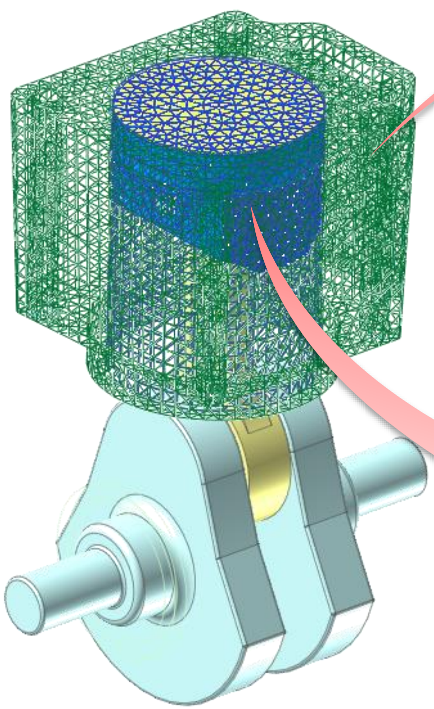
Piston Lubrication Modeling Process

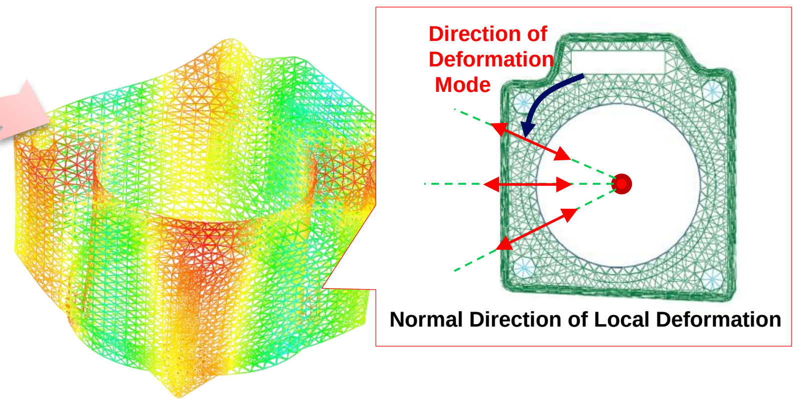
❖ Pre-stage of Piston Lubrication Creation Process

✓ Steps to create the RFlex bodies of Piston & Cylinder

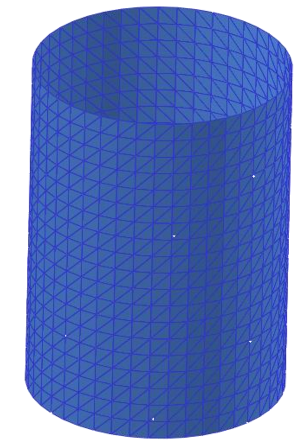
① RFlex bodies: user prepares the RFlex Bodies which includes the mode shapes with respect to local deformation

② PatchSet: user creates the PatchSet to that RFlex Bodies to define the EHD zone

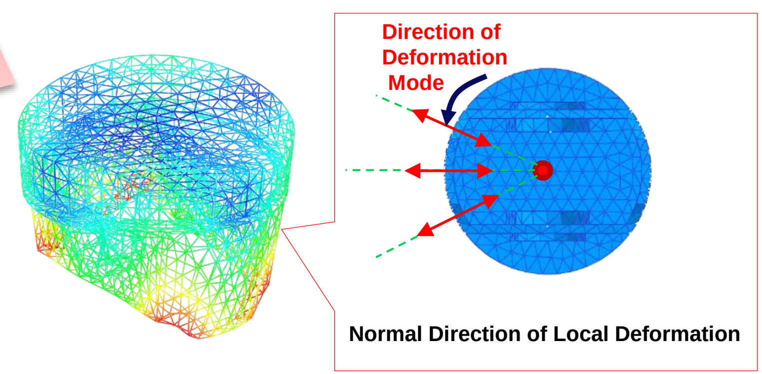




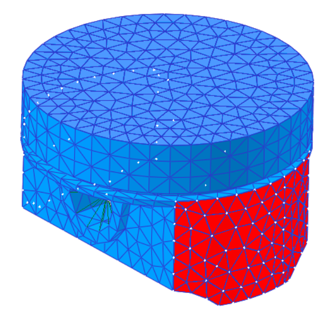
① Cylinder RFlex Body with Mode Shapes



② Cylinder PatchSet



② Piston RFlex Body with Mode Shapes

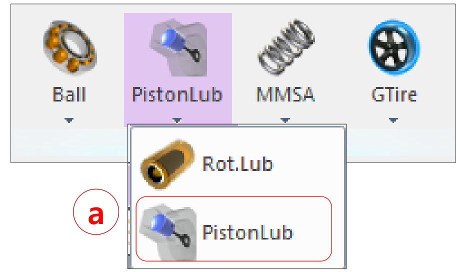


② Piston PatchSet

Piston Lubrication Modeling Process

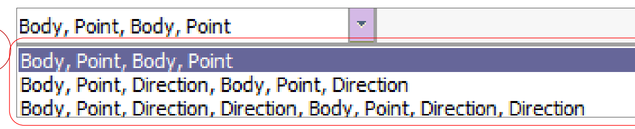
❖ Create the Piston Lubrication Entity

① Piston Lubrication Icon in the EHD Toolkit

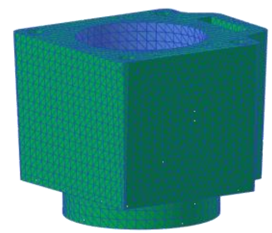


② Create the Piston Lubrication EHD

a. Click the **"Piston Lubrication" Icon**
b. Select the **Creation option**
c. Select the **Cylinder** body[Base Body]
d. Pick the **Point as Base Marker** of Cylinder body
e. Select the **Piston** body[Action Body]
f. Pick the **Point as Action Marker** of Piston body



c Base Body = Cylinder



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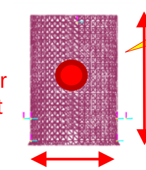
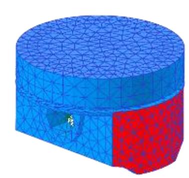


Point of Cylinder must to be located at the center of cylinder patchset

e Action Body = Piston



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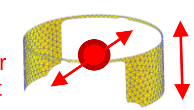


Point of Piston must to be located at the center of Piston patchset

You can define the EHD more easily using the option below,
"Body,Point,Direction,Direction,Body,Point,Direction,Direction"

- 1st Body: Cylinder
- Point: Base Marker Position
- Direction: Y-Axis Direction of Base Marker
- Direction: X-Axis Direction of Base Marker
- 2nd Body: Piston
- Point: Action Marker Position
- Direction: Y-Axis Direction of Base Marker
- Direction: X-Axis Direction of Base Marker

Piston Lubrication Modeling Process

❖ Define the Piston Lubrication properties

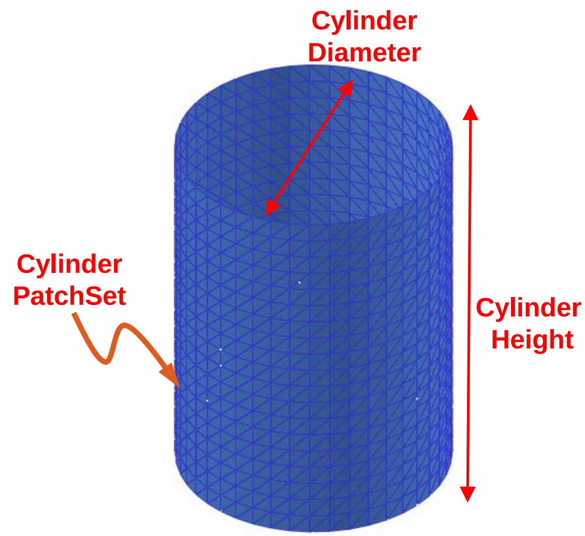
✓ **EHD Properties**

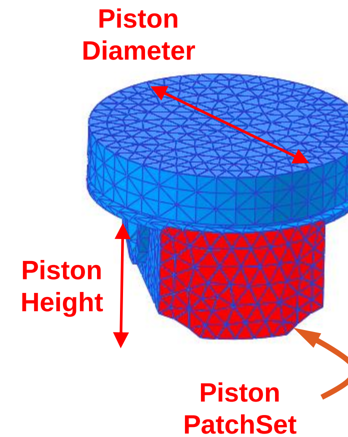
[Geometry Dimensions]

a. Piston Diameter
b. Piston Height
c. Cylinder Diameter
d. Cylinder Height

[RFlex]

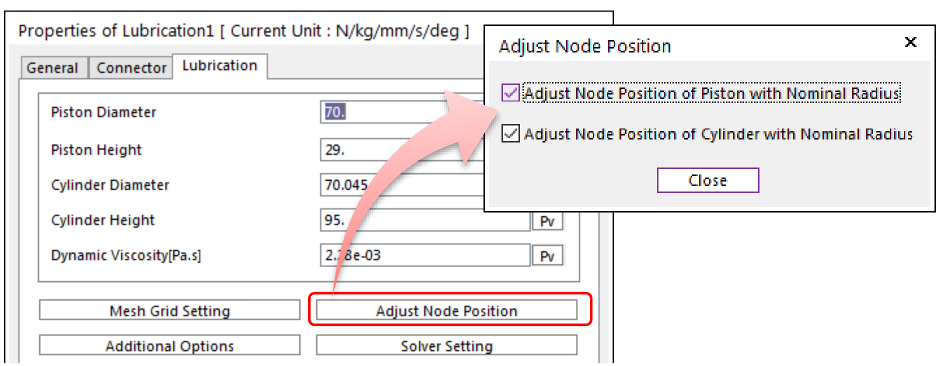
e. Piston.PatchSet
f. Cylinder.PatchSet

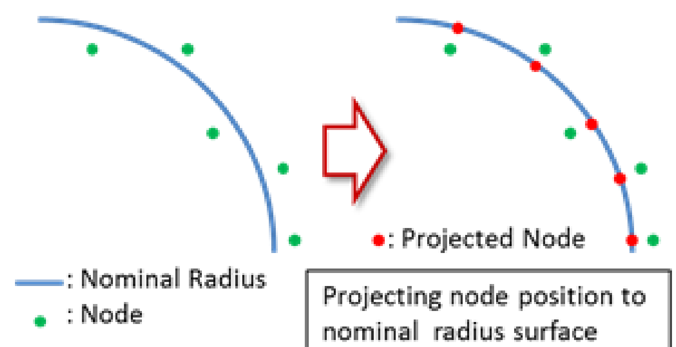




[Adjust Node Position Option]

In the case of RFlex Body, the node position could be located at an arbitrary point according to its mesh quality. So, it must to be updated to the nominal radius for an accurate EHD solution.





Piston Lubrication Modeling Process

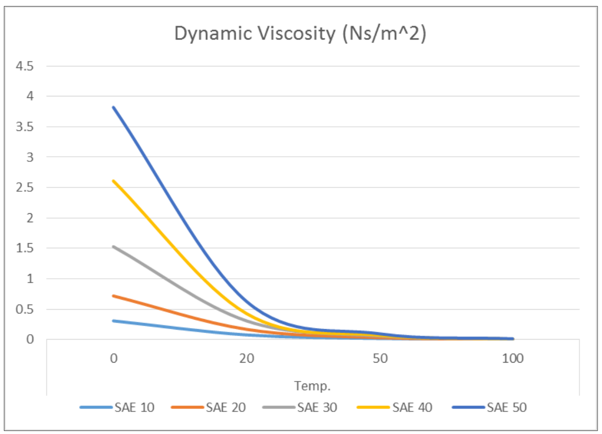
❖ Define the Piston Lubrication properties

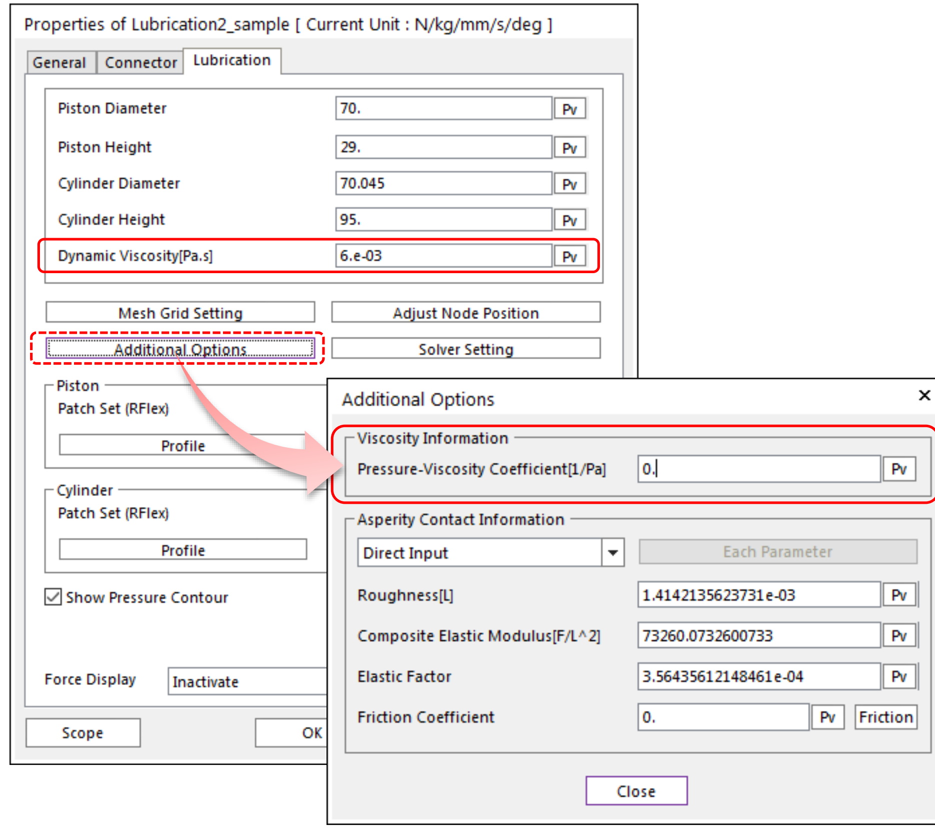
✓ **EHD Material Properties**

[Oil Properties]

a. **Dynamic Viscosity**

: In this example, it is defined as the constant viscosity value for oil dynamic viscosity.





a. **Pressure-Viscosity Coefficient**

$\mu = \mu_o e^{\alpha\, p}$

where, α is the pressure-viscosity coefficient.

Piston Lubrication Modeling Process

❖ Define the Piston Lubrication properties

✓ **EHD Material Properties**

[Asperity Contact Properties]

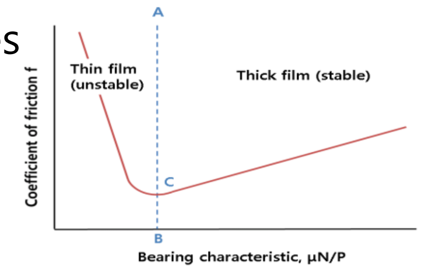
➢ Direct Input / Each Parameters & Calc.

a. Roughness

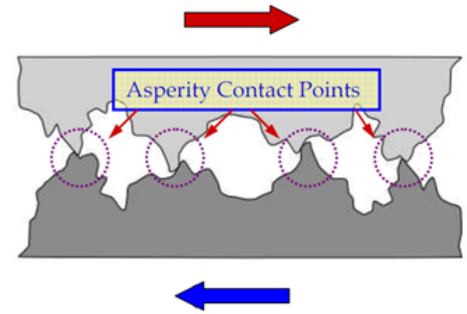
b. Composite Elastic Modulus

c. Elastic Factor

d. Friction Coefficient



Thin Film	Thick Film
Height / Roughness < 4	Height / Roughness ≥ 4
Metal-to-metal Contact	EHD Lubrication



Contact Pressure at the Point of the Surface

$$p_a(h) = KE'F_{5/2}(h/\sigma_s)$$

$$F_{5/2}(h/\sigma_s) = 4.4086 \times 10^{-5}(4 - h/\sigma_s)^{6.804}$$

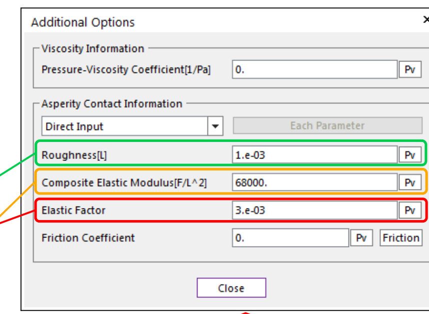
p_a is the asperity contact pressure [F/L^2].

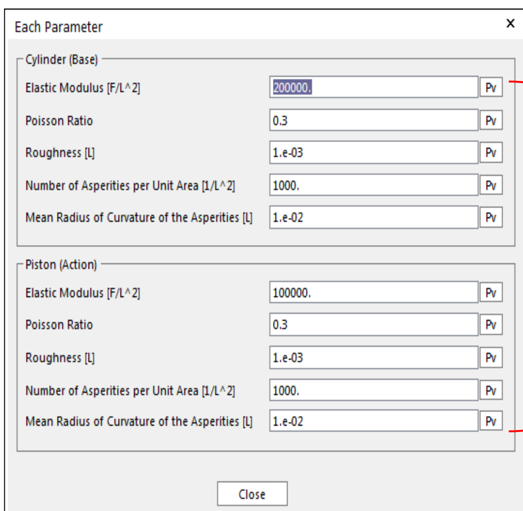
h is the film thickness [L].

σ_s is the roughness[L].

K is the elastic factor.

E' is the composite elastic modulus [F/L^2]





E_a, E_b : *Elastic Modulus*

v_a, v_b : *Poisson Ratio*

σ_a, σ_b : *roughness of each body*

η_a, η_b: *No. of Asperities per unit area*

β_a, β_b : *Mean radius of curvature of the asperities*

$$\sigma_s = \sqrt{\sigma_a^2 + \sigma_b^2}$$

$$E' = \frac{1}{\left[\frac{1 - v_a^2}{E_a}\right] + \left[\frac{1 - v_b^2}{E_b}\right]}$$

$$K = \frac{16\sqrt{2}}{15}\pi(\sigma_s\beta\eta)^2\sqrt{\frac{\sigma^2}{\beta}}$$

$$\eta = \sqrt{\eta_a\eta_b} \quad \beta = \left[\frac{1}{2\beta_a} + \frac{1}{2\beta_b}\right]^{-1}$$

Piston Lubrication Modeling Process

❖ Define the Piston Lubrication properties

✓ **Film Thickness**

: it can define the user defined film thickness as a boundary condition

a. Height Length

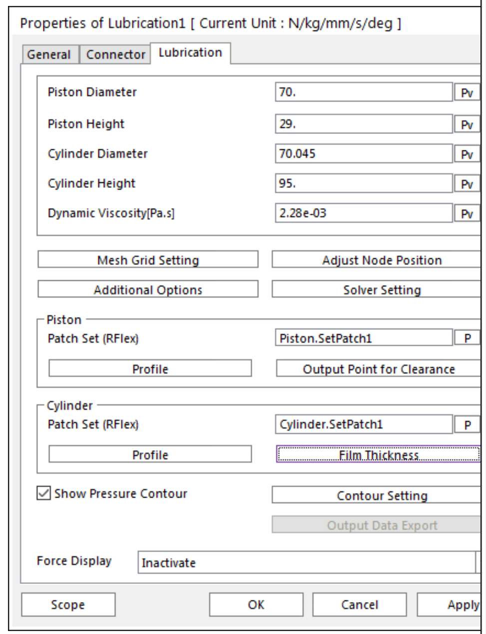
b. Reference Marker

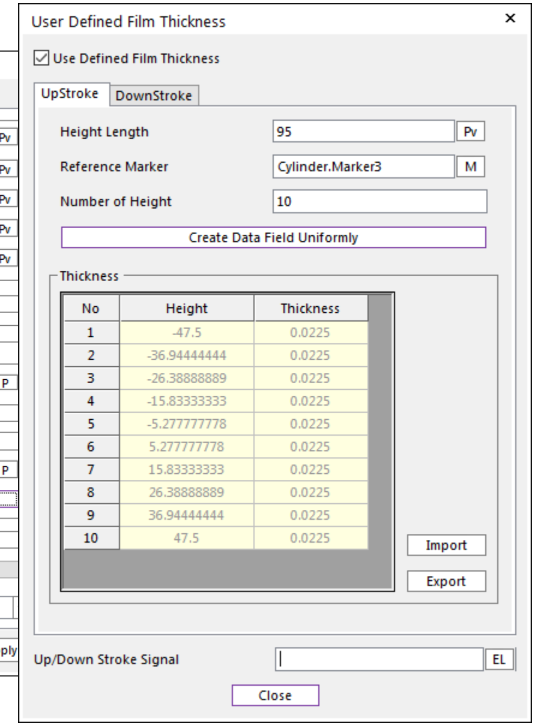
c. Number of Height

d. Thickness

  a. Height

  b. Thickens



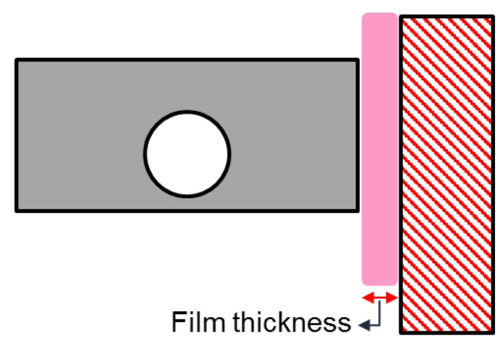


e. Up/Down Stroke Signal

: User defined oil film thickness can be defined as up & down stroke separately. So, it is necessary to judge the up/down state condition. It is judged by the pre-defined user expression in this field.

- Negative value(-) → Down-Stroke User Oil Film

- Positive value(+) → Up-Stroke User Oil Film



Piston Lubrication Modeling Process

❖ Define the Piston Lubrication Outputs

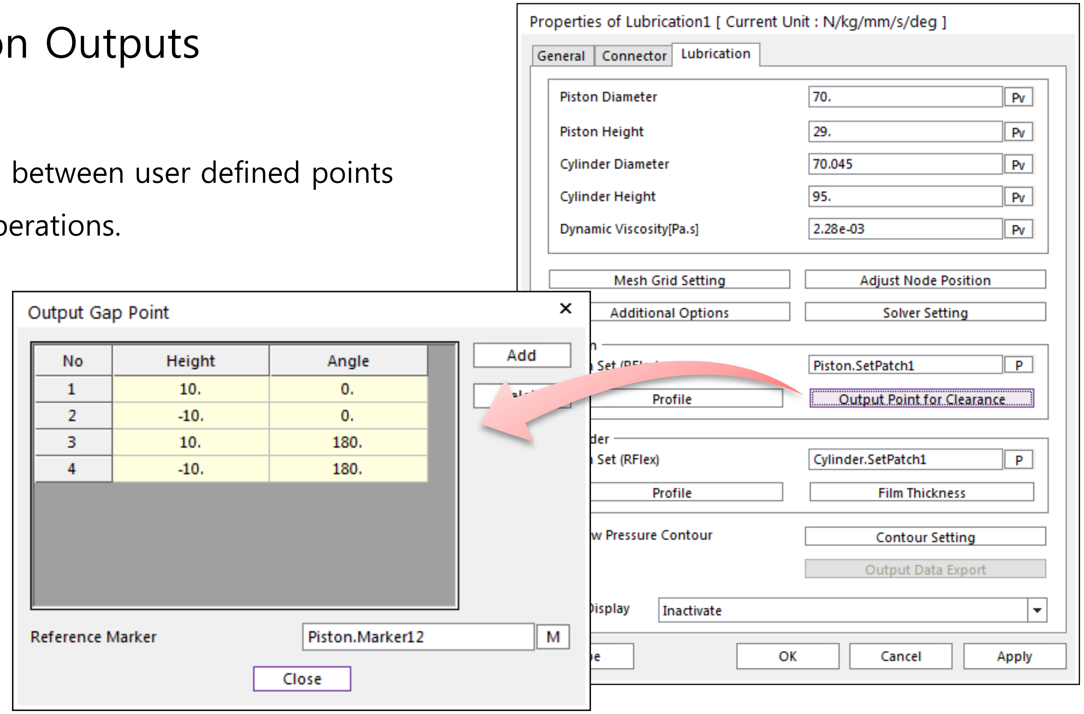
✓ **Output Point for Clearance**

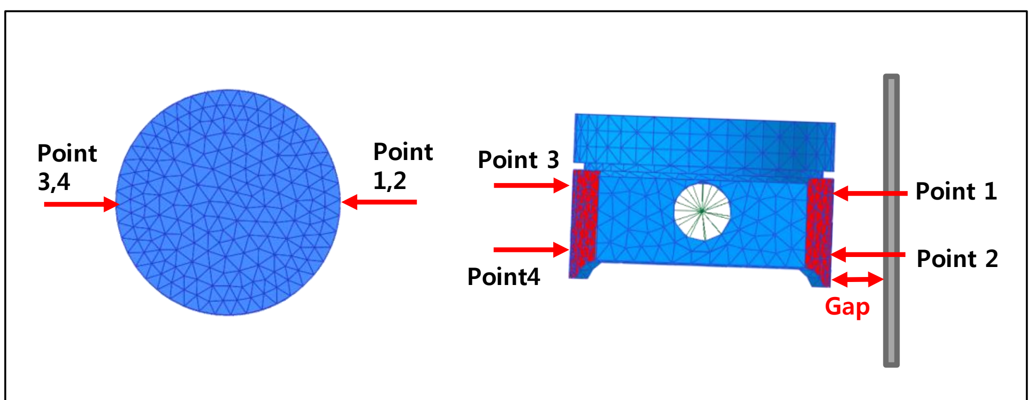
: it can print out the clearance values between user defined points on piston and cylinder wall during operations.

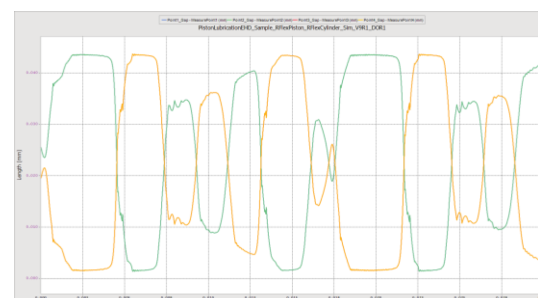
a. Height

b. Angle

c. Reference Marker







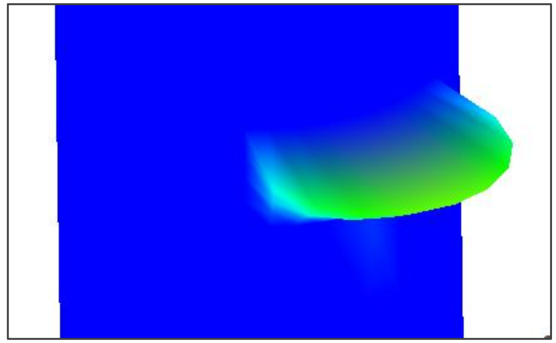
Piston Lubrication Modeling Process

❖ Define the Piston Lubrication Outputs

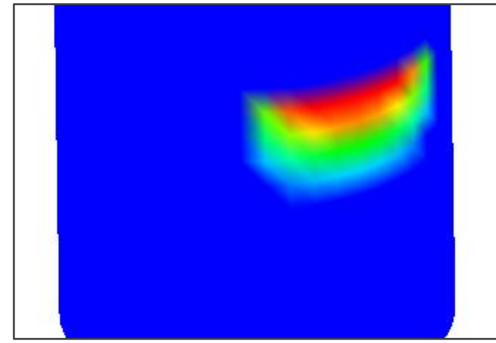
✓ **Contour Setting**

a. Contour Type
   a. 3D Surface
   b. Projection
b. Pressure Type
   a. Hydrodynamic
   b. Asperity
   c. Hydrodynamic + Asperity
c. Min/Max Option
   a. Cut Off Pressure
d. Color Option

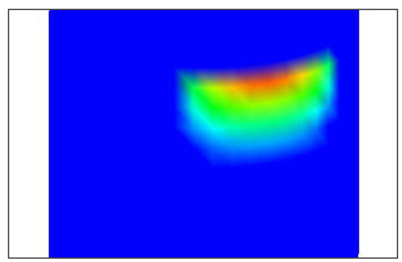
[3D Surface]



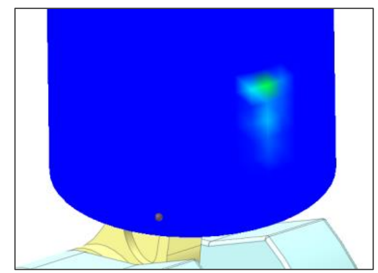
[Projection]



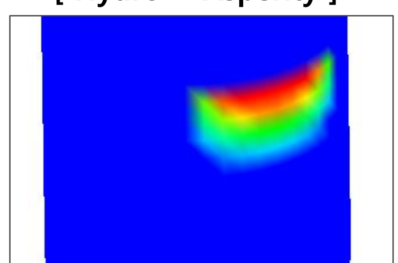
[Hydrodynamic]



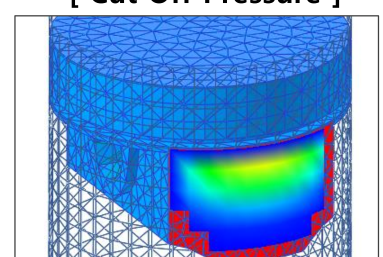
[Asperity]



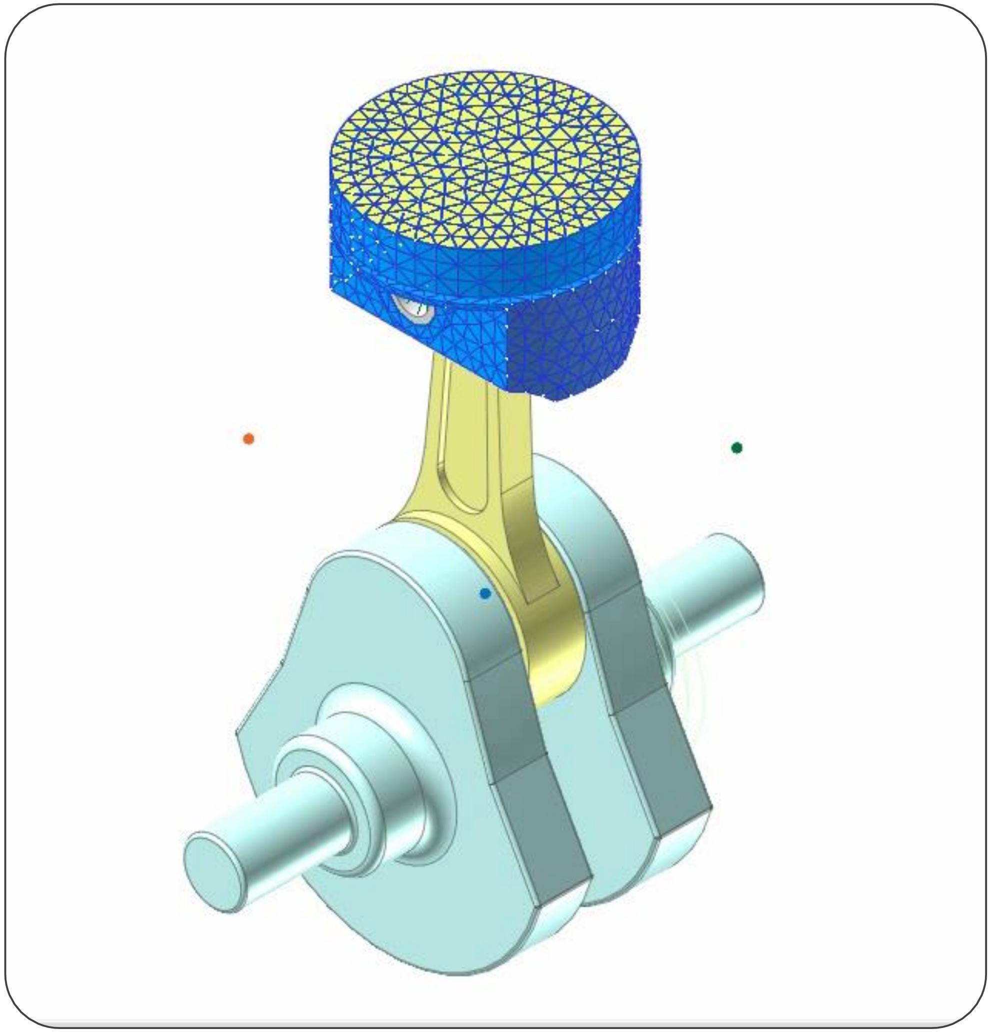
[Hydro + Asperity]



[Cut Off Pressure]



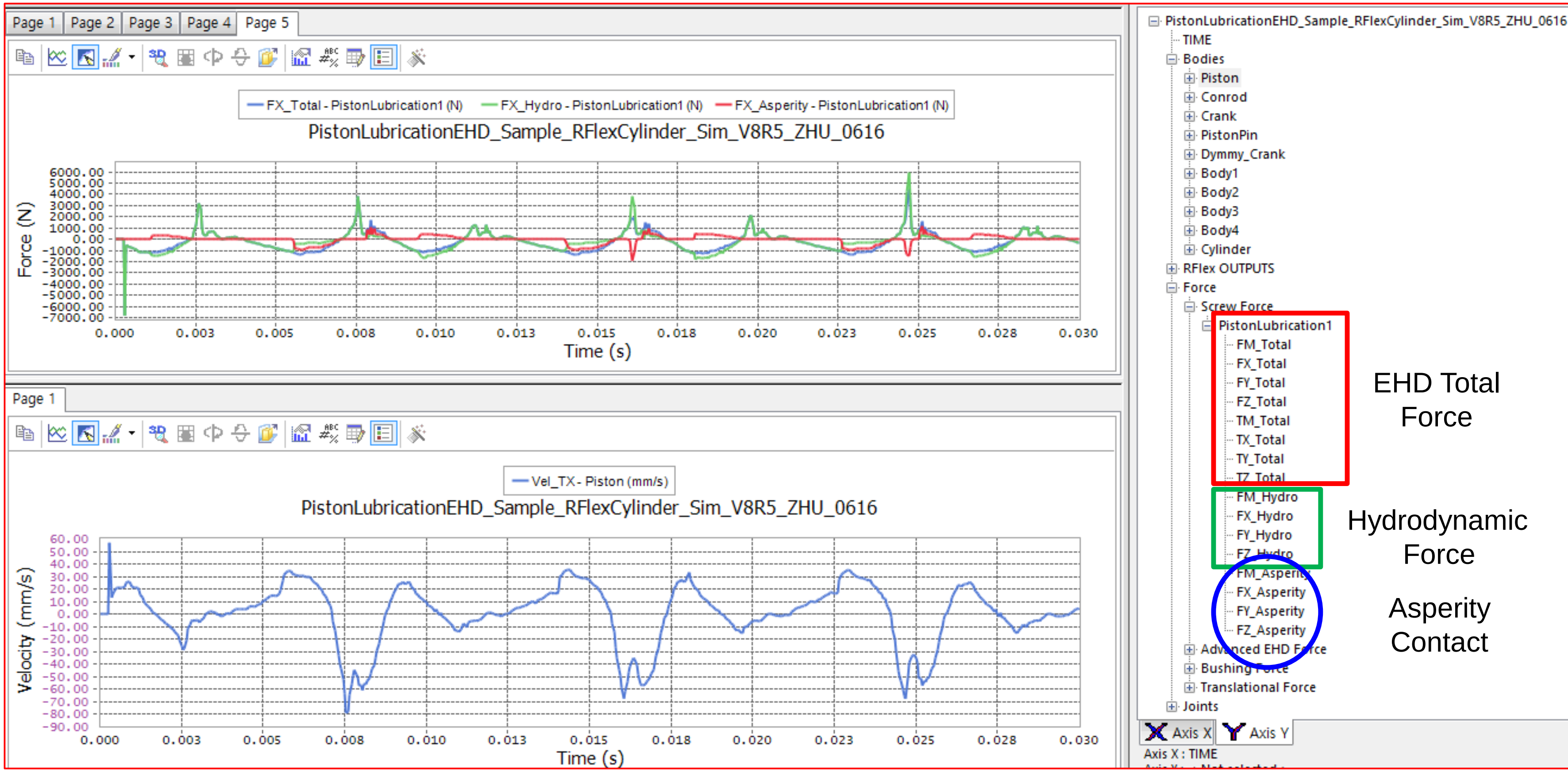
EHD Toolkit



Piston Lubrication Modeling Process

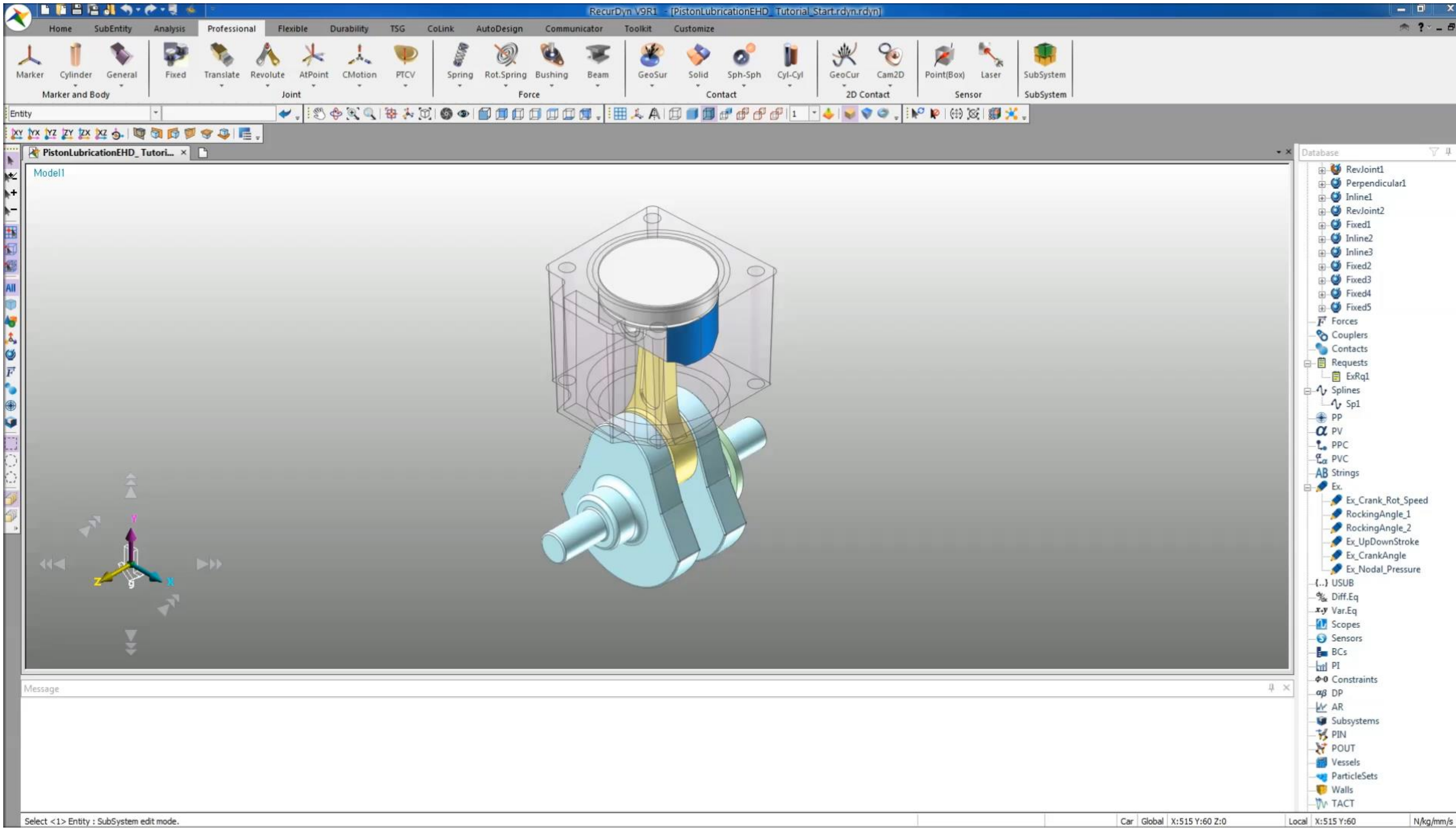
❖ EHD Plot Results

✓ EHD Force Results



Hydrodynamic Force: The force magnitude and components resulting from hydrodynamic pressure with respect to EHD reference marker.(**FM_Hydro**, **FX_Hydro**, **FY_Hydro**, **FZ_Hydro**)

Asperity Force: The force magnitude and components resulting from asperity contact pressure with respect to EHD reference marker.(**FM_Asperity, FX_Asperity, FY_Asperity, FZ_Asperity**)


RecurDyn V9R1 - [PistonLubricationEHD_Tutorial_Start.rdyn.rdyn]
Home
SubEntity
Analysis
Professional
Flexible
Durability
TSG
CoLink
AutoDesign
Communicator
Toolkit
Customize
Marker
Cylinder
General
Marker and Body
Fixed
Translate
Revolute
AtPoint
CMotion
PTCV
Joint
Spring
Rot.Spring
Bushing
Beam
Force
GeoSur
Solid
Sph-Sph
Cyl-Cyl
Contact
GeoCur
Cam2D
2D Contact
Point(Box)
Laser
Sensor
SubSystem
SubSystem
Entity
PistonLubricationEHD_Tutori...
Model1
Database
RevJoint1
Perpendicular1
Inline1
RevJoint2
Fixed1
Inline2
Inline3
Fixed2
Fixed3
Fixed4
Fixed5
Forces
Couplers
Contacts
Requests
ExRq1
Splines
Sp1
PP
PV
PPC
PVC
Strings
Ex.
Ex_Crank_Rot_Speed
RockingAngle_1
RockingAngle_2
Ex_UpDownStroke
Ex_CrankAngle
Ex_Nodal_Pressure
USUB
Diff.Eq
Var.Eq
Scopes
Sensors
BCs
PI
Constraints
DP
AR
Subsystems
PIN
POUT
Vessels
ParticleSets
Walls
TACT
Message
Select <1> Entity : SubSystem edit mode.
Car
Global
X:515 Y:60 Z:0
Local
X:515 Y:60
N/kg/mm/s

RecurDyn/EHD Tutorial

[Piston Lubrication]

Step 01 – Import RFlex Bodies

Steps

① Open the "**PistonLubricationEHD_Tutorial_Start.rdyn**" model in RecurDyn V9R1

② Select **G-Manager** icon in G-Manager group of Flexible tab

③ Select the **Cylinder** rigid body.

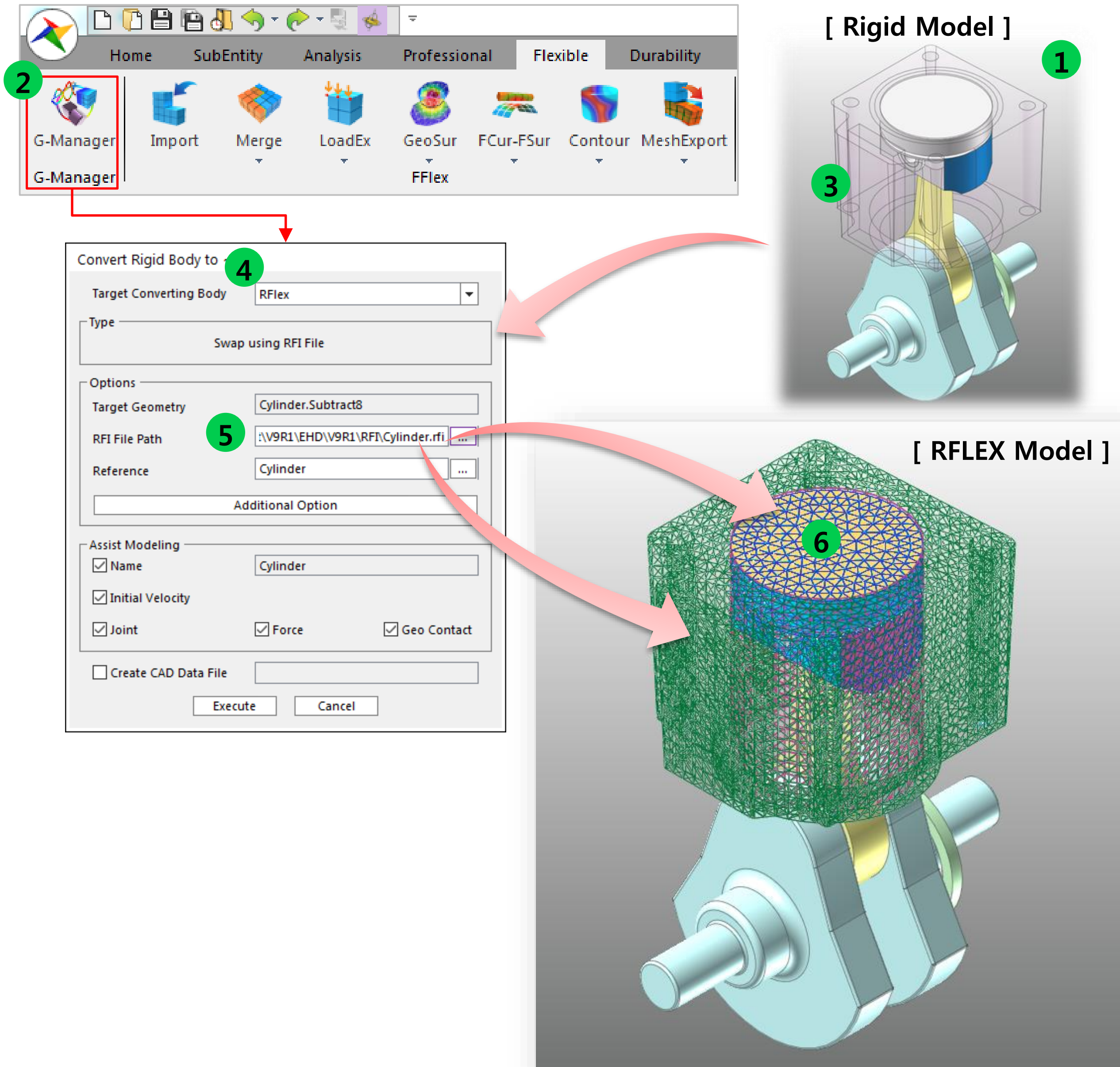
④ In G-Manger dialog, change the "**Target converting body**" to "**RFlex**"

⑤ Specify the RFI file in the "**RFI File Path**" input field using the already provided "**Cylinder.rfi**" and click **Execute**.

⑥ **Swap** the **Piston** body as same as above STEP 2~5, using the provided "**Piston.rfi**" file.

⑦ **Save** the model as "PistonLubricationEHD_Tutorial_Rflex.rdyn"

※ You can simulate and review the result of EHD applied to the rigid bodies. *PistonLubricationEHD_Tutorial_Rigid.rdyn*



Step 02 – Make a PatchSet

Steps

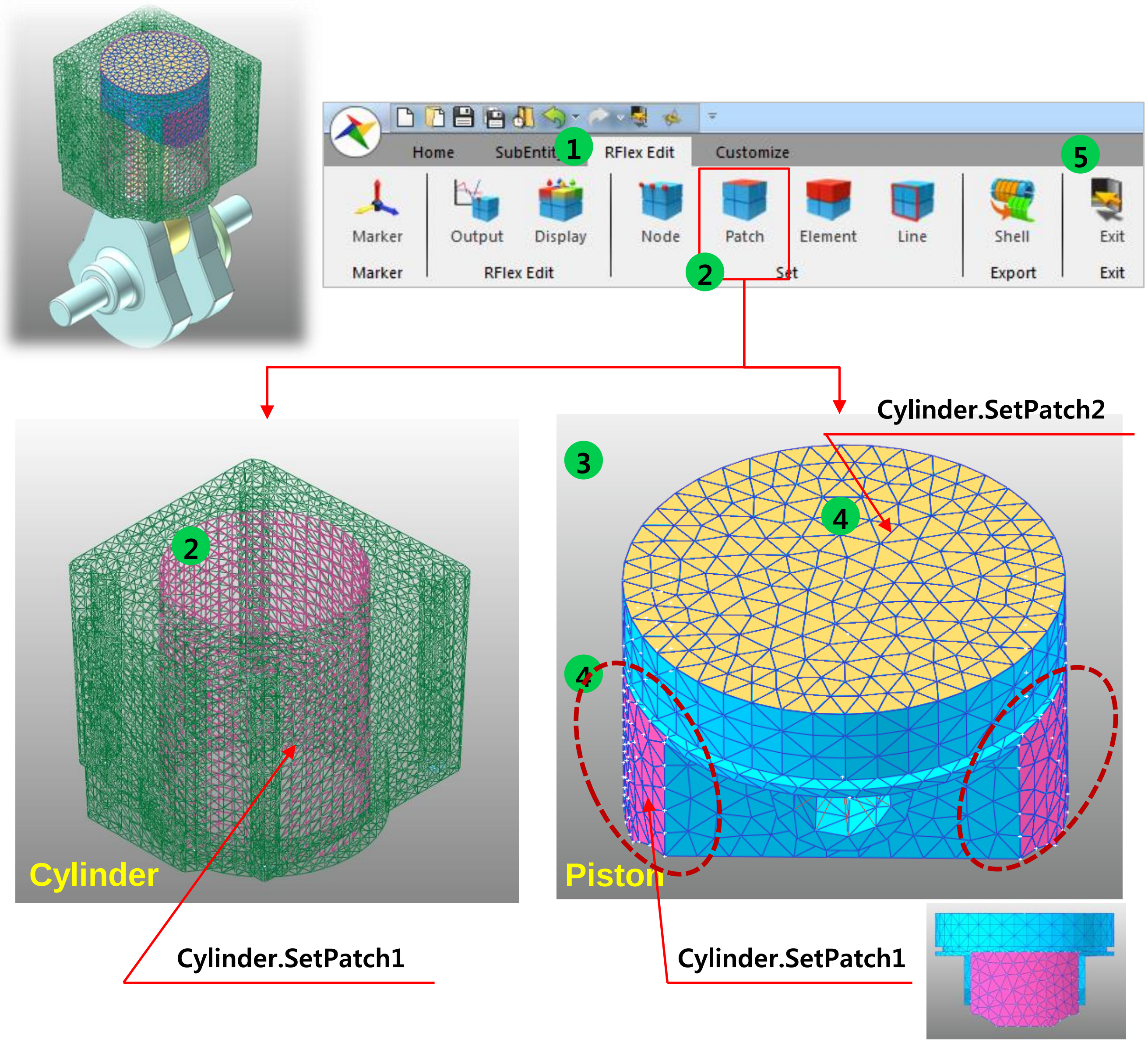
① **Enter** the **edit mode** of the Cylinder Body to create the PatchSet.

② Create **PatchSet** as an EHD **Cylinder** Wall as shown figure. (Use Add/Remove (Continuous))

③ **Exit** the **edit-mode**, and **enter** the **Piston** body.

④ Create **2 PatchSets** as for Piston. (**SetPatch1** using both side surfaces to apply EHD and **SetPatch2** using the upper surface to apply Gas-force Pressure) as shown in the figure.

⑤ **Exit** the **edit-mode**.



Step 03 – Create the Modal Pressure to the Piston

Steps

① Select "**Pressure**" icon (**Modal Pressure Load**) in **RFlex** Group of **Flexible** tab.

② In a Modal Pressure Load dialog, set **Piston.SetPatch2** as the **Patch Set**

③ Change the **Pressure Direction** from "Up" to "**Down**" direction

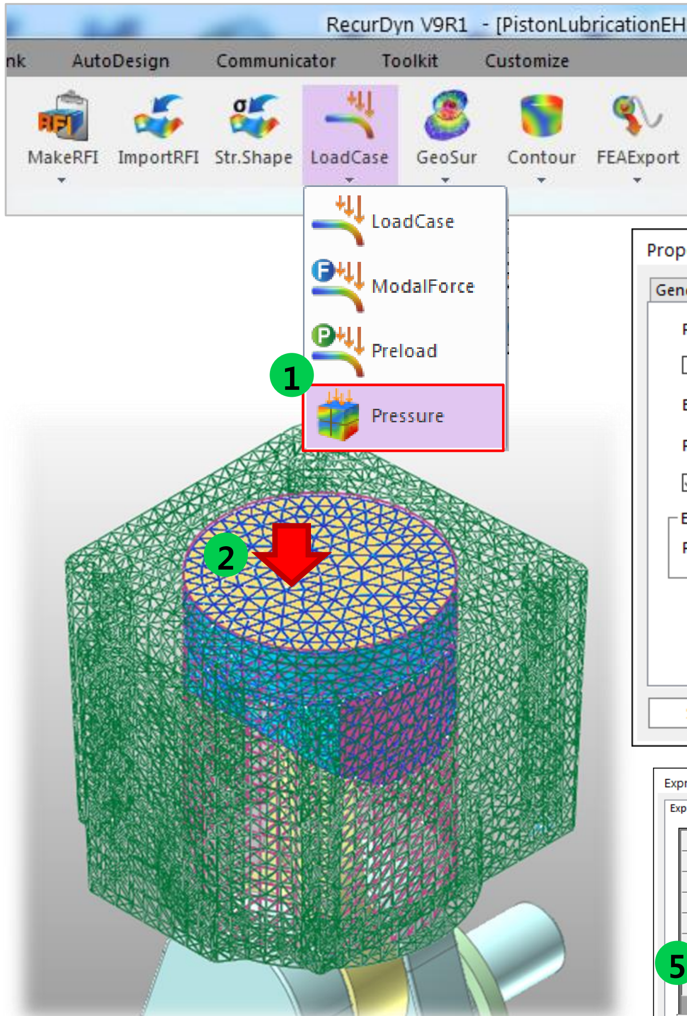
④ Click the **EL button** of **[Expression]-[Pressure]**.

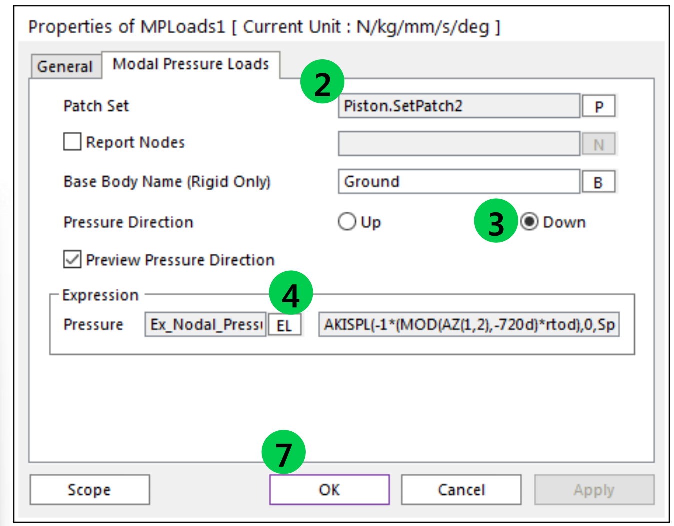
⑤ In the Expression List dialog, **select** the "**Ex_Nodal_Pressure**" expression.

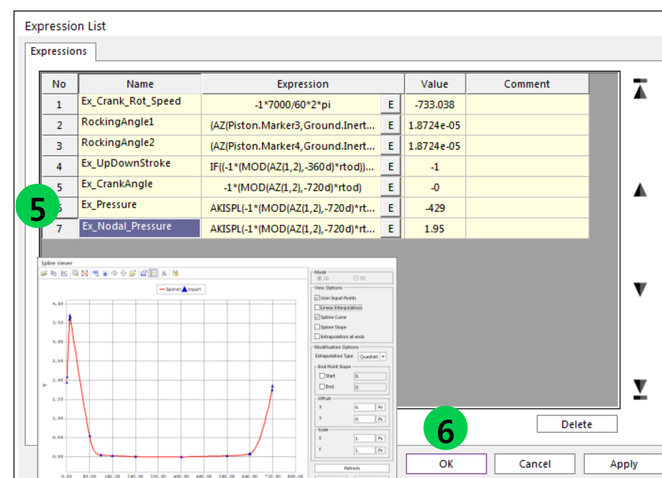
⑥ Close Expression List dialog

⑦ Click the "OK" to close the dialog.

※ The firing gas force is defined by Function Expression. In that expression, the gas force will be generated using a spline curve w.r.t the Crank Angle vs. Gas Force







Step 04 – Create Piston Lubrication EHD Entity

Steps

① Select **PistonLub** icon in the Toolkit group of the Toolkit tab.

② Set the **Creation option** to **"Body,Point,Direction,Direction, Body,Point,Direction,Direction"** (You can define the EHD axis more clearly)

③ Choose the **Cylinder** RFlex Body as Base-body of EHD

④ Pick the **Center Point of Base Body (Cylinder)**. In this tutorial, it is **"0,-46.5,0"**

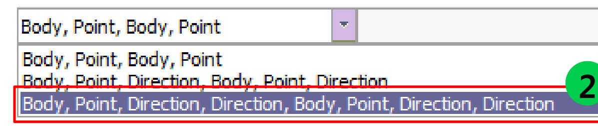
⑤ Set the **direction #1 of Base-Body** to Global Y Axis (0, 1, 0)
→ Y-axis direction of Base Marker

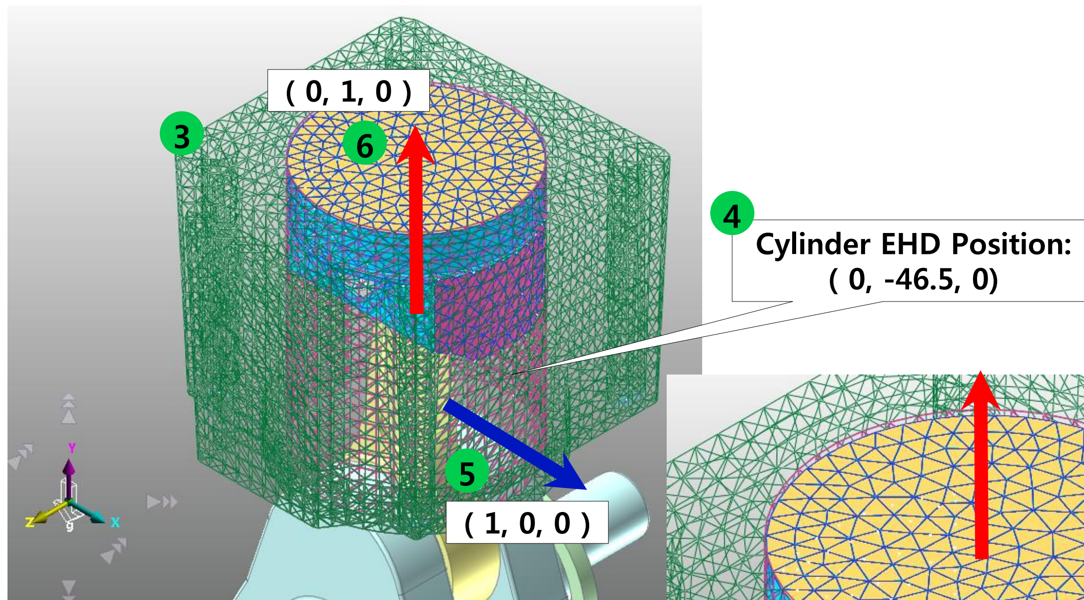
⑥ Set the **direction #2 of Base-Body** to Global X Axis (1, 0, 0)
→ X-axis direction of Base Marker

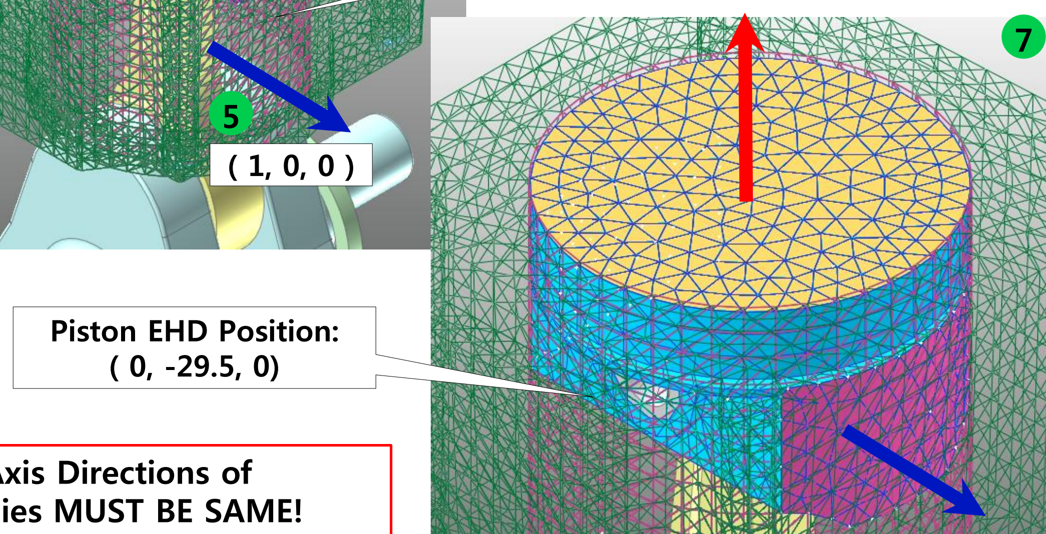
⑦ Define the **Action Body** as same as above steps 3 ~ 6

- **Action Body: Piston**
- **Center Point: 0,-29.5,0**
- **Direction #3: Global Y Axis**
- **Direction #4: Global X Axis**

⑧ **Lubrication1** is created.







X, Y Axis Directions of both bodies MUST BE SAME!

Step 05 – Define the EHD Geometry Properties

Steps

[EHD Geometry Setting]

① **Open** the Properties Dialog of **Lubrication1** (PistonLub EHD)

② **Input** the EHD Geometry **Properties** as below:

- Piston Diameter: 70
- Piston Height: 29
- Cylinder Diameter: 70.045
- Cylinder Height: 95

③ Input "**Piston.SetPatch1**" in the **Piston PatchSet** field.

④ Input "**Cylinder.SetPatch1**" in the **Cylinder PatchSet** field.

[Mesh Grid Setting]

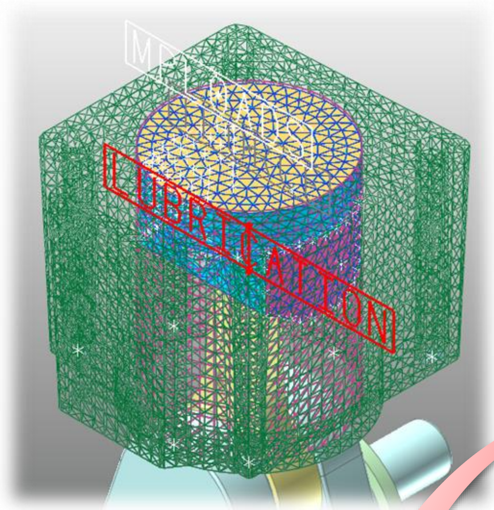
⑤ Click the "**Mesh Grid Setting**" button.

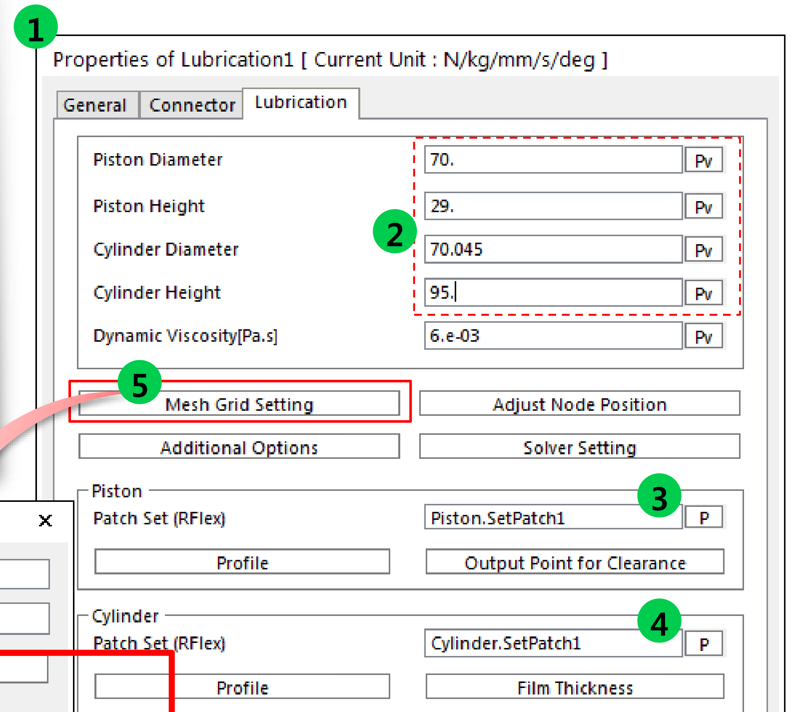
⑥ In the Mesh Grid Setting dialog,

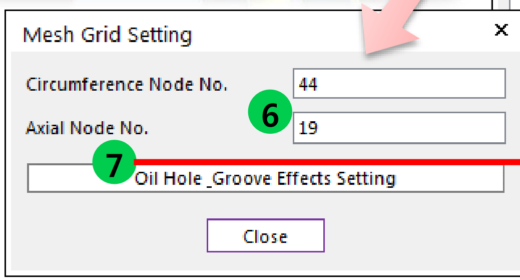
- **Circumference Node No.: 42**
- **Axial Node No.: 21**

⑦ Open the "**Oil Hole_Groove Effect Setting**" dialog, and check on the "**View Nodes**", then you can see the Mesh Grid Display.

⑧ Close the dialog.



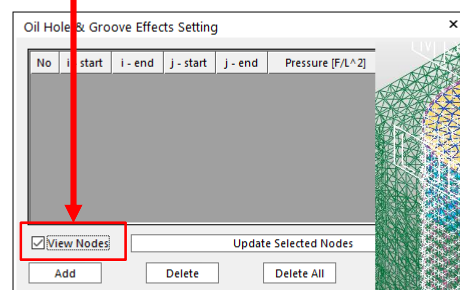


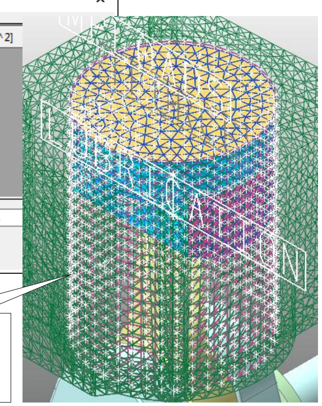


Tips: How to decide the No. of Mesh Grid

To improve the efficiency of the simulation of RecurDyn/EHD Model, make the length of the mesh grid similar to the maximum gap between piston and cylinder.

In the Tutorial, In this tutorial, the maximum gap is about 5 mm.
The circumference length is "π x 70.045 = 220.05" and height is "95"
Therefore, the recommended values are:
- Circumference Node No. is 44 (5x44 = 220)
- Axial Node No. is 19 (5x19 = 95)





Mesh Grid Preview

Step 06 – Define the EHD Material Properties

Steps

① In the property dialog of **Lubrication1,** Input the **Dynamic Viscosity** as "**6e-3**".

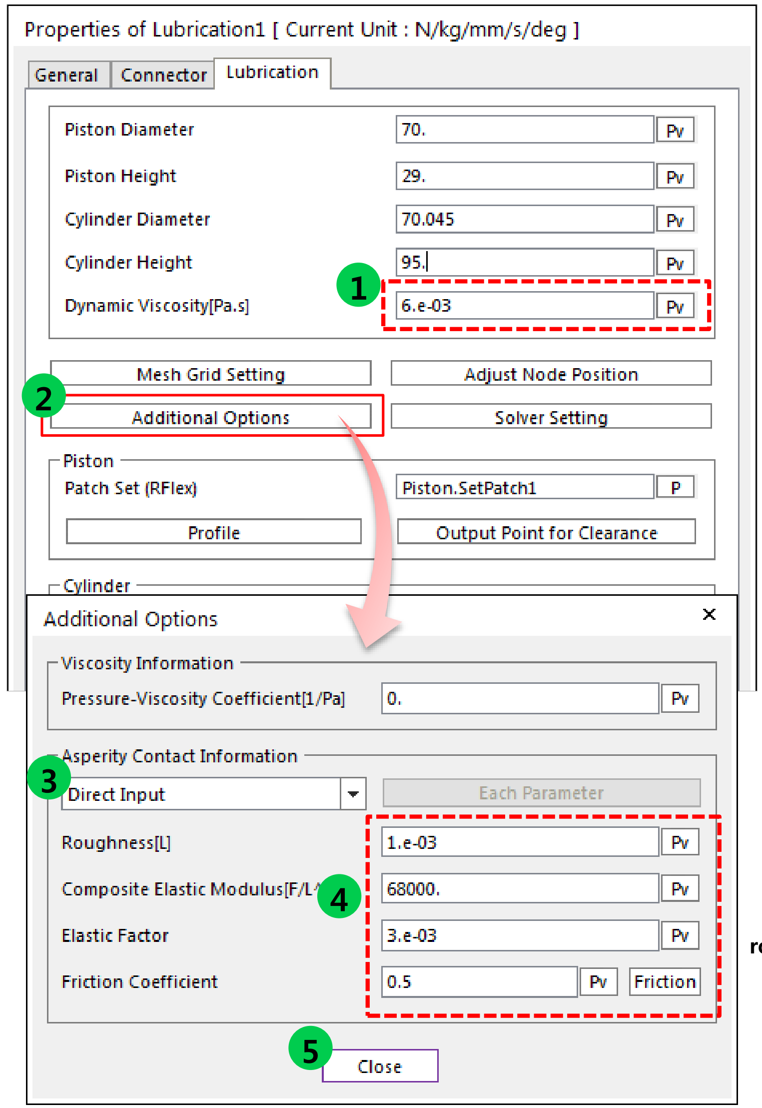
② Click the "**Additional Options**" **button.**

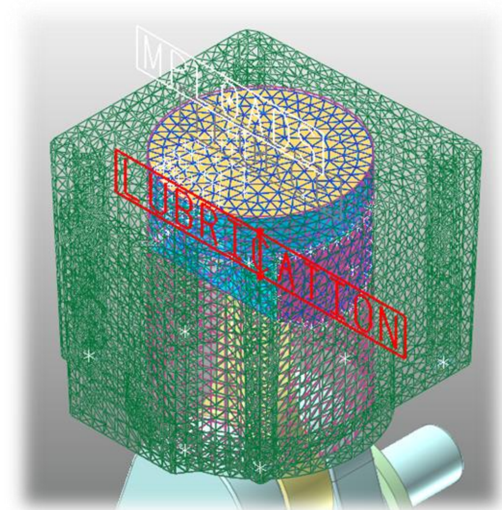
③ Use "**Direct Input**" in Asperity Contact Information.

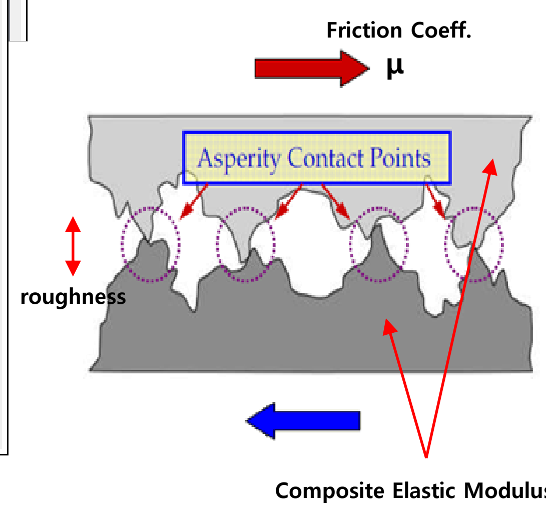
④ Input the values as shown below:

- **Roughness: 0.001**
- **Composite Elastic Modulus: 68000**
- **Elastic Factor: 0.003**
- **Friction Coefficient: 0.5**

⑤ Close the dialog







Step 07 – Set the EHD Solver Settings

Steps

① In the property dialog of **Lubrication1,** click the "**Solver Setting**" button

② Set the number of "**Maximum Iteration**" to "**200**"

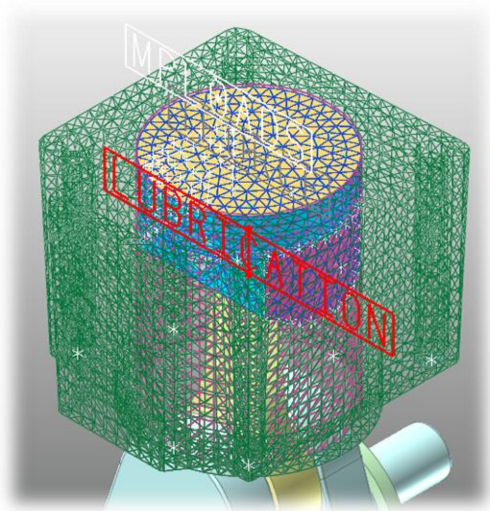
③ Set the "**Maximum Error**" to "**1e-2**"

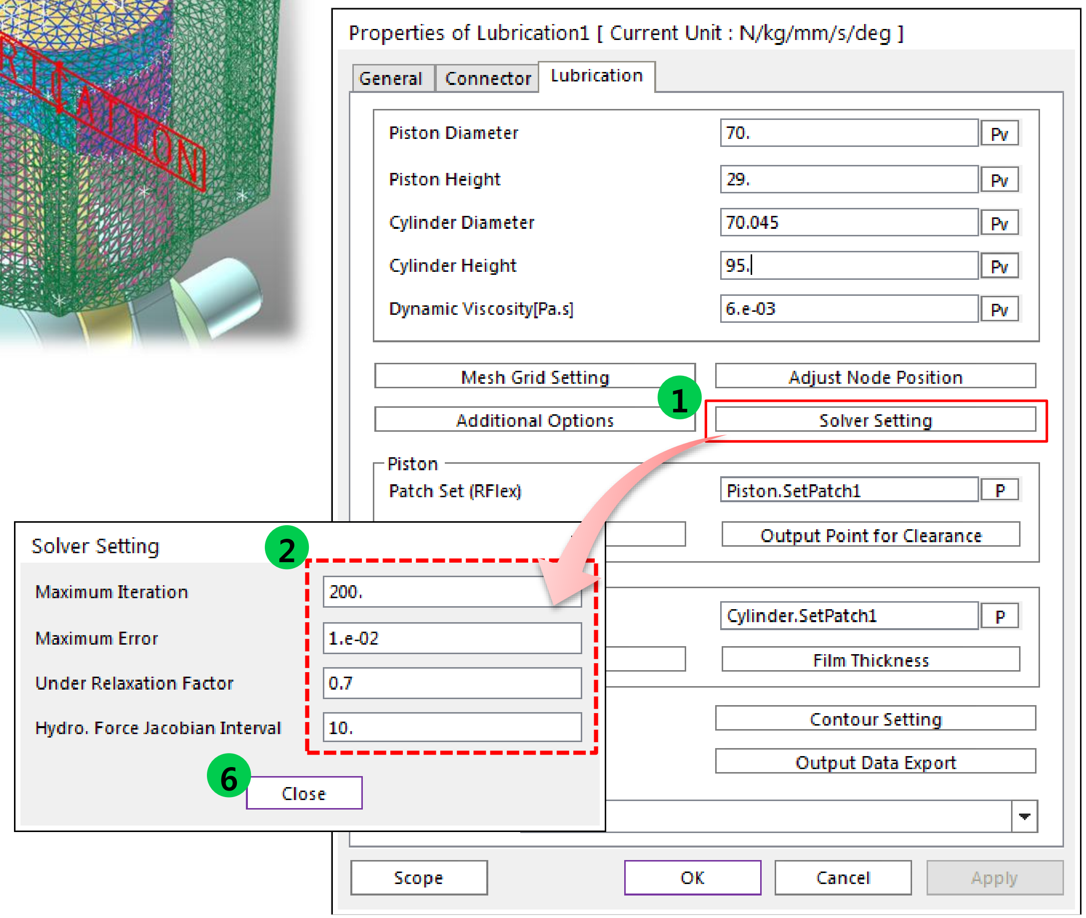
④ Set the "**Under Relaxation Factor**" to "**0.7**"

⑤ Set the "**Hydro. Force Jacobian Interval**" to "**10**"

(The bigger the value that you use, the faster the solving speed can be. However, increasing this value can reduce the accuracy)

⑥ **Close** the dialog





Step 08 – Run EHD Dynamic Analysis

Steps

① Open the property dialog of **Cylinder** RFlex Body, and select only **5 mode shapes (seq 7~ seq 11)** and close the dialog

② Open the property dialog of **Piston** RFlex Body, and select only **5 mode shapes (seq 7 ~ seq 11)** and close the dialog.

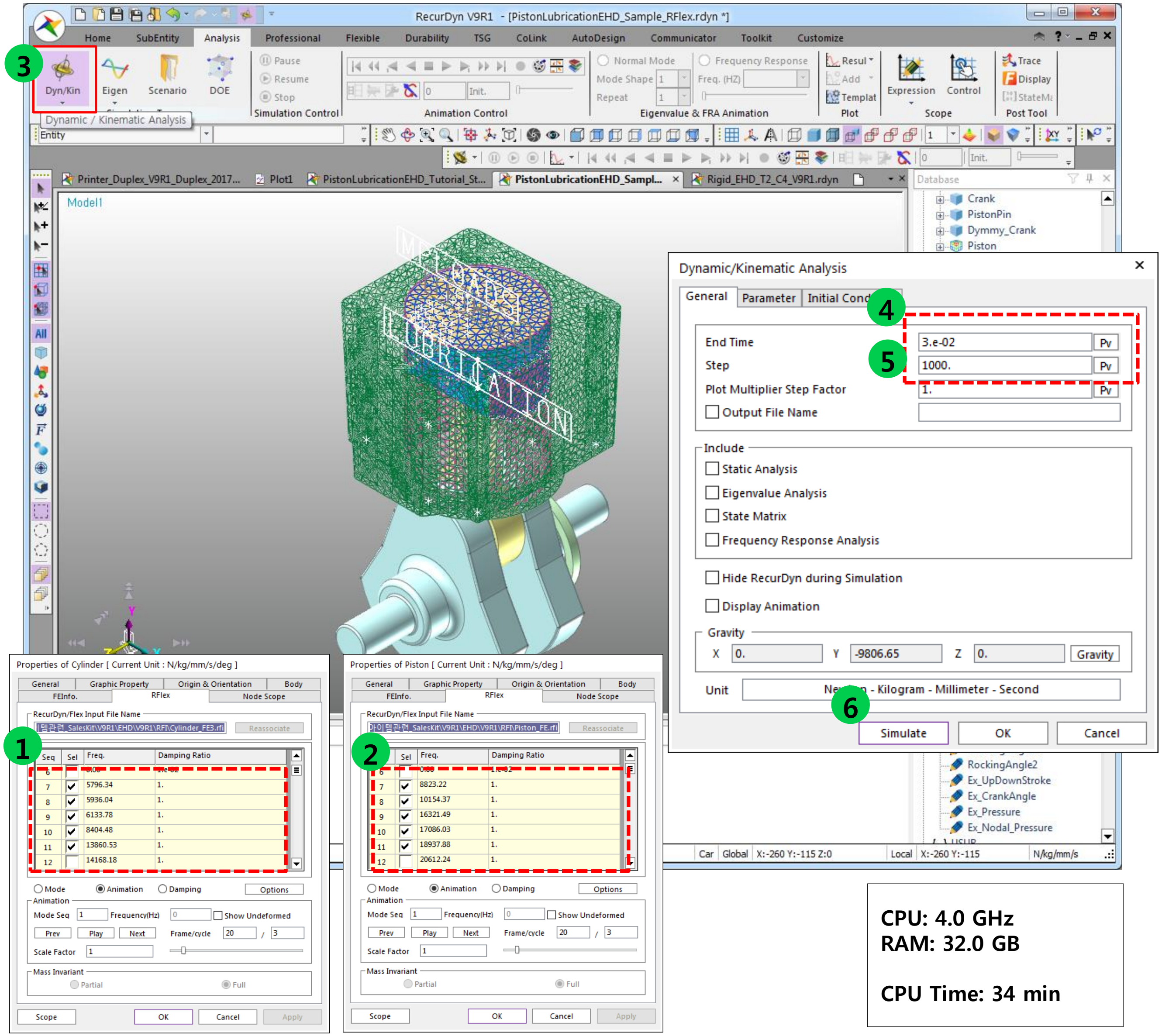
※ The more mode shapes are selected, the longer the solving speed would be.

③ Select **Dyn/Kin** icon in Simulation Type group of Analysis tab.

④ Set the **End Time** to "**3.e-2**"

⑤ Set the **Step to "1000"**

⑥ Click the "**Simulate**" button



CPU: 4.0 GHz
RAM: 32.0 GB

CPU Time: 34 min

Step 09 – Review the EHD Analysis Results (1)

Steps

[EHD Contour Result]

① **Open** property dialog of **Lubrication1** & **check on** the "**Show Pressure Contour**"

② Click the "**Contour Setting**" button

③ Set **Pressure Type** to **"Hydrodynamic + Asperity"**

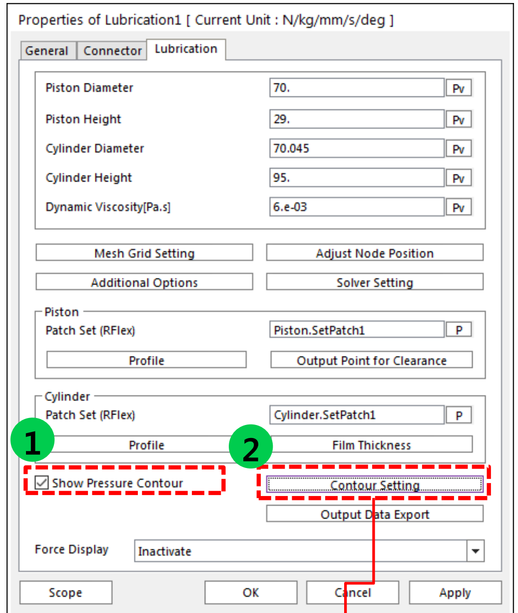
④ Click the **Apply** Button

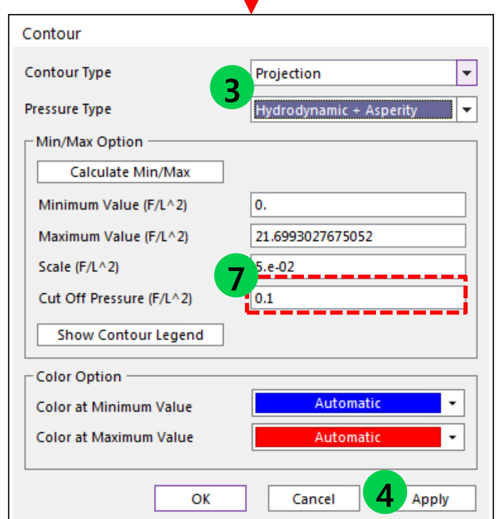
⑤ **Play** the **Animation**

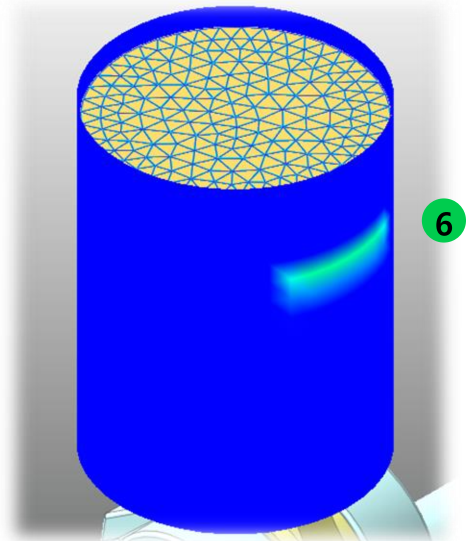
⑥ You can see the contour plot of the **EHD force result** in the working plane

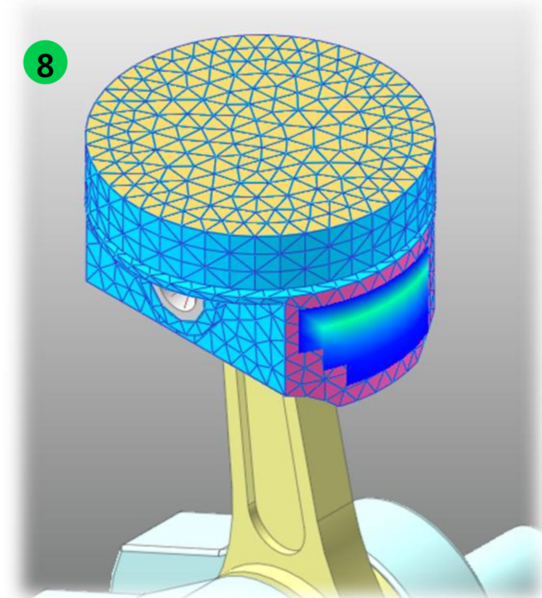
⑦ Set the **Cut Off Pressure** to "**0.1**", then click the **Apply** button.

⑧ **Play** the **Animation**, you can see the contour plot and the values less than the Cut Off value will not be displayed.









Step 10 – Review the EHD Analysis Results (2)

Steps

[EHD Plot Results]

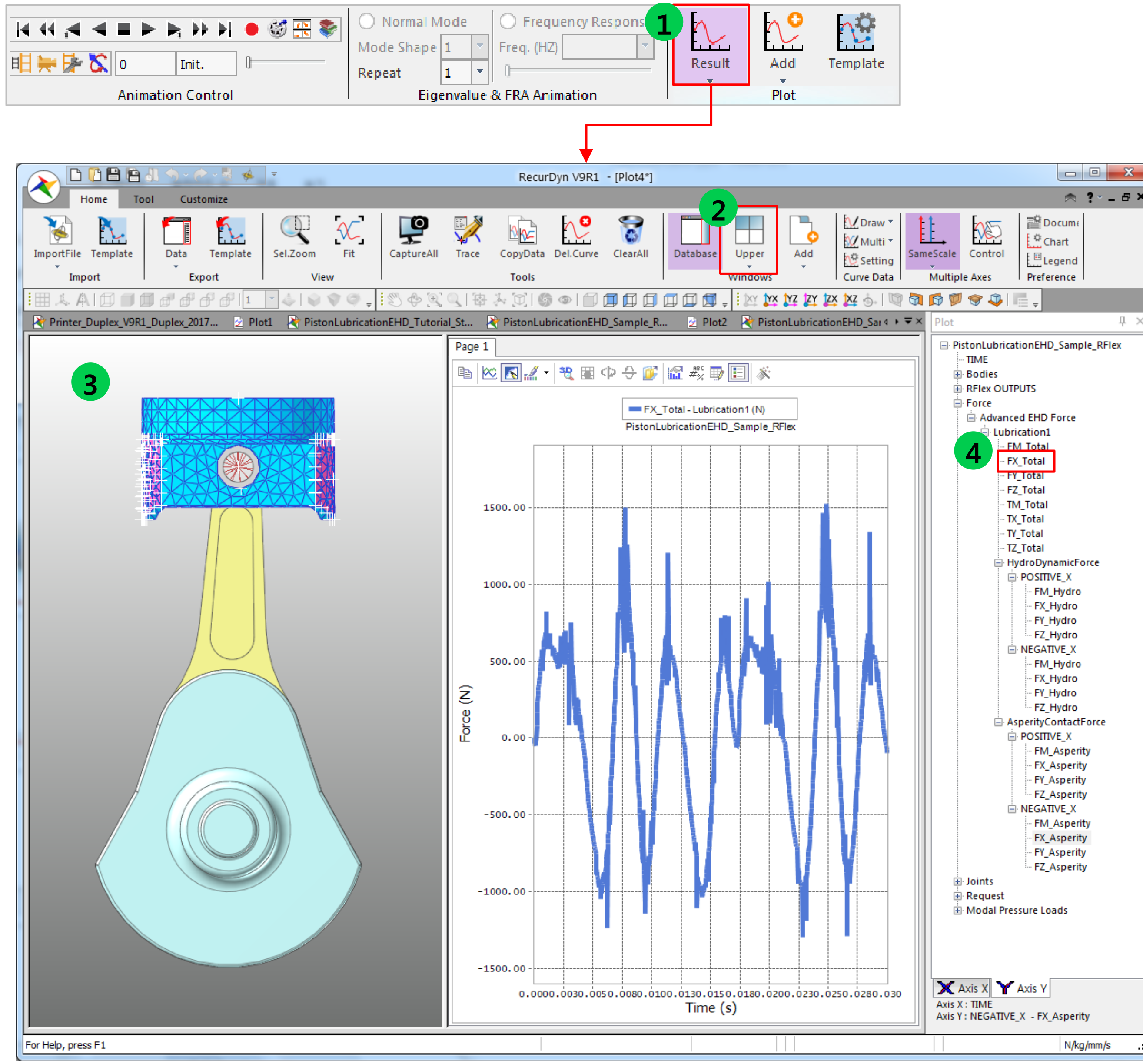
① Select the "**Result**" icon in the Plot group of Analysis Tab.

② Select **Upper** icon in Windows group of Home tab to Split the Plot Window

③ Load animation to the left-side window. ([Tool]-[Animation]-[**LoadAni**])

④ Click the Right-side Plot window, and **draw the curve** from Plot Database ("**Force/Advanced EHD Force/Lubrication1/FX_Total**")

※ User can see the Hydro+Asperity Total Lubrication Force between Piston and Cylinder. Also, user can see the contact area in the left-side animation result.



Step 11 – Review the EHD Analysis Results (3)

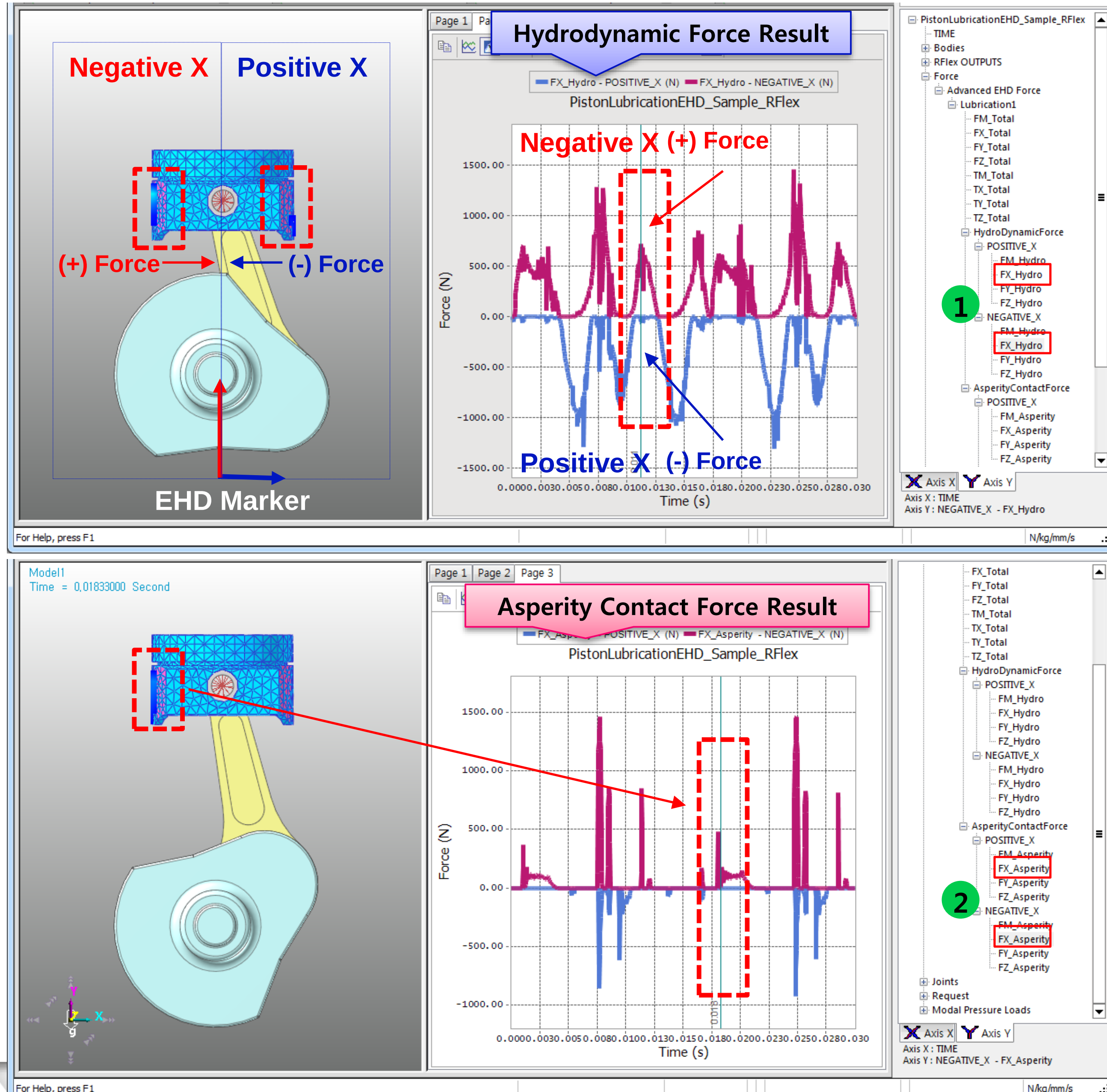
Steps
[EHD Plot Results]

① Draw the curves from Plot Database "…/Lubrication1/HydroDynamicForce/Positive_X/**FX_Hydro**" and "…/Lubrication1/HydroDynamicForce/Negative_X/**FX_Hydro**".

② **Add a New Page ([Home]-[Windows]-[Add])**

③ Then draw the curves in the new page. "…/Lubrication1/AsperityContactForce/Positive_X/**FX_Asperity**" and "…/Lubrication1/AsperityContactForce/Negative_X/**FX_Asperity**".

※ You can see where the contact area is and the magnitude of the contact force.



Step 12 – Create Output Points for Clearance

Steps

① Return to the Working window of RecurDyn, open the property dialog of **Lubrication1** (EHD property)

② Click the "**Output Point for Clearance**" button

③ Set the **reference marker** to "**Piston.Marker1**" (Action Marker of Lubrication1)

④ **Add** 4 **Output Gap points**

⑤ Set the **Height / Angle** as below:

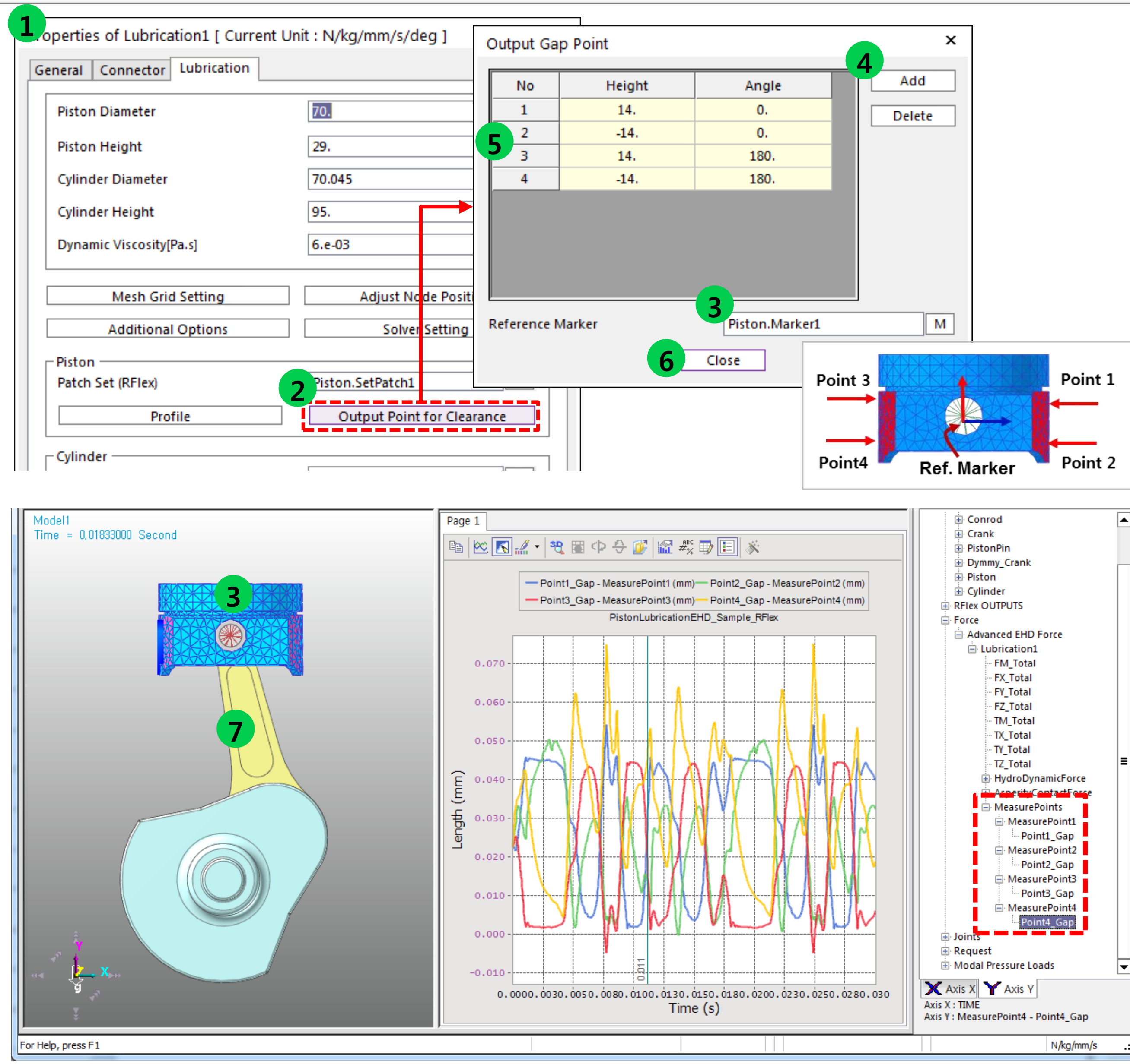
1) 14, 0

2) -14, 0

3) 14, 180

4) -14, 180

⑥ **Close** the dialog



Step 13 – Modify the Piston Profile

Steps
[Piston Profile Modification]

① Click the "**Profile**" button.

② Check on "**Use Profile**" option, in the **Piston Profile** dialog

③ Set the values as below:

1) **Profile Length: 29**

2) Number of Angle: 44

3) Ref. Marker: Piston.Marker1

4) No. of Height: 19

④ Click the "**Create Data Field Uniformly**" button

⑤ The input filed of **Profile** is filled automatically

(You cannot modify the values directly in this dialog)

⑥ **Export** the data as *.csv

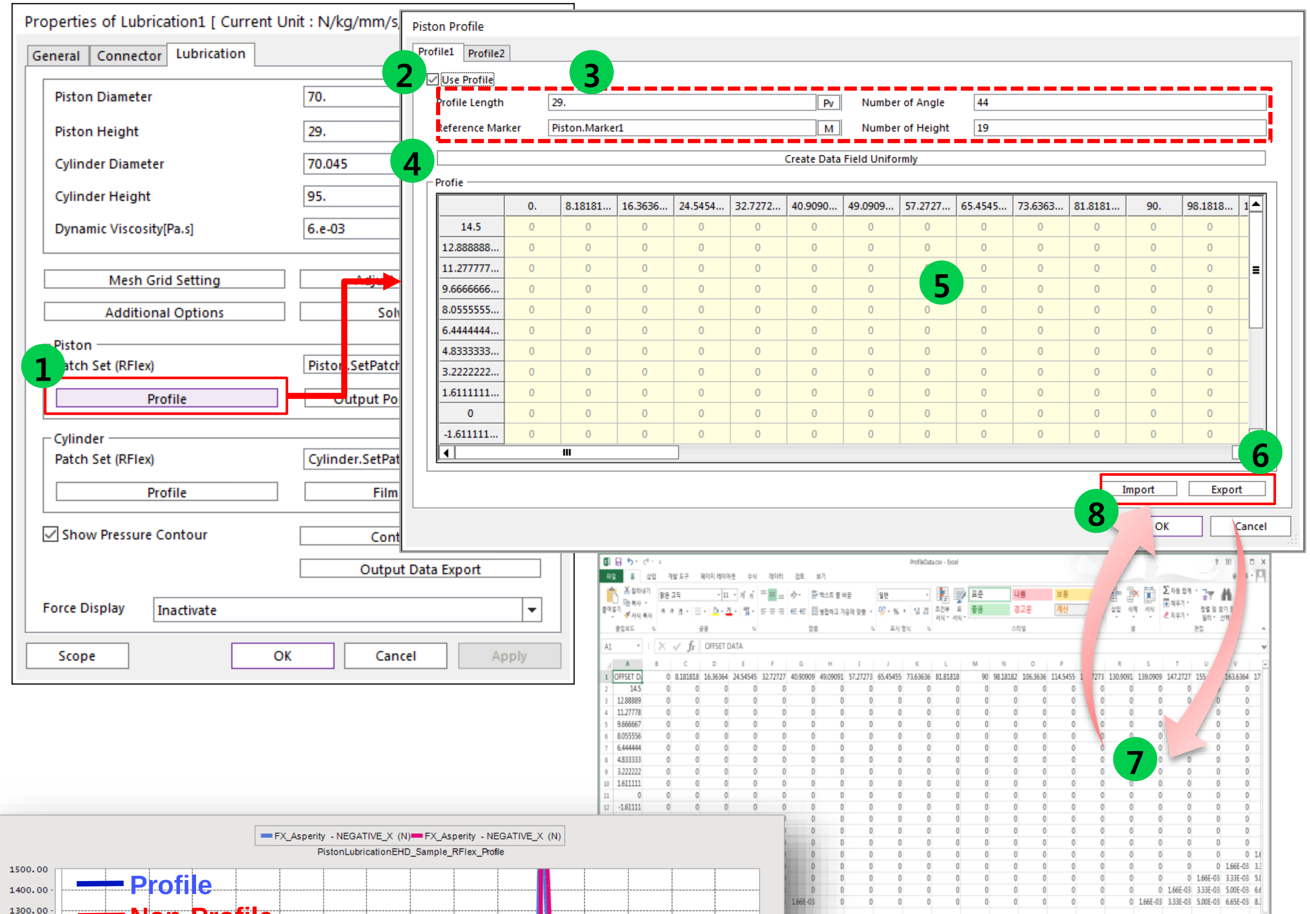
⑦ **Open** the *.csv file by **Excel**, and **modify** the profile data.

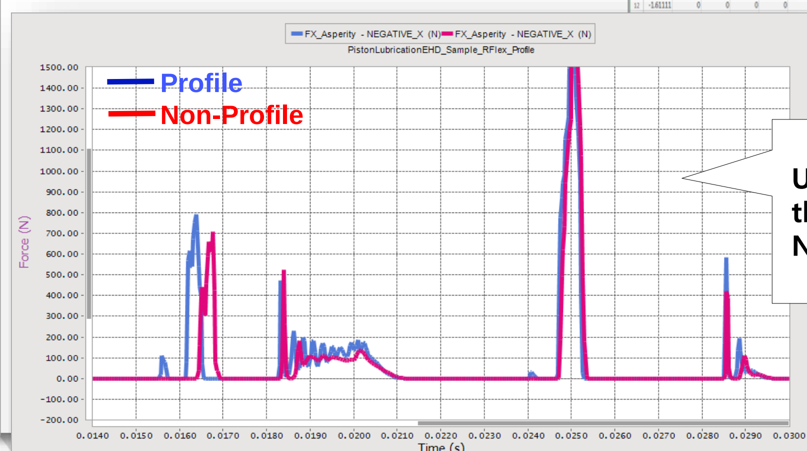
⑧ **Import** the modified *.csv in **Piston Profile** dialog.

(In this tutorial, you can use pre-created "**ProfileData.csv**")

⑨ **Close** the Profile dialog

⑩ You can run **simulation** again using the new setting.





User can compare the Asperity Contact force between Non-profile and Profile model