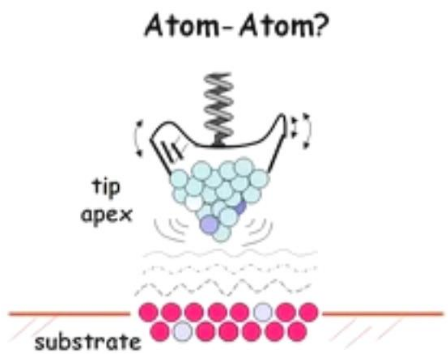
Easy guide to understanding RecurDyn Contact

FunctionBay

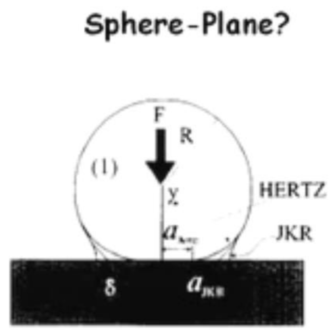
Index

Contact mechanics

Researches on contact mechanics



Micro approach-DEM,FEM…



Source: Capella & Dietler

Analytical approach-Hertz

Ueber die Berührung fester elastischer Körper.

(Von Herrn *Heinrich Hertz.*)

In der Theorie der Elasticität werden als Ursachen der Deformationen theils Kräfte, welche auf das Innere der Körper wirken, theils auf die Oberfläche wirkende Druckkräfte angenommen. Für beide Arten von Kräften kann der Fall eintreten, dass dieselben in einzelnen unendlich kleinen Theilen der Körper unendlich gross werden, so zwar, dass die Integrale der Kräfte über diese Theile genommen einen endlichen Werth behalten. Beschreiben wir alsdann um den Unstetigkeitspunkt eine geschlossene Fläche, deren Dimensionen sehr klein gegen die Dimensionen des ganzen Körpers sind, sehr gross hingegen im Vergleich zu den Dimensionen des Theils, in welchem die Kräfte angreifen, so können die Deformationen ausserhalb und innerhalb dieser Fläche ganz unabhängig von einander betrachtet werden. Ausserhalb hängen die Deformationen ab von der Gestalt des Gesammtkörpers, der Vertheilung der übrigen Kräfte und den endlichen Integralen der Kraftcomponenten im Unstetigkeitspunkte, innerhalb hängen sie nur ab von der Vertheilung der im Innern selbst angreifenden Kräfte. Die Drucke und Deformationen im Innern sind gegen die im Aeussern unendlich gross.

Im Folgenden wollen wir einen hierher gehörigen Fall behandeln, der praktisches Interesse hat*), den Fall nämlich, dass zwei elastische isotrope Körper sich in einem sehr kleinen Theil ihrer Oberfläche berühren, und durch diesen Theil einen endlichen Druck der eine auf den andern ausüben. Die sich berührenden Oberflächen stellen wir uns als vollkommen glatt vor, d. h. wir nehmen nur einen senkrechten Druck zwischen den sich berührenden Theilen an. Das beiden Körpern nach der Deformation gemeinsame Stück der Oberfläche wollen wir die Druckfläche, die Begrenzung

*) Vgl. *Winkler*, Die Lehre von der Elasticität und Festigkeit, Prag 1867; I, p. 43. *Grashof*, Theorie der Elasticität und Festigkeit, Berlin 1878; p. 49—54.

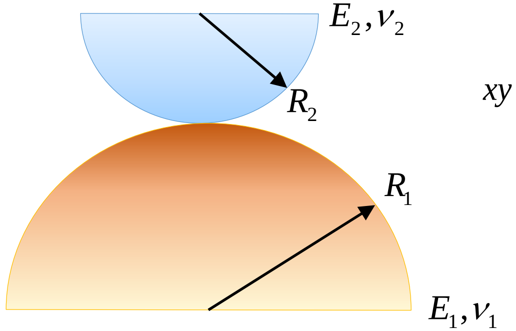
- 1881년 first research by Heinrich Hertz – "On the contact of elastic solids"
- 1932년 contact between two rigid spheres by Bradley
- 1965년 The Relation between Load and Penetration in the Axisymmetric Boussinesq Problem by Sneddon
- 1971년 Johnson-Kendall-Roberts found found a similar solution for the case of adhesive contact
- 1975년 Effect of contact deformations on the adhesion of particles by Derjaguin, BV and Muller, VM and Toporov
- 1992년 Maugis improved the accuracy of contact mechanism

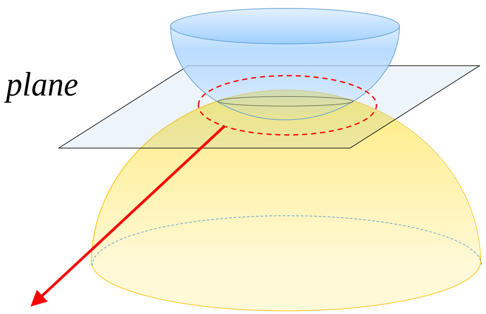
Analytical approach have had no big change since the first theory of contact mechanics.
Instead, micro approach, such as the researches on adhesion or interaction between atoms

※ Purdue University Lecture 8 Introduction to Contact Mechanics

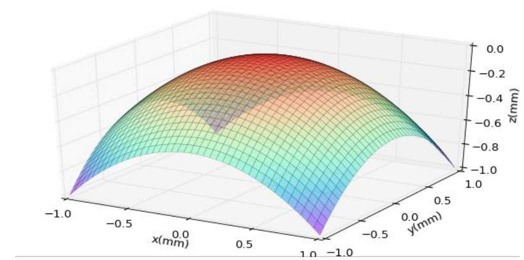
Hertz contact model

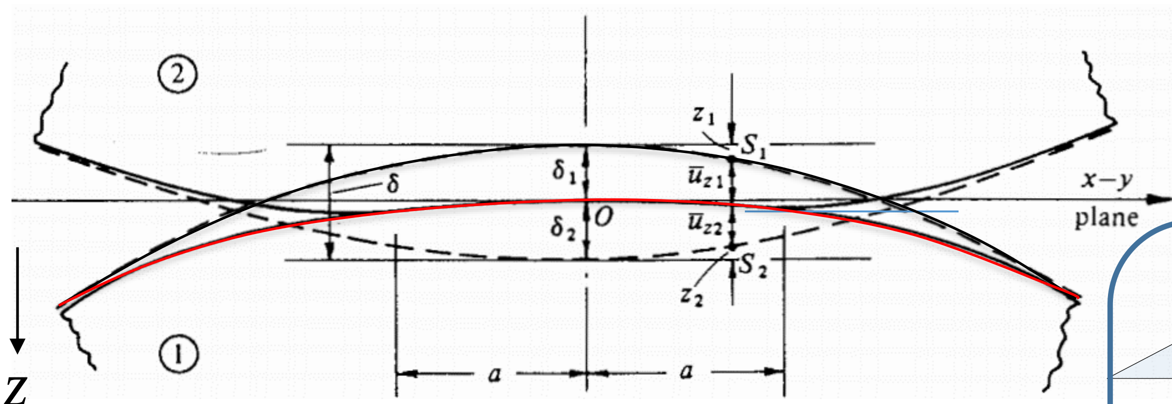
Assumptions in Hertzian theory

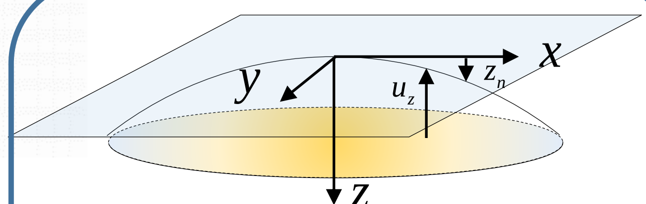




Shape function of z







$$z_n = \frac{1}{2R'}x^2 + \frac{1}{2R''}y^2$$

R' : x방향의 곡률반경

R'' : y 방향의 곡률반경

$$h = z_1 - z_2$$

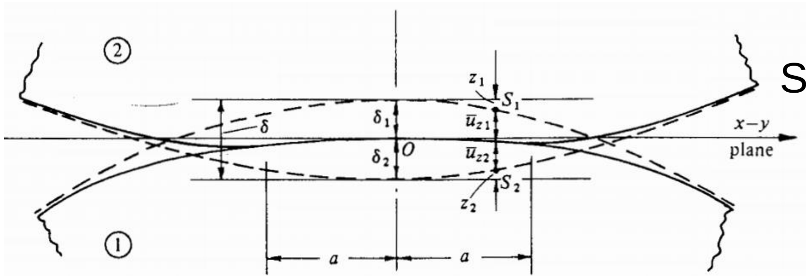
$$z_1 = \frac{1}{2R_1'}x^2 + \frac{1}{2R_1''}y^2$$

$$z_2 = -\left(\frac{1}{2R_2'}x^2 + \frac{1}{2R_2''}y^2\right)$$

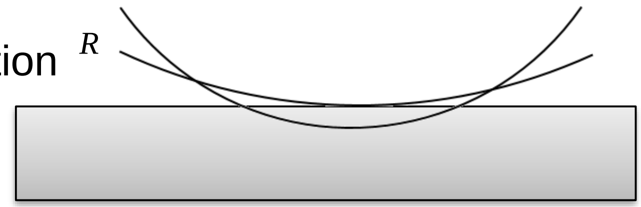
$$\bar{u}_{z1} + \bar{u}_{z2} + h = \delta_1 + \delta_2$$

Hertz contact model

Simplification of the function of h



Simplification



$$h = Ax^2 + By^2 = \frac{1}{2R}x^2 + \frac{1}{2R}y^2$$

$$h = z_1 - z_2 = \frac{1}{2R_1'}x^2 + \frac{1}{2R_1''}y^2 + \frac{1}{2R_2'}x^2 + \frac{1}{2R_2''}y^2$$

$$\text{where, } R_1' = R'' = R_1, \quad R_2' = R_2'' = R_2$$

$$h = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)x^2 + \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)y^2$$

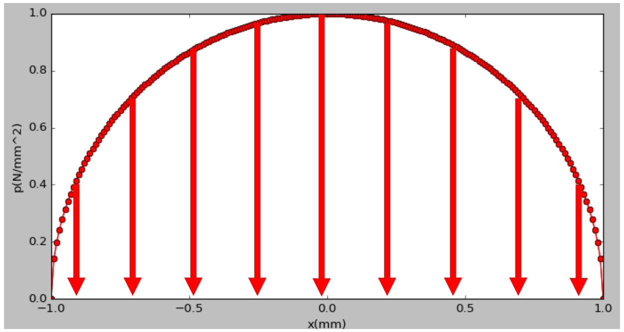
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Express the function of h in r-θ coordinate

$$h = \frac{1}{2R}x^2 + \frac{1}{2R}y^2 \Rightarrow \frac{1}{2R}r^2 \quad (r - \theta\, coordinate)$$

Hertz contact model

Assumption on the pressure of the contact surface



$$p(r) = p_0 \sqrt{a^2 - r^2} / a$$

$$\begin{cases} \bar{u}_{z1} = \dfrac{1-\nu_1^{\ 2}}{E_1} \dfrac{\pi p_0}{4a} \left(2a^2 - r^2\right) \\ \bar{u}_{z2} = \dfrac{1-\nu_2^{\ 2}}{E_2} \dfrac{\pi p_0}{4a} \left(2a^2 - r^2\right) \end{cases}$$

$$\bar{u}_{z1} + \bar{u}_{z2} = \delta_1 + \delta_2 - h$$

$$\bar{u}_{z1} + \bar{u}_{z2} = \delta - \frac{1}{2R} r^2 \quad (\delta = \delta_1 + \delta_2)$$

$$\frac{1-\nu_1^{\ 2}}{E_1} \frac{\pi p_0}{4a} \left(2a^2 - r^2\right) + \frac{1-\nu_2^{\ 2}}{E_2} \frac{\pi p_0}{4a} \left(2a^2 - r^2\right) = \delta - \frac{1}{2R} r^2 \quad (\delta = \delta_1 + \delta_2)$$

Hertz contact model

$$\frac{\pi p_0}{4a}\left(2a^2 - r^2\right)\left(\frac{1-\nu_1{}^2}{E_1} + \frac{1-\nu_2{}^2}{E_2}\right) = \delta - \frac{1}{2R} r^2$$

$$\frac{\pi p_0}{4aE}\left(2a^2 - r^2\right) = \delta - \frac{1}{2R} r^2$$

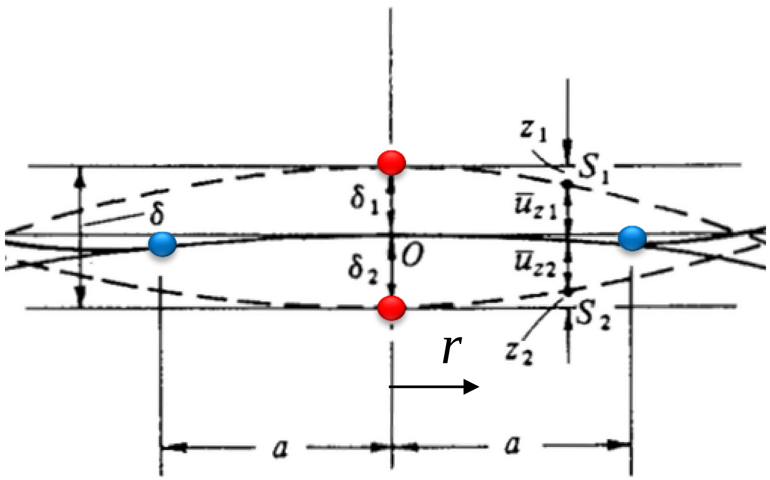
$$\left(\frac{1}{E} = \frac{1-\nu_1{}^2}{E_1} + \frac{1-\nu_2{}^2}{E_2}\right)$$

Boundary Condition

Regard δ when r = 0 as the deformation

$$\text{where, } \; r = 0 \quad \text{than, } \quad \delta = \frac{\pi p_0 a}{2E}$$

$$\text{where, } \; r = a, \delta = 0 \quad \text{than, } \quad a = \frac{\pi p_0 R}{2E}$$



Hertz contact model

Total load, P (p : contact pressure)

$$P = \int_0^a 2\pi r \cdot p(r) dr = \frac{2\pi p_0}{a} \int_0^a r\sqrt{a^2 - r^2}\, dr = \frac{2}{3}\pi p_0 a^2$$

$$P = \frac{2}{3}\pi p_0 a^2 \Rightarrow p_0 = \frac{3P}{2\pi a^2}$$

$$\delta = \frac{\pi p_0 a}{2E}, \quad a = \frac{\pi p_0 R}{2E}$$

$$a = \frac{\pi p_0 R}{2E} = \frac{3PR}{4Ea^2} \quad \left(\text{where, } p_0 = \frac{3P}{2\pi a^2}\right)$$

$$\delta = \frac{a^2}{R} = \frac{1}{R}\left(\frac{3PR}{4E}\right)^{2/3} = \left(\frac{9P^2}{16RE^2}\right)^{1/3}$$

$$p_0 = \frac{3P}{2\pi a^2} = \left(\frac{6PE^2}{\pi^3 R^2}\right)^{1/3}$$

$$\therefore a = \left(\frac{3PR}{4E}\right)^{1/3}, \delta = \left(\frac{9P^2}{16RE^2}\right)^{1/3}, p_0 = \left(\frac{6PE^2}{\pi^3 R^2}\right)^{1/3}$$

Hertz contact model

Hertz Contact Formulation

$$P = \sqrt{\frac{16RE^2}{9}}\delta^{3/2} = K \cdot \delta^{1.5}$$

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

$$K = \sqrt{\frac{16RE^2}{9}}$$

$$E = \frac{E_1 E_2}{E_2\left(1-\nu_1{}^2\right) + E_1\left(1-\nu_2{}^2\right)}$$

RecurDyn Contact Formulation

$$F = K \cdot \delta^n$$

$$K = f\left(R_1, R_2, E_1, E_2, \nu_1, \nu_2\right)$$

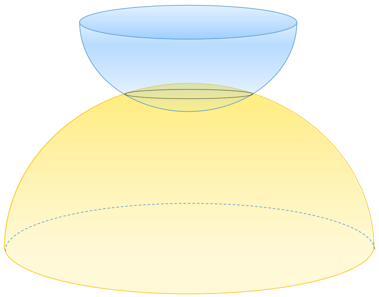
$$n = 1.5$$

References

- H. Hertz, "Über die Berührung fester elastischer Körper," Gesammelte Werke (P. Lenard, ed.), Bd. 1,(J.A. Barth, Leipzig, 1895) pp. 155-173. Originally pub-lished in Journal f. d. reine u. angewandte Mathematik 92,156-171 (1881).
- 'Contact mechanics' in Wikipedia
- R S Dwyer-Joyce, "Tribological Design Data Part 3: Contact Mechanics" University of Sheffield
- K.L. Johnson, "Contact Mechanics" Cambridge University Press 1985 ISBN 0 521 347963
- Georges Cailletaud, St´ephanie Basseville1,Vladislav A. Yastrebov, "Contact mechanics I: basics", EMESURF short course on contact mechanics and tribology, Paris, France, 21-24 June 2010
- https://woodem.org/theory/contact/hertzian.html

Hertz contact model – parameters

- Various radii for the sphere-sphere contact (steel)



- E1,E2=210Gpa
- E = 115Gpa
- ν1, ν2=0.3

$$R = \frac{R_1 R_2}{R_1 + R_2} \quad K = \sqrt{\frac{16RE^2}{9}}$$

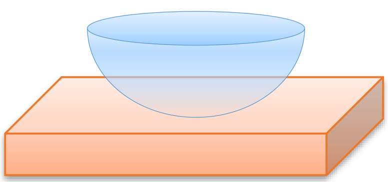
$$E = \frac{E_1 E_2}{E_2\left(1-\nu_1^2\right)+E_1\left(1-\nu_2^2\right)}$$

MMKS

R1(mm)	R2(mm)	R	K
0.5	1	0.333333333	88823
0.5	10	0.476190476	106163
0.5	100	0.497512438	108514
0.5	1000	0.499750125	108758
0.5	10000	0.499975001	108782
0.5	100000	0.4999975	108785
0.5	1000000	0.49999975	108785

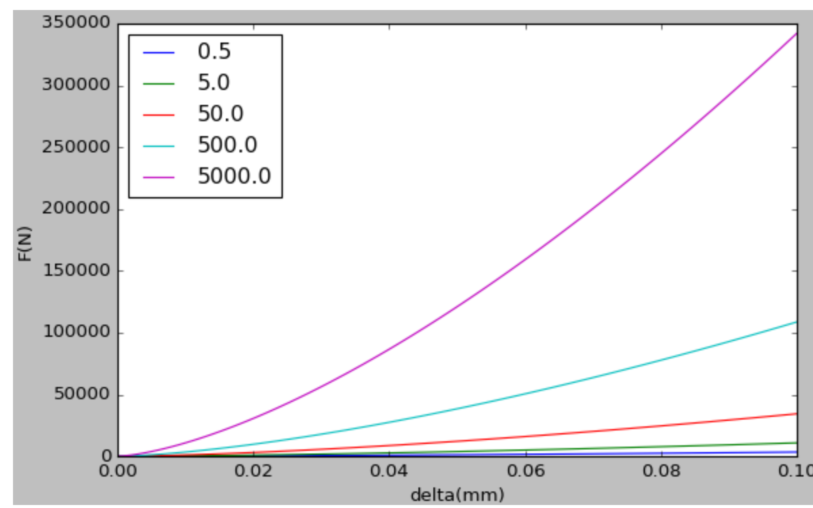
RecurDyn Default value = 100000

- Various radii for the sphere-plane contact (Steel)



- E1,E2=210Gpa
- E = 115Gpa
- ν1, ν2=0.3

R1(mm)	R2(mm)	R	K
0.5	500000	0.4999995	108785
5	500000	4.99995	344008
50	500000	49.9950005	1087802
500	500000	499.5004995	3438385
5000	500000	4950.49505	10824577



Hertz Contact FD curve

Hertz contact model – parameters

- Various material properties

Material Properties

Material	E(Gpa)	ν
Steel	210.00	0.3
Aluminum	70.00	0.32
Bronze	120.00	0.34
Oak Wood	11.00	0.35
Plastic	2.40	0.39
Rubber(EPDM)	0.02	0.5

R1=0.5mm ,R2=500000mm

	Steel	Aluminum	Bronze	Oak Wood	Plastic	Rubber
Steel	108786	54955	80559	11210	2636	25
Aluminum		36763	46690	10182	2575	25
Bronze			63963	10819	2614	25
Oak Wood				5909	2177	25
Plastic					1334	25
Rubber						13

Contact Stiffness K for MMKS Model

- Conclusion
  - Stiffness (K) for the contact based on Hertzian contact theroty can be calculated using the material properties (E, ν) and radii of the curvature of the solids

$$K = \sqrt{\frac{16RE^2}{9}}$$

$$\begin{cases} R = \dfrac{R_1 R_2}{R_1 + R_2} \\ E = \dfrac{E_1 E_2}{E_2\left(1-\nu_1^2\right) + E_1\left(1-\nu_2^2\right)} \end{cases}$$

RecurDyn Contact

RecurDyn Contact Computing process

Geometry approach

Solver does nothing yet

Interference between Bounding Buffer Cubics

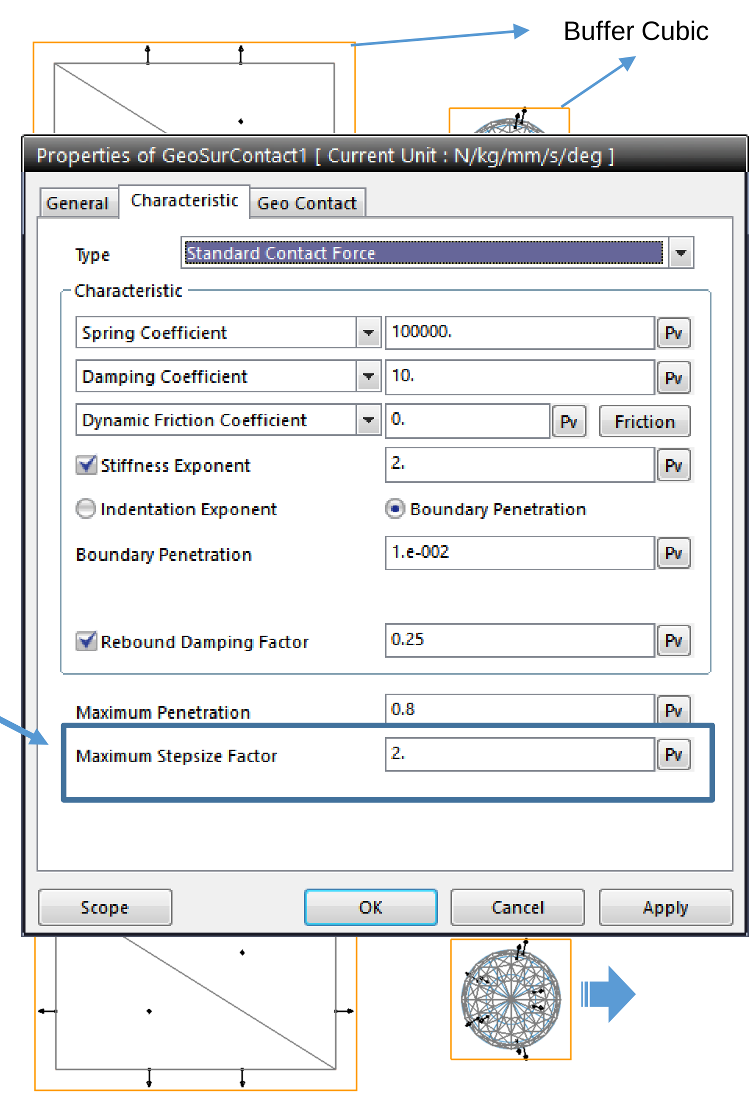
If the boundary buffer cubics interfere, Max. Step Size Factor is used to decrease the step size of the solver

Contact occurence

Contact Event occurs and Contact Force is calculated

Geometry seperation

The direction of the motion is changed by the contact force, and geometries are separated. If the bounding buffer cubic are separated, the max. stepsize factor is not used



RecurDyn Contact formula

- Normal Force

$$f_n = f_{ns} + f_{nd} \quad \begin{cases} f_{ns} : \text{stiffness force of contact} \\ f_{nd} : \text{damping force of contact} \end{cases}$$

- Stiffness Force: Hertz Contact이론에 기반한 수식 사용

$$f_{ns} = K \cdot \delta^{ms}$$

- Damping Force
  - Boundary Penetration Method

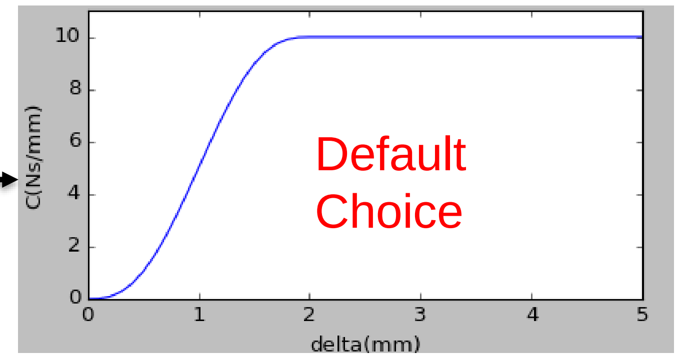
$$f_{nd} = step(\delta, 0, \delta_{\max}, C_{\max}) \cdot \dot{\delta}$$

  - Indentation Exponent Method

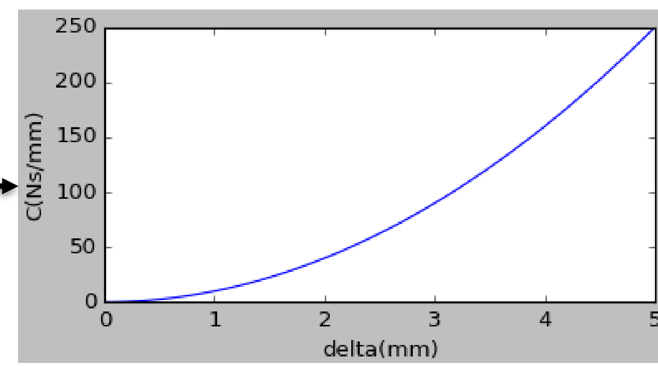
$$f_{nd} = C_{\max} \cdot \delta^{mi} \cdot sgn(\dot{\delta}) \cdot \dot{\delta}^{md}$$

$$\text{default parameters: } md = 1,\ mi = 2$$

$$f_{nd} = C_{\max} \cdot \delta^2 \cdot \dot{\delta}$$



δ – c curve of BPM

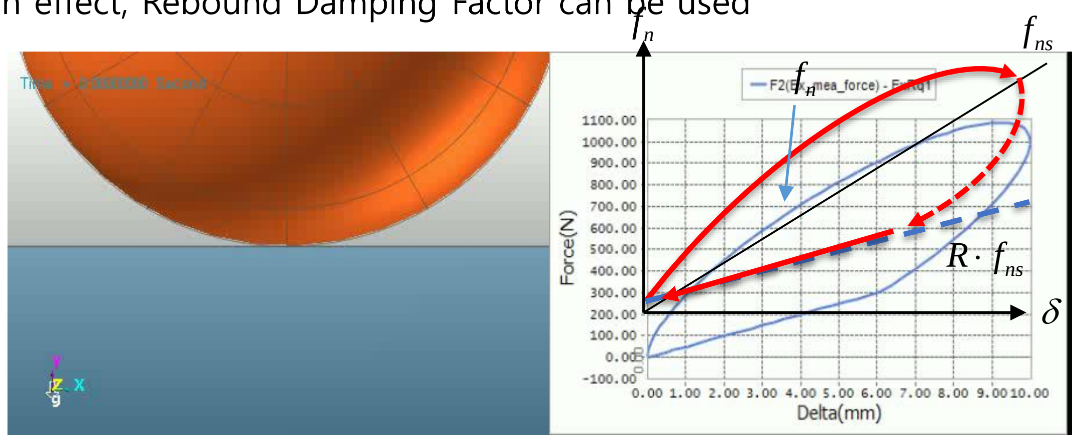


δ – c curve of IEM

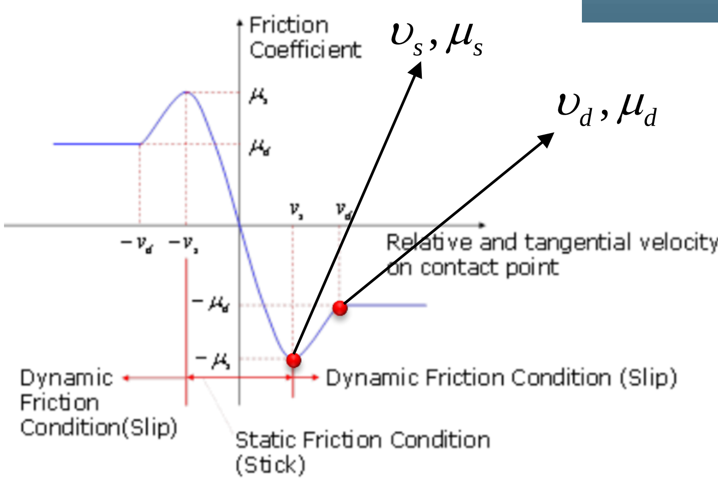
RecurDyn Contact formula

- Damping Force (Cont.)
  - Rebound Damping Factor
    - ✓ The direction of the Damping force changes according to the relative velocity of the contact geometry
    - ✓ Excessive damping force can cause adhesion effect
    - ✓ To reduce the adhesion effect, Rebound Damping Factor can be used

$$f_n = \max(f_n ,\ \ R \cdot f_{ns})$$



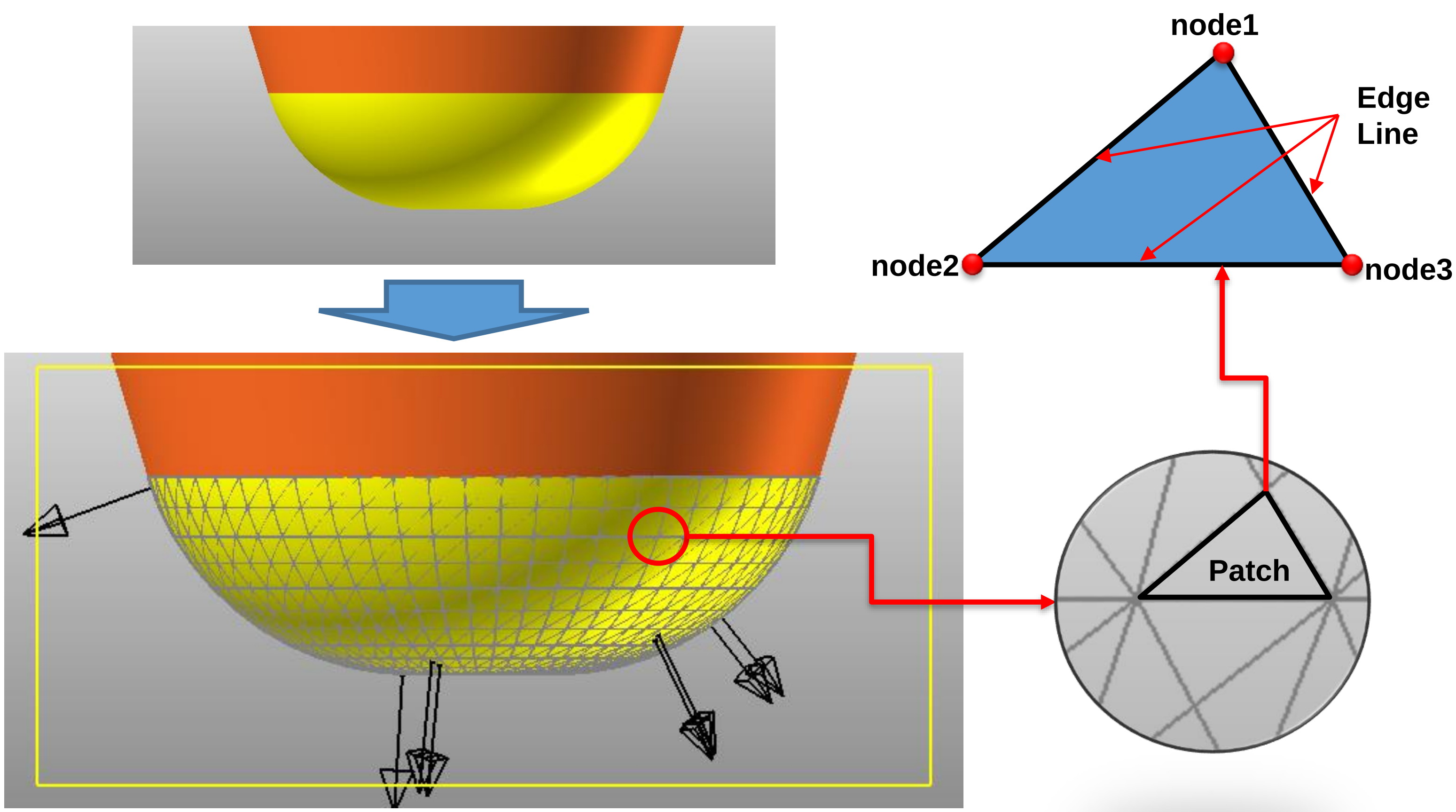
- Friction Force



The friction coefficient is expressed as a continuous function using the Static friction coefficient, Dynamic friction coefficient and the threshold velocify

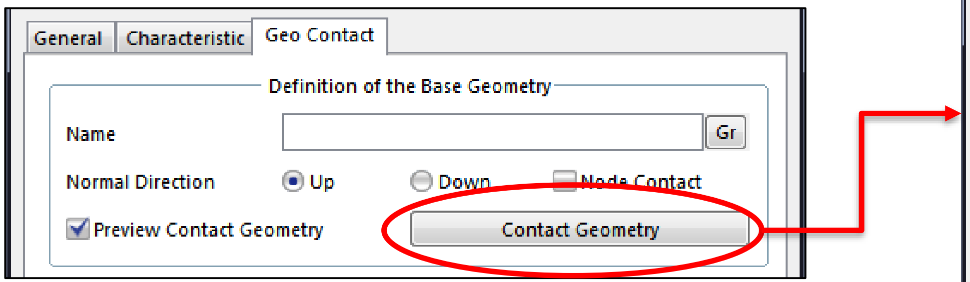
Faceting

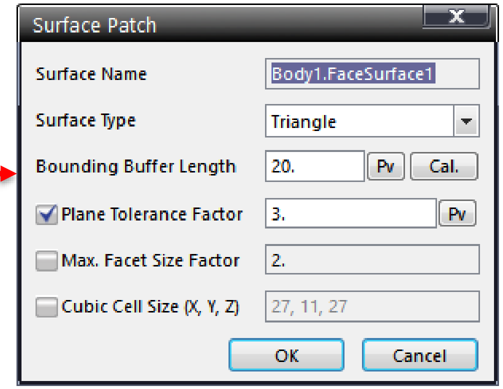
- Faceting
  - The free surface of the geometry is divided using the polygons
    - Since it is too expensive to use the free surface as it is, RecurDyn used polygon 'facets' for contact simulation



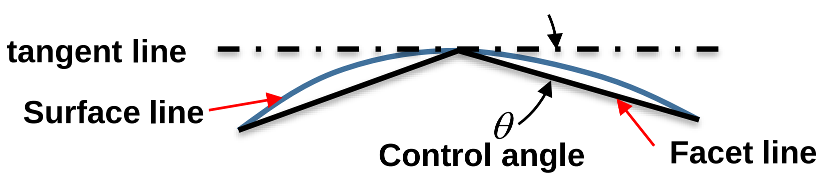
Faceting

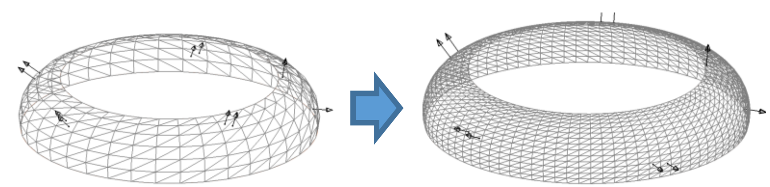
- Faceting control parameters





- Plane Tolerance Factor (0.01~10)
  - The smaller this value is, the more accurate and more facets are generated

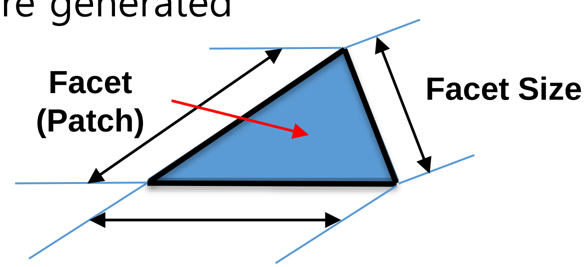


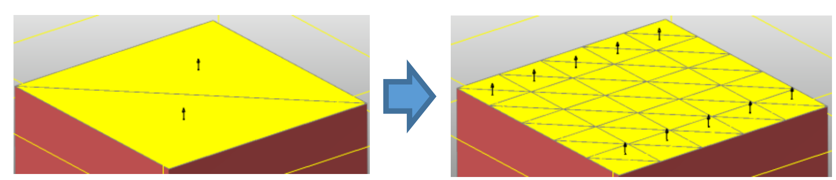


Plane Tolerance Factor 5

Plane Tolerance Factor 2

- Max. Facet Size Factor
  - This limits the size of the facet Facet. The smaller this value is, the more facets are generated



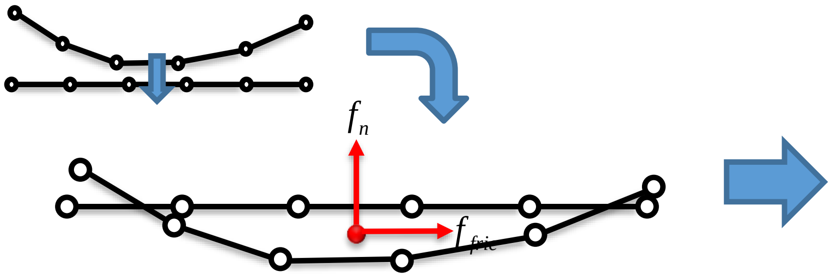


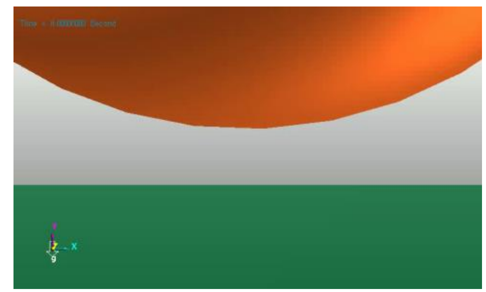
Max. Facet Size Factor 10

Max. Facet Size Factor 2

Contact Event

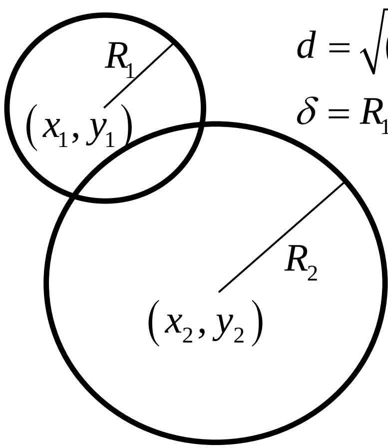
- Solid contact – (Solid contact)
  - Contact occurs at the representative point when the facets penetrates the other geometry





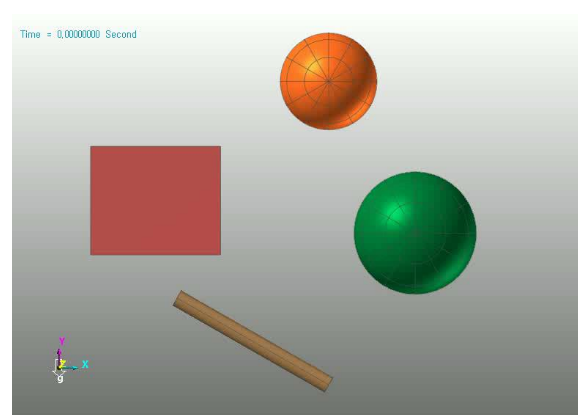
Simulation

- Analytical contact – (Primitive contact)
  - Mathematical function of the geometry is used for contact
  - Facets are not used



$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

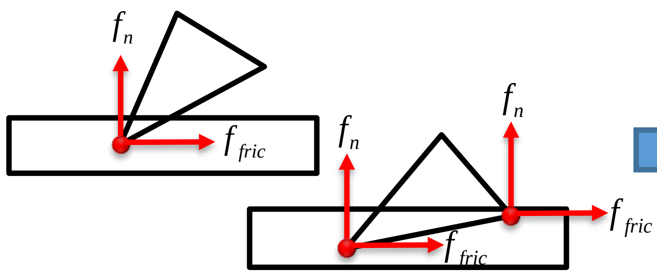
$$\delta = R_1 + R_2 - d$$

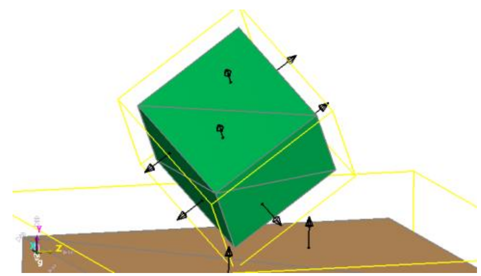


Simulation

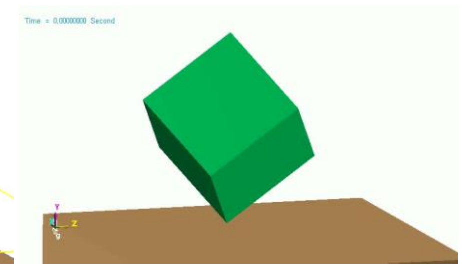
Contact Event

- Point(Node) contact – (Geo contact, Surface contact)
  - Contact force is calculated when a node penetrates the facet of the other geometry



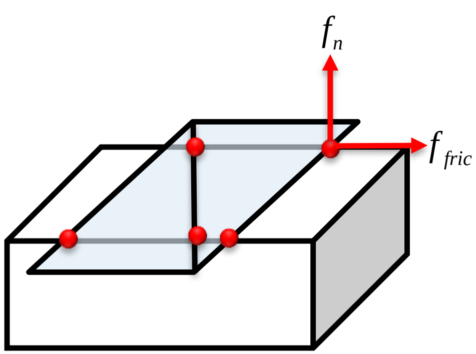


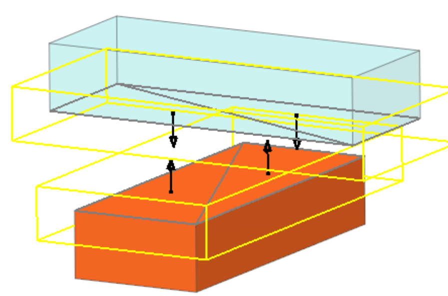
Model



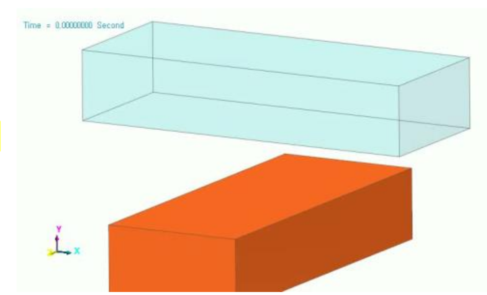
Simulation

- Edge contact – (Geo)
  - Contact force is calculated when an edge penetrates at the edge of the other geometry





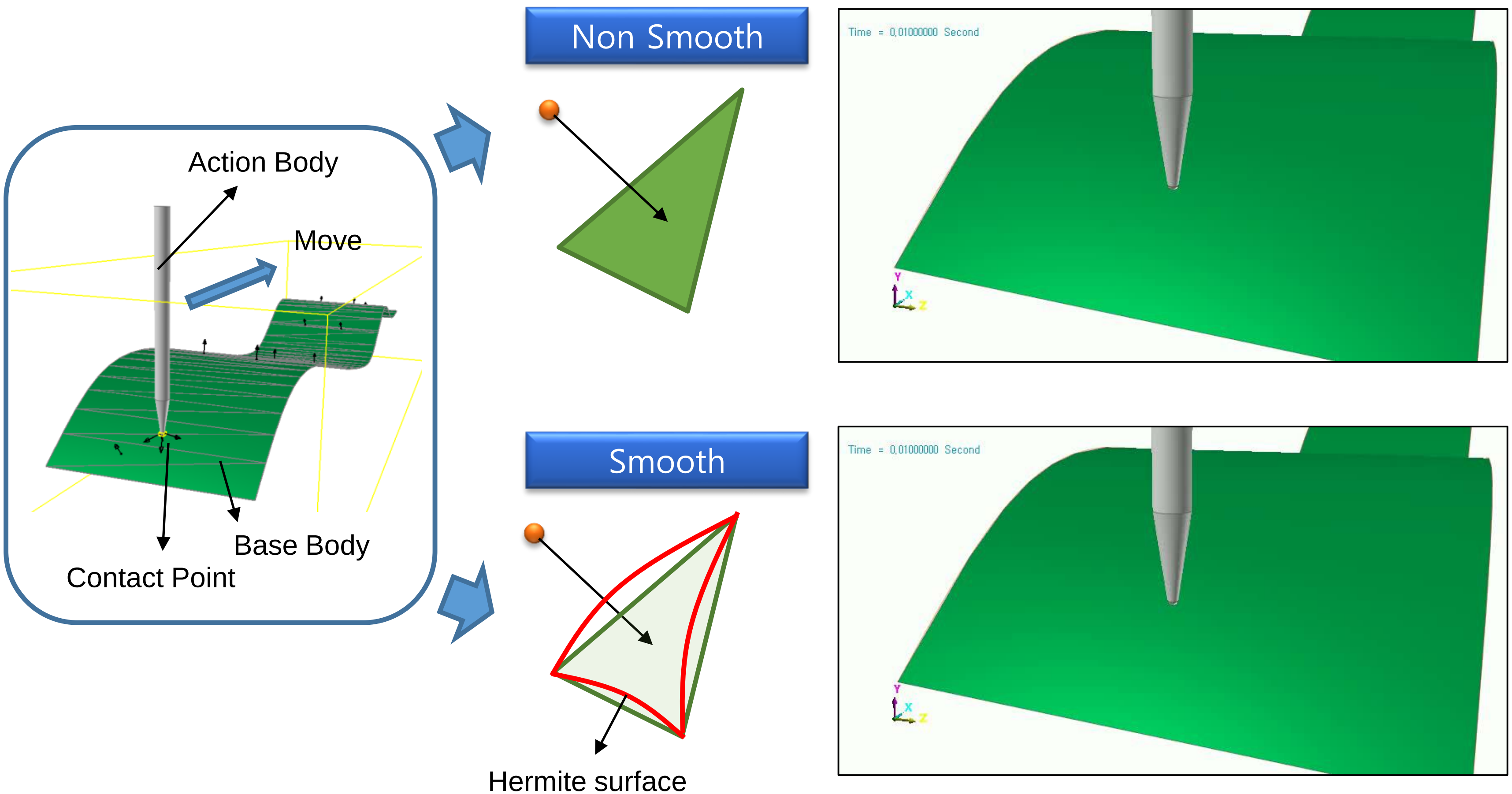
Model



Simulation

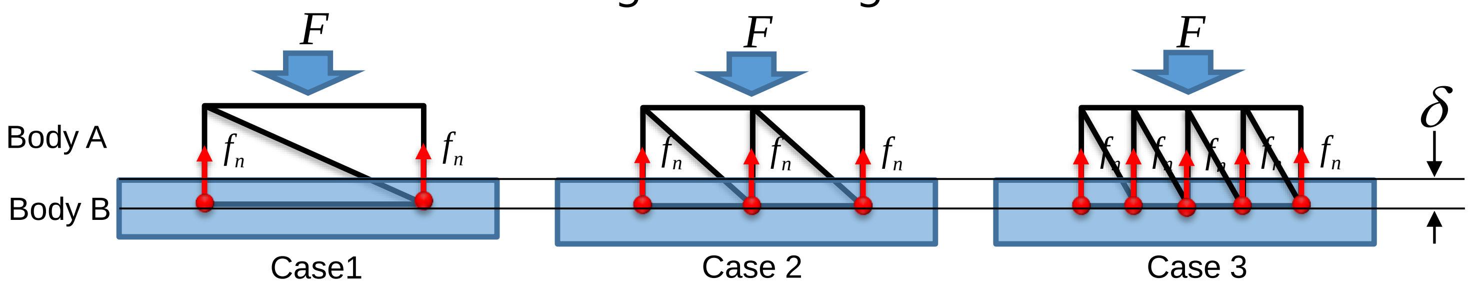
Smooth Contact – Geo contact

- Facets are converted to a Hermite surface for contact
  - Discontinuity at the node and edge of the facets is removed
  - Only Geo Contact supports 'Smooth contact option'



CPM – Geo contact

- CPM(consistence penetration method)
  - Numerical method to remove the effect that contact stiffness increases proportionally to the number of contact nodes
  - Prevent the solution change according to the number of facets



$$F = k\delta + k\delta \qquad F = k\delta + k\delta + k\delta \qquad F = k\delta + k\delta + k\delta + k\delta + k\delta$$

$$\delta = \frac{F}{2k} \neq \delta = \frac{F}{3k} \neq \delta = \frac{F}{5k}$$

  - K is recalculated to be inverse proportional to the number of contact nodes

$$k' = k / n \ (n : \text{contact point number})$$

$$F = k'\delta + k'\delta \qquad F = k'\delta + k'\delta + k'\delta \qquad F = k'\delta + k'\delta + k'\delta + k'\delta + k'\delta$$

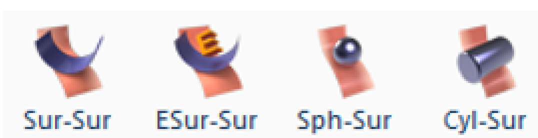
$$\delta = \frac{F}{k} = \delta = \frac{F}{k} = \delta = \frac{F}{k}$$

Consistence Penetration Method

Contact Entities- General 3D Contacts

- Solid Contact Event is used
- Rigid – Rigid
- Effective when penetration is small and radii is big

- Point Contact Event and Edge Contact Event are used
- Rigid – Rigid, Rigid – FE, FE – FE
- Best choice for most of the contact problems
- Geo Sph and Geo Cyl used Analytical Contact algorithm
- CPM and Smooth patch are supported



- Legacy contact entities developed long time ago
- Rigid – Rigid
- Contact point cannot be displayed

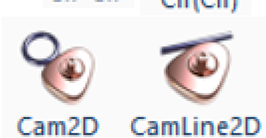
In most cases,
Geo Contact or Solid Contact is recommended

Contact Entities- Primitive 3D Contacts & 2D Contacts

- Analytical Contact Event is used
- Rigid – Rigid
- For RecurDyn Geometry (sphere, box, …)
- Fast and accurate calculation
- Parametrization of the contact geometry is supported

- Point Contact Event and Edge Contact Event are used
- 2D Curve(Polyline, Spline, Circle, Arc, Edge Curve) is used
- Rigid – Rigid, Rigid – FE, FE - FE

- Point Contact Event is used
- 2D Curve (Polyline, Spline, Circle, Arc, Edge Curve)
- Rigid – Rigid



- Analytical Contact Event is used
- Rigid – Rigid
- Circle, Edge Curve or Outline are used

General Procedure of Contact Modeling

RECURDYN

General steps for contact modeling

Step1
Choose the type of the contact entity according to the geometry and contact type

Step2
Select Base & Action Geometry

Step3
Create the Contact Surface and Contact entity

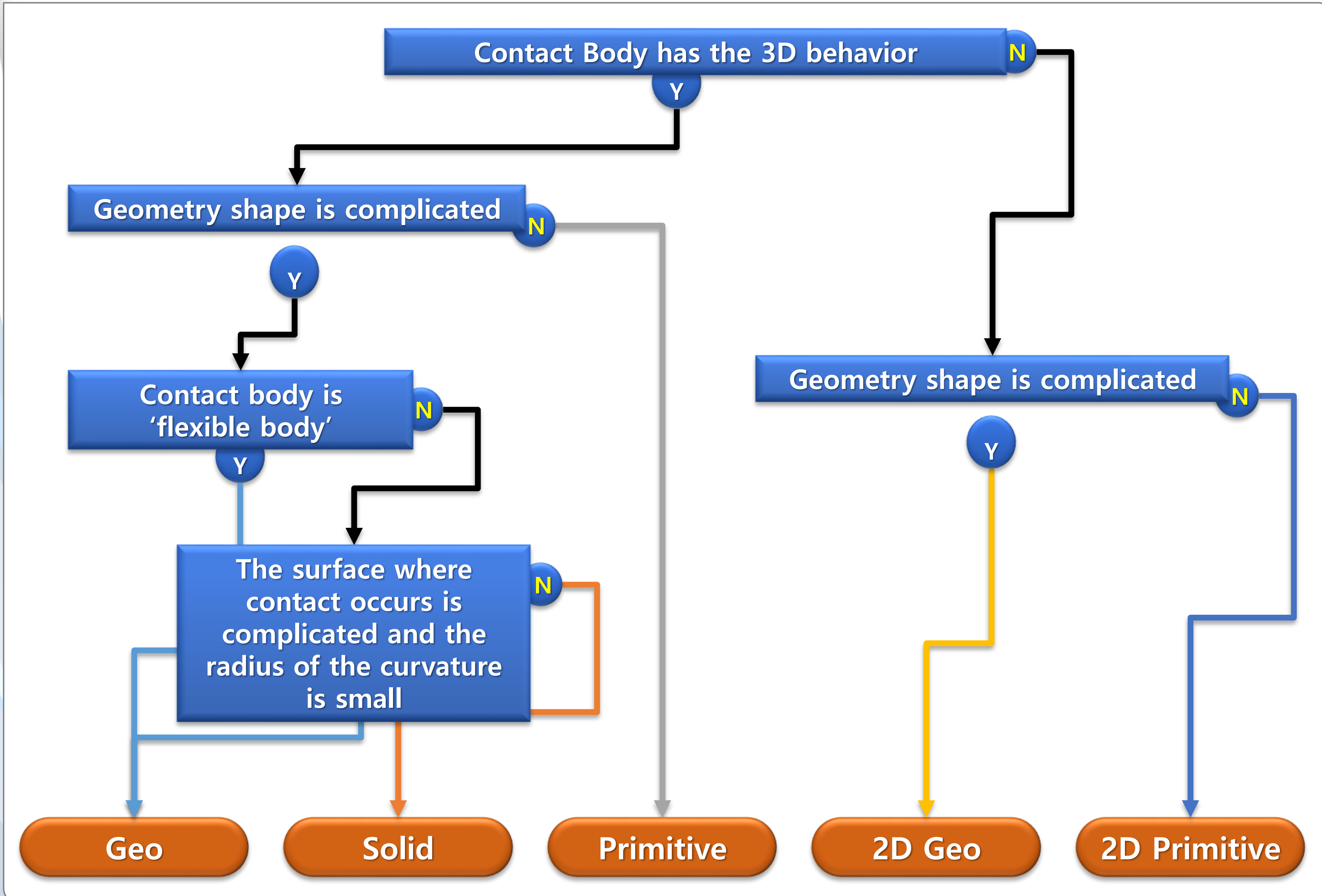
Step4
Adjust the Facet information

Step5
Tune Contact Parameter

Step6
Adjust the other optional parameters

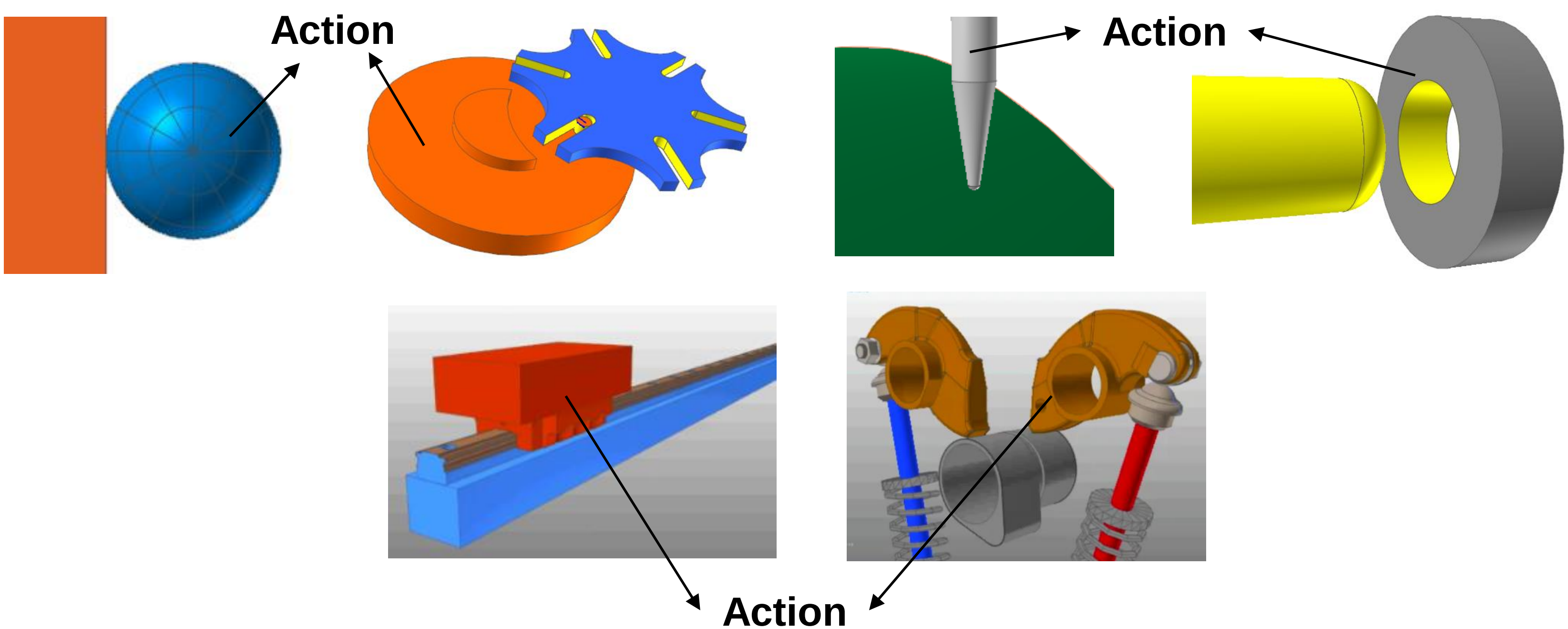
Step7
Simulation and calibration

Step1 Choose the type of the contact entity (according to the geometry and contact type)



Step2 Select Base & Action Geometry

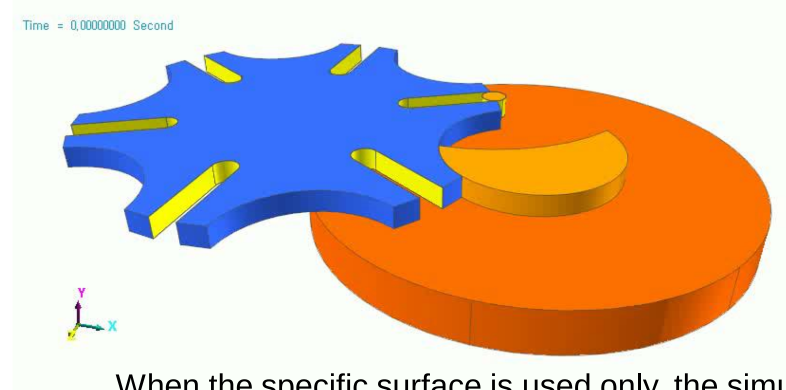
- The geometry whose contact surface is small → as Action
  - Using the fine facets for the smaller contact surface can give the smoother contact result
- The geometry which is more rounded → as Action
- The geometry which has the bigger movement → as Action
  - The solver calculates the Action Body more efficiently



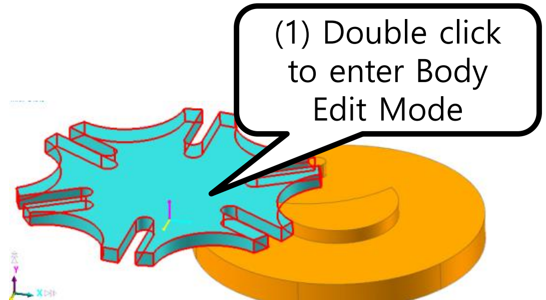
Step3 Create the Contact Surface and Contact entity

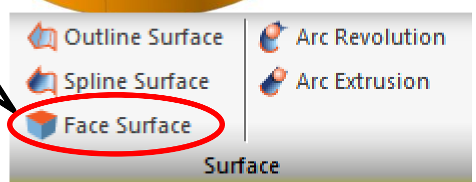
- General Contact be used for both of Solid and Surface. But using the specific surface only can reduce the computational overhead

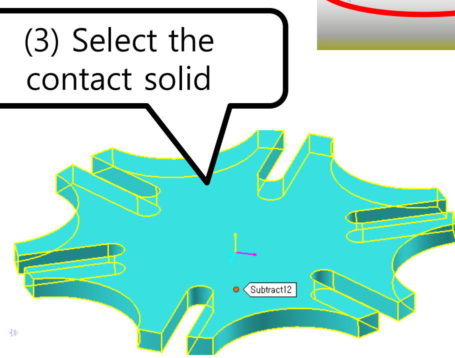
  - How to create the Surface

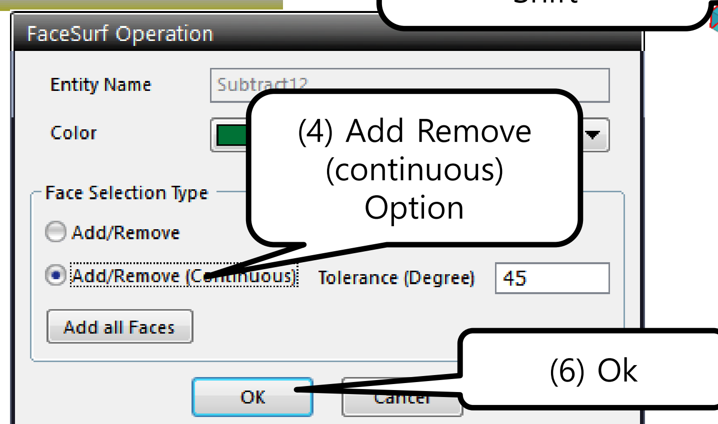


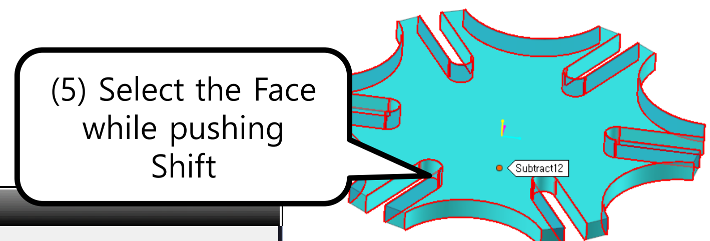
When the specific surface is used only, the simulation time is 3 times faster than using the solid

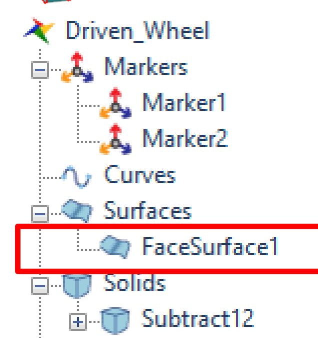






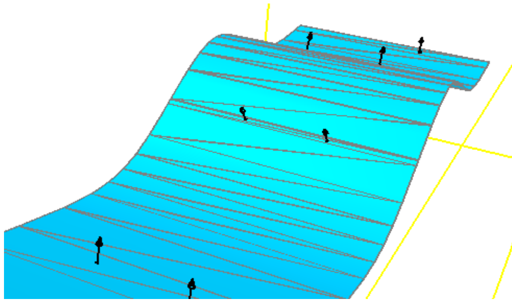




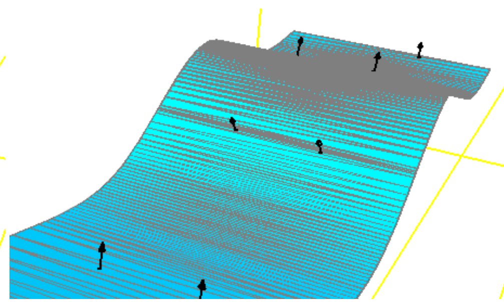


Step4 Adjust the Facet information

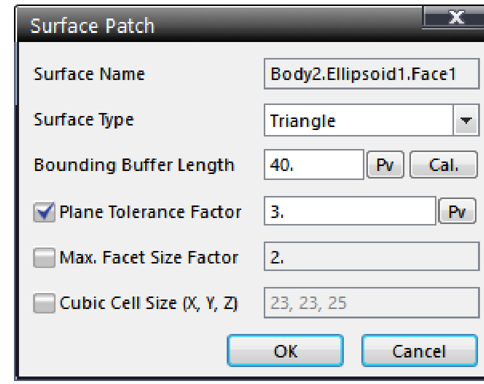
- Faceting can affect the accuracy and the simulation speed of Geo contact and Solid Contact a lot
  - The size of the facets where 'point contact' occurs should be as small as representing the surface well



Plane Tolerance Factor: 3.0



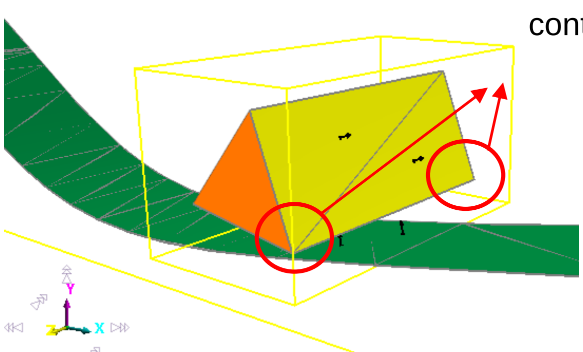
Plane Tolerance Factor: 0.2



Default value of Faceting control

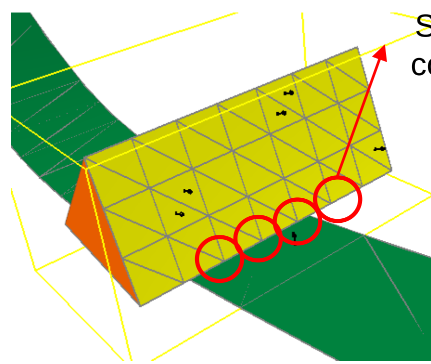
  - To generate the uniform contact force, the smaller facet size is desired

Point cannot contact

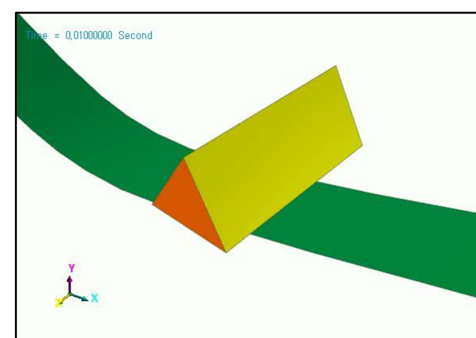


Max. Facet Size Factor: 10.0

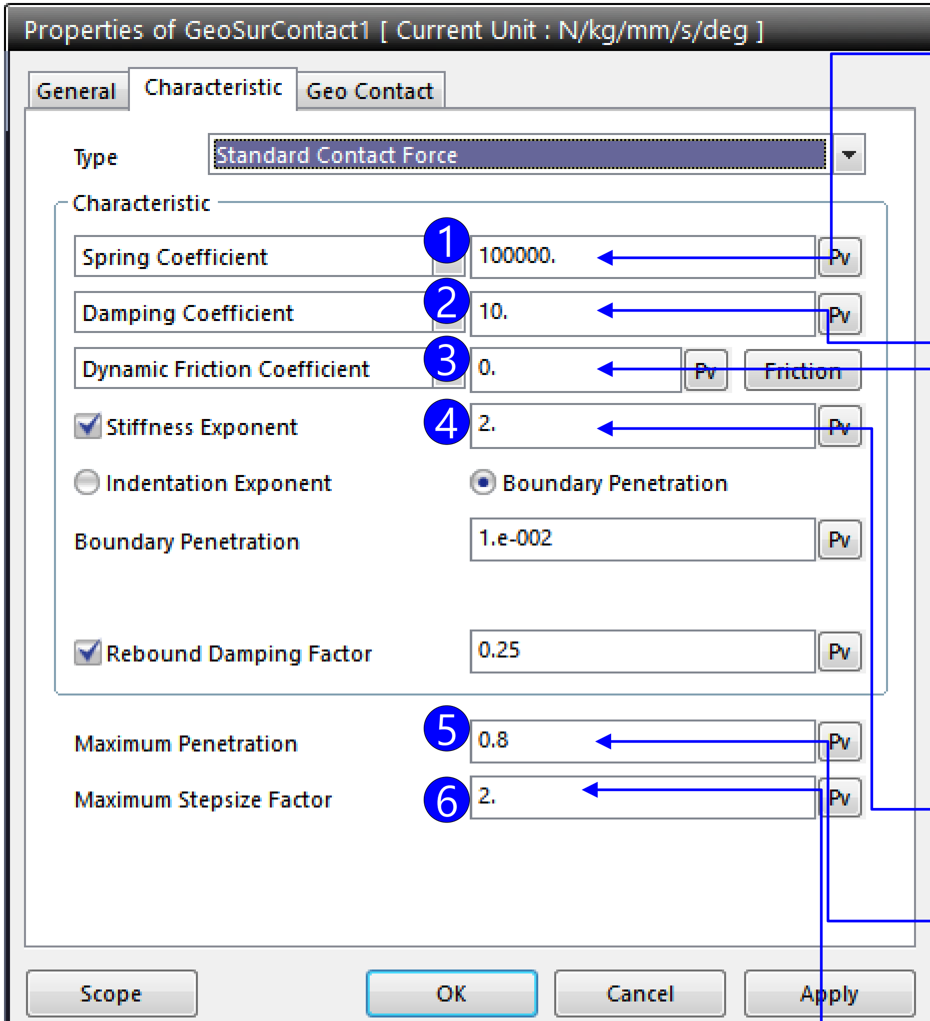
Several points can contact the surface



Max. Facet Size Factor: 2.0



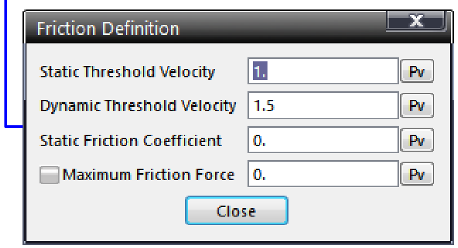
Step5 Tune Contact Parameter



1 K can be determined by Hertzian Contact Theory **(Where to tune)**

$$K = \sqrt{\frac{16RE^2}{9}} \Leftarrow \begin{cases} R = \dfrac{R_1 R_2}{R_1 + R_2} \\ E = \dfrac{E_1 E_2}{E_2\left(1-\nu_1^2\right) + E_1\left(1-\nu_2^2\right)} \end{cases}$$

2 Damping Coefficient : Typically 1/10,000 of **Stiffness is used (Where to tune)**



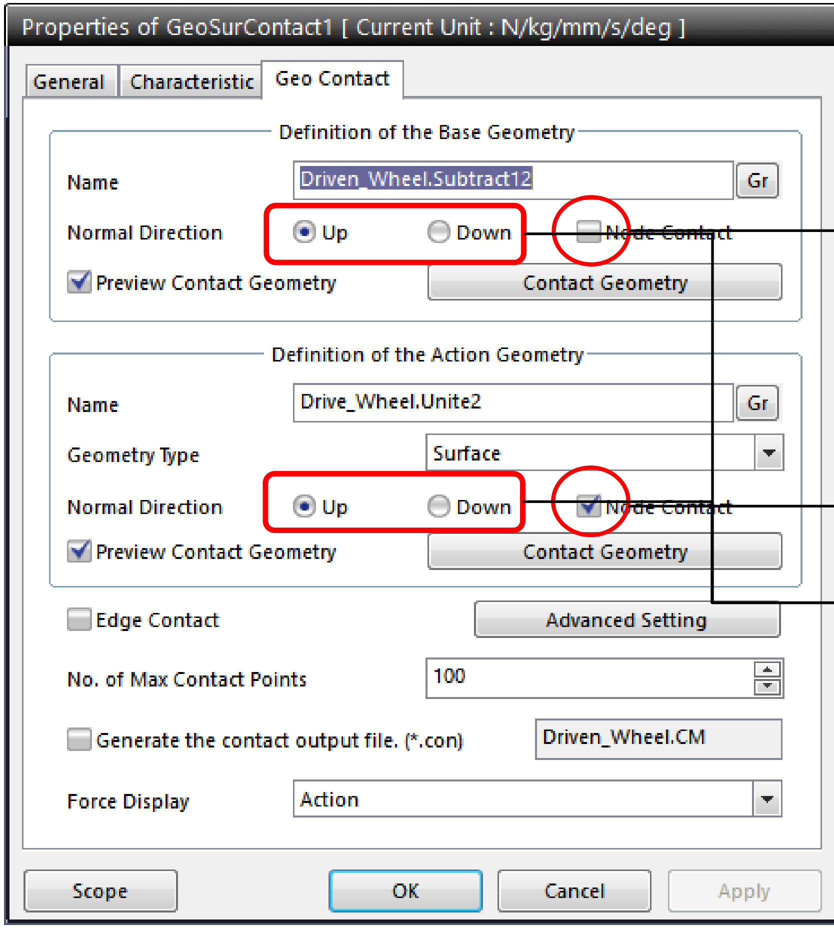
3 Static/Dynamic Friction Coefficient can be determined by experiments or the results of the papers **(in most cases, use the default value for Threshold Velocity)**

4 In most cases, 1.5 is used for Stiffness Exponent (based on Hertzian Contact Theory) **(Where to tune)**

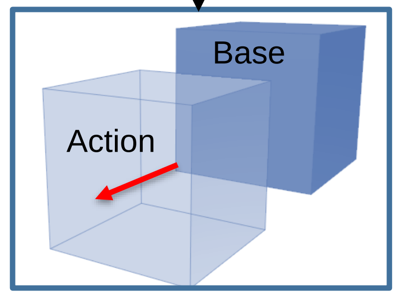
5 Usually, default value can be used

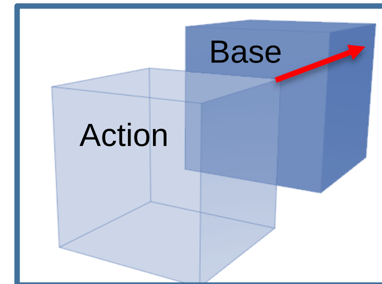
6 Use **10.0** if the bodies are far away each other
Use **1.0** if the bodies are very close from the initial position

Step6 Adjust the other optional parameters #1

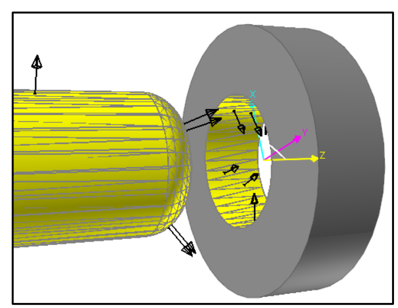


'Node Contact' option generates contact event between the facets and the points (nodes)
It is recommended to use this option for Action Geometry only

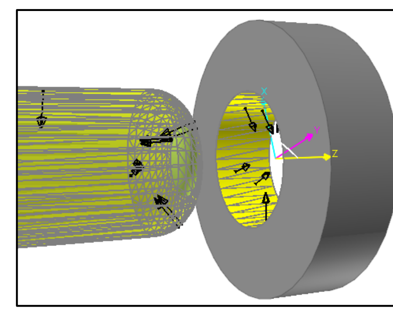




Normal Direction Check
The direction of surface where the contact occurs
It is displayed on the view

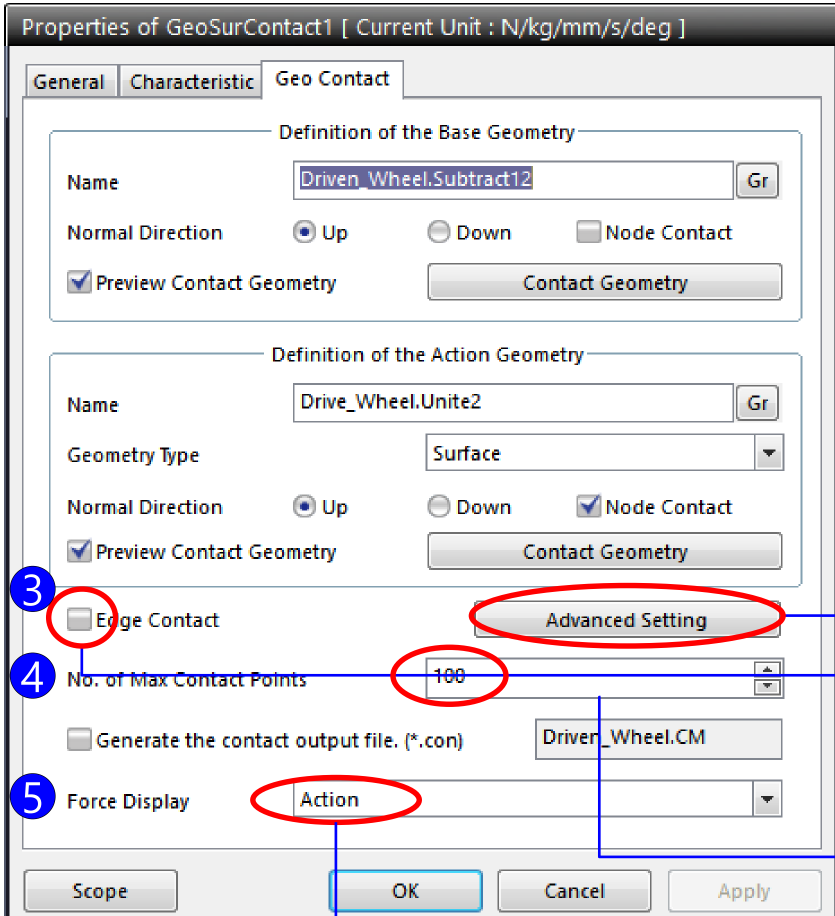


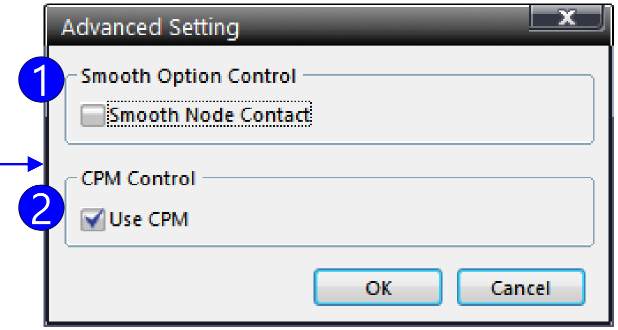
Base: up Action: up
Good!



Base: up Action: down
Wrong!

Step6 Adjust the other optional parameters #2





1 When to use Smooth Option (The default is OFF)

- Tight contact between a shaft and a hollow cylinder
- Contact point moves along the large curved surface
- Contact point moves smoothly along the surface

2 When NOT to use CPM Option (The default is ON)

- The contact force directions are not uniform
- Tight contact between a shaft and a hollow cylinder

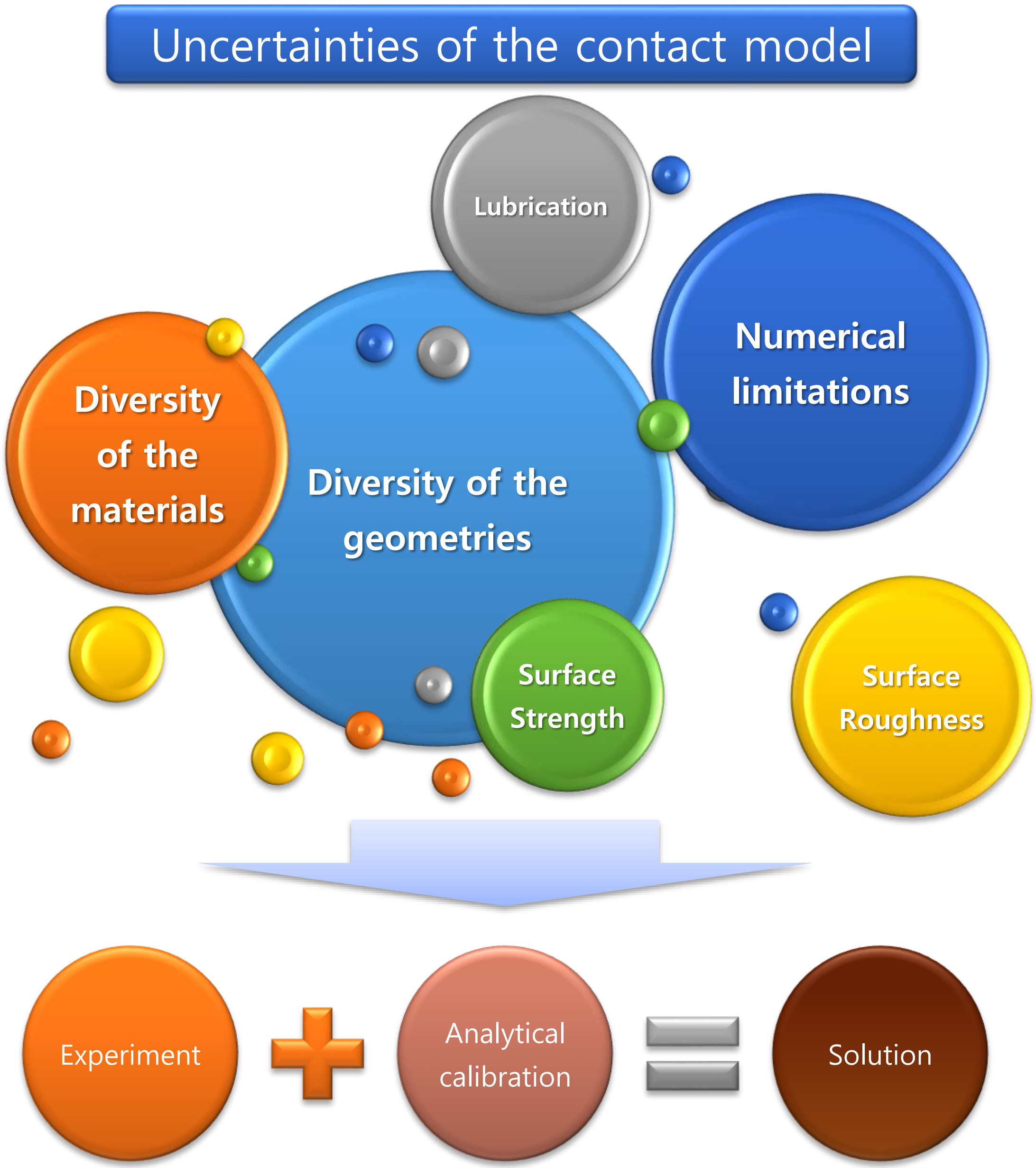
3 When to use Edge Contact (The default is OFF)

- Main contact points are the vertices of the geometry

4 No. of Max Contact Points does NOT affect the simulation result at all
In most cases, 100 is recommended

5 Force Display:
Displays the contact force vector during animation
In most cases, only Action is used

Step7 Simulation and calibration #1



Step7 Simulation and calibration #2

- Calibrate the parameters after reviewing the simulation results and simulation performance
  - Check Point 1: Occurrence of the Contact Event
    - If contact doesn't occur or one body pass through the other body
      - ✓ Check the distance between the bodies and use the finer Facets
      - ✓ Increase the Maximum Penetration
      - ✓ Check the Normal direction of the contact surfaces
  - Check Point 2: Penetration
    - If there is too big penetration or one body pass through the other body
      - ✓ Increase the Stiffness coefficient
      - ✓ Increase the Stiffness Exponent
      - ✓ Check off CPM(consistence penetration method)
    - If the penetration itself is very important (eg. MTT)
      - ✓ Calculate the load and find the stiffness to generated the expected penetration
  - Check Point 3: Rebound characteristics
    - If the body doesn't rebound or rebounds too much
      - ✓ Adjust the Stiffness coefficient
      - ✓ Adjust the Stiffness Exponent
      - ✓ Adjust the Damping coefficient (the variation should be smaller than stiffness)
    - If logarithmic decrement is given
      - ✓ Find the Damping coefficient using the repetitive simulation

Step7 Simulation and calibration #3

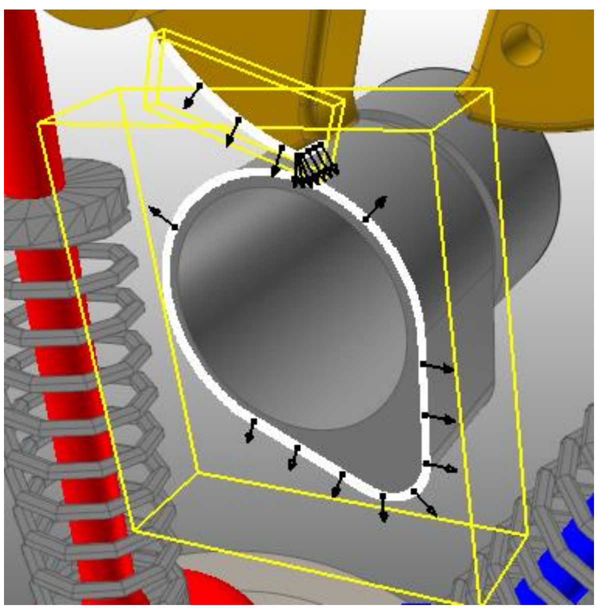
- Check Point 4: Step Size of the solver
  - If simulation takes too long (especially, if the step size gets too small)
    - ✓ as far as the rebound characteristics and the penetration is reasonable
      - ❖ Decrease the Stiffness
      - ❖ Increase the Stiffness Exponent
      - ❖ Adjust the Damping coefficient
    - ✓ Set Maximum Step Size equal to or less than 0.001 (in Solver setting)
- Check Point 5: Linearity of Contact Force
  - If the contact point moves but does not apart and the contact force oscillates
    - ✓ Use the finer Facets
    - ✓ Use the Smooth contact option
    - ✓ Decrease the Stiffness and Increase the Stiffness Exponent

Case study

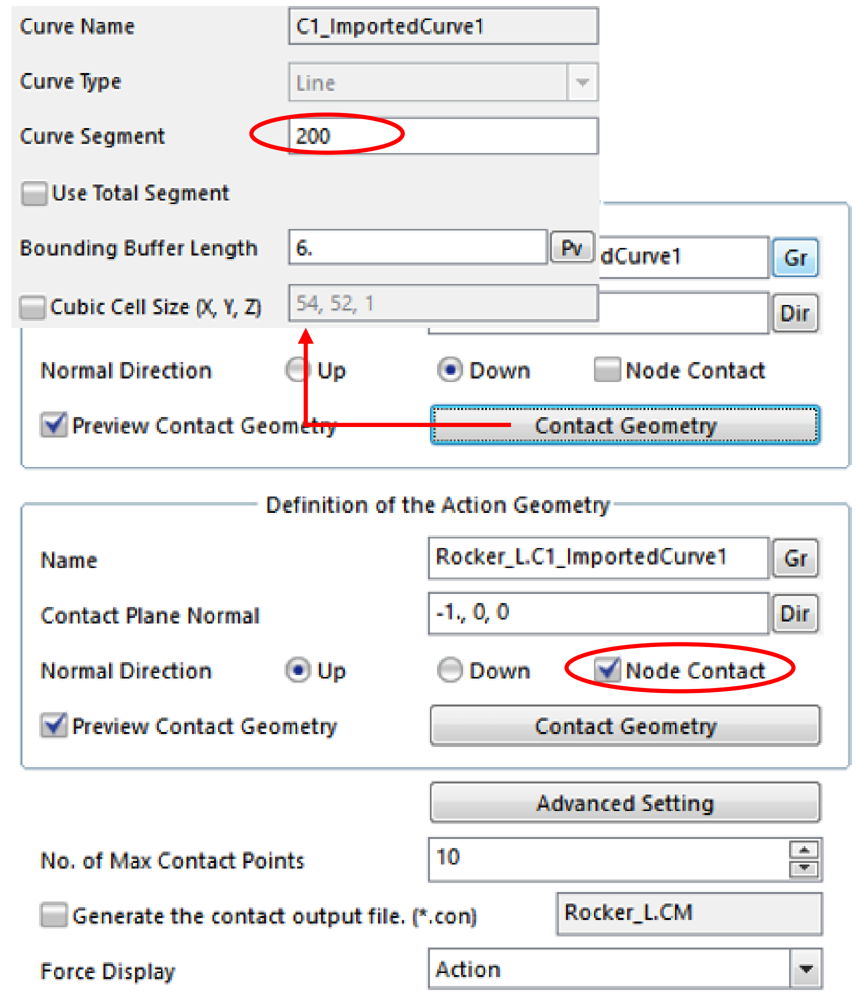
Cam System

Sim time: 2sec, CPU time 6.6sec

- Description
  - Cam Body, Rocker Body and Valve contact each other
    - 4 Geo Curve Contacts
    - 2D Geo Curve Contact is used
    - CPM, Smooth options are used
    - Curve Segment = 200
    - K:100000 C:10 Exp:1.5 Fric:0.1

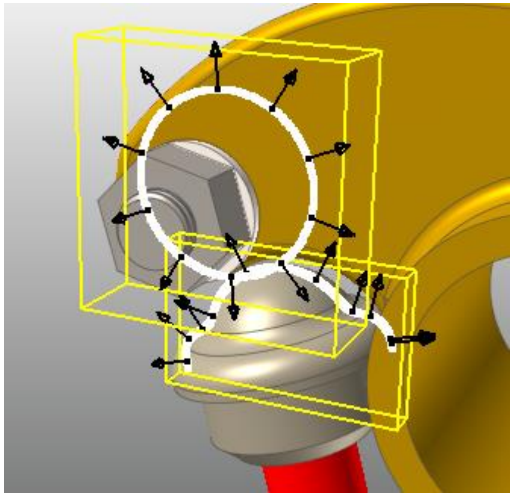


Cam to Rocker

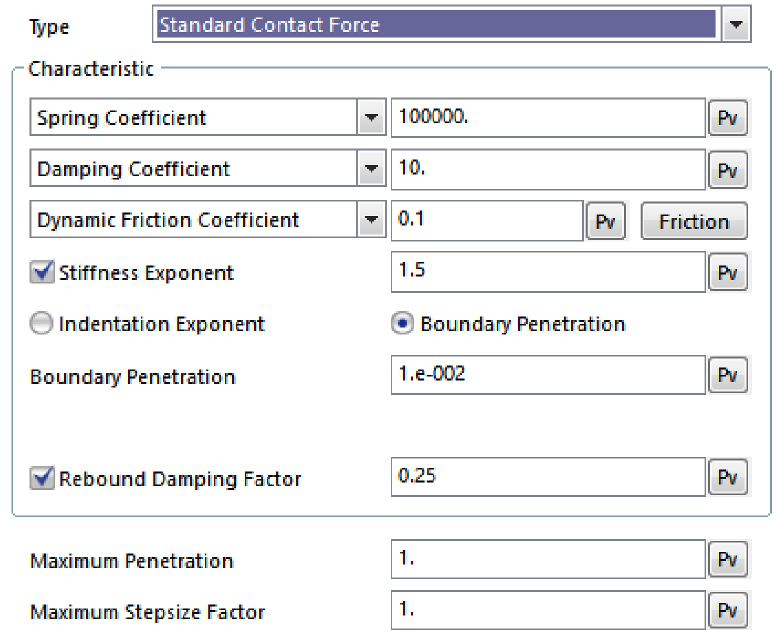


GeoCurve Dbox

Cam System

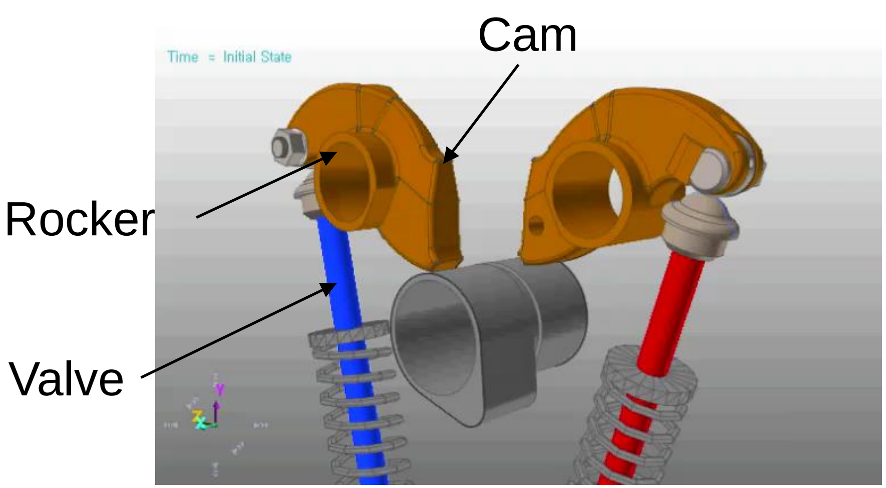


Cam to Rocker

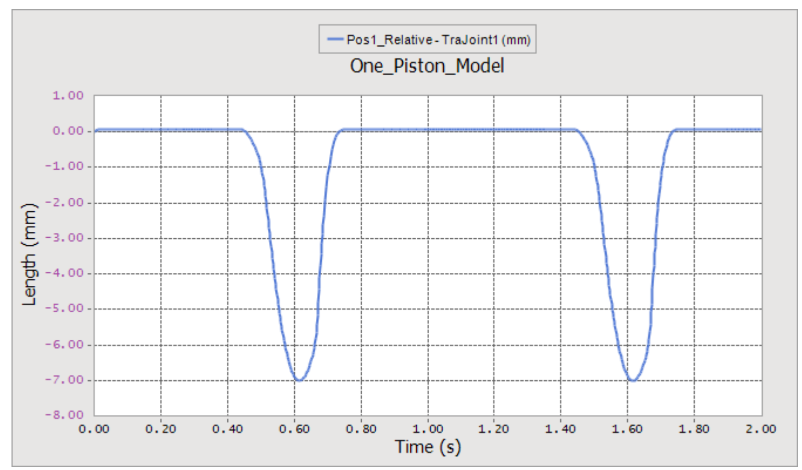


Characteristic Dbox

- Animation and Plot



Cam working animation



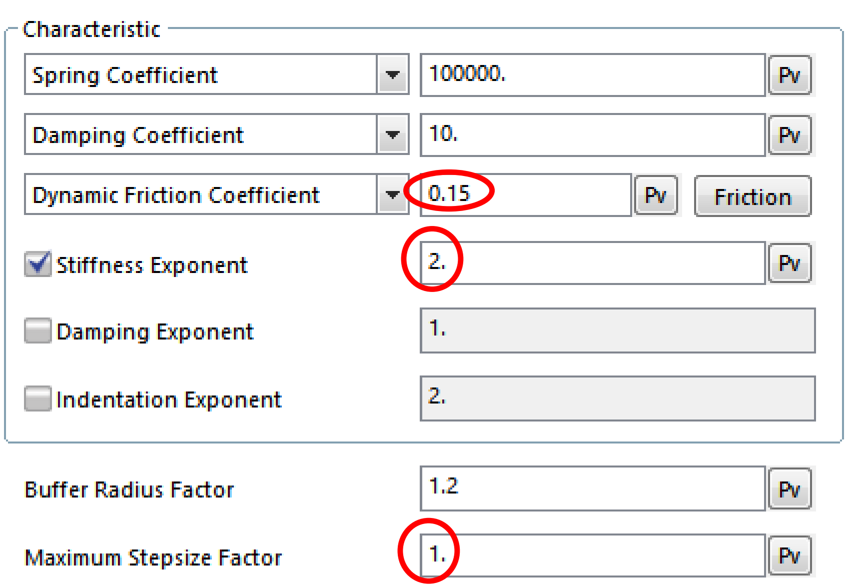
Valve displacement

Ball Bearing

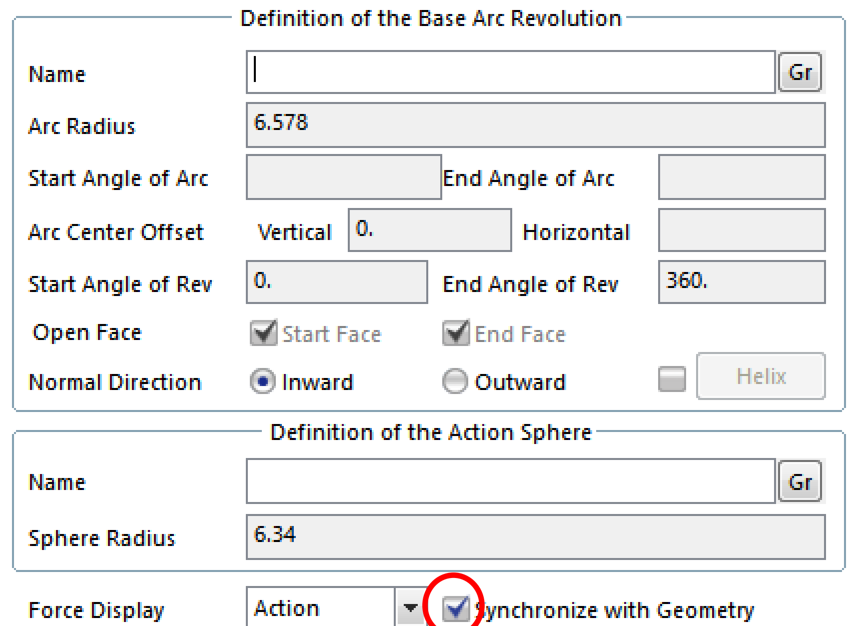
Sim time: 4sec, CPU time 6.4sec

Description

- Balls and Arc Revolution Geometry contact each other
  - 40 Sphere To Arc Revolution Contact (Analytical contact)
  - Face surfaces are used and finer facets are used
  - K = 100000 C = 10 Exp = 2.0 Fric = 0.15



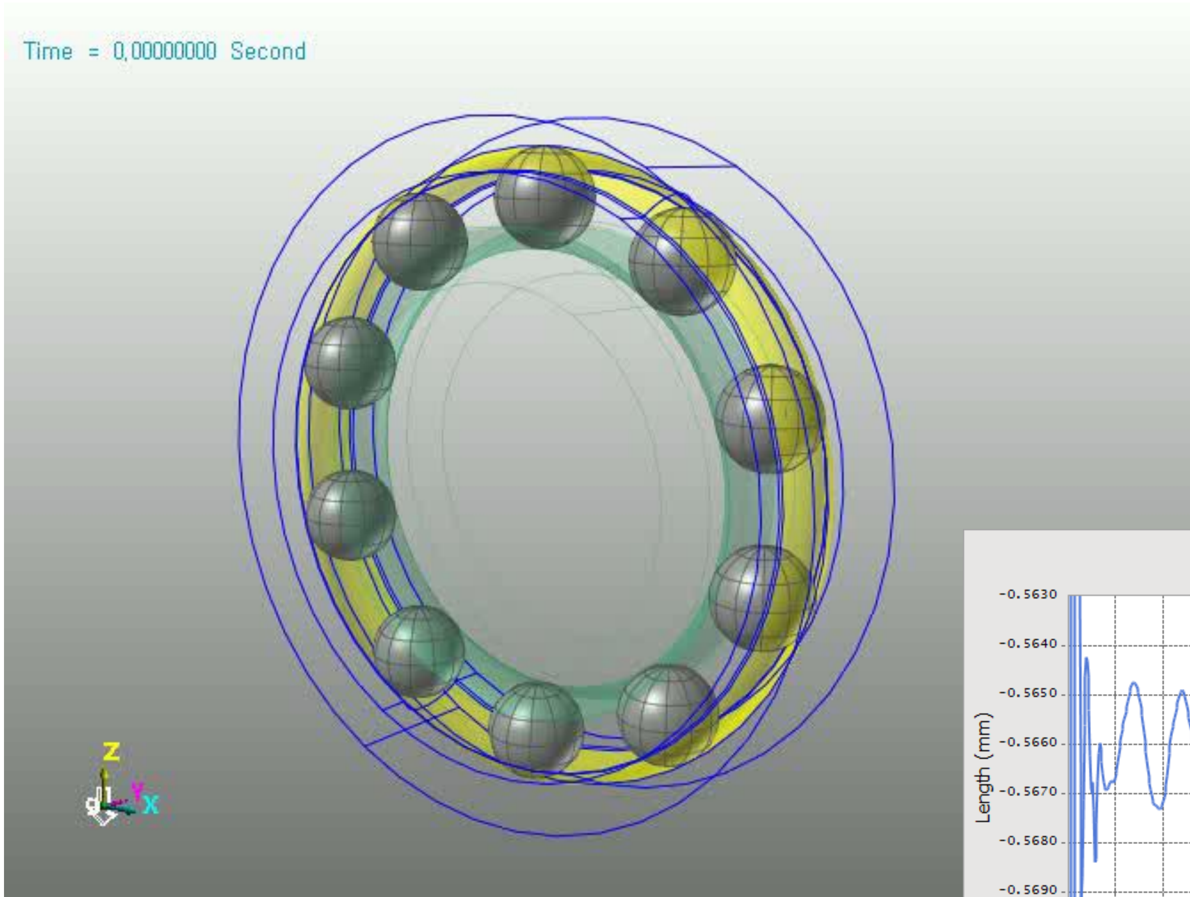
Characteristic Dbox



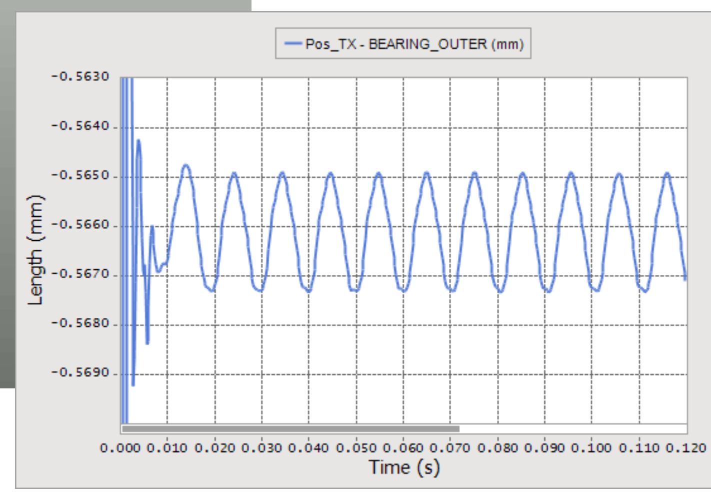
SphereToArcRevolution Dbox

Ball Bearing

- Animation and Plot



Ball bearing animation



Outer ring vertical displacement

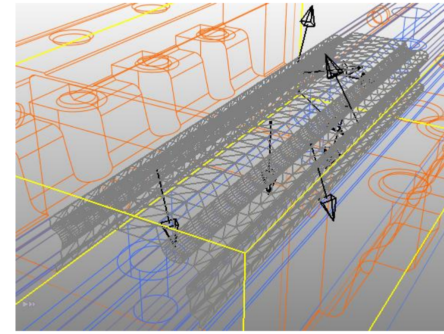
Linear guide modeling

Sim time: 1sec, CPU time 6.4sec

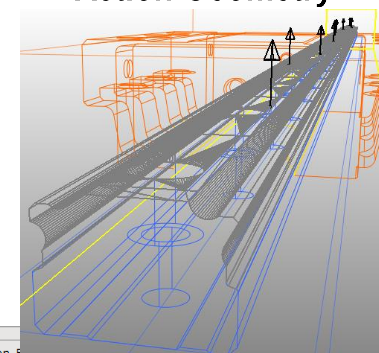
- Description
  - LM Guide moves along the Steel Rail
    - 1 Geo Surface Contact
    - Face surfaces are used
    - CPM is not used
    - K = 1000 C = 0.1 Exp = 2.0 Fric = 0.1
    - Max. Facet Size factor is used
      - ✓ Base : PTF = 0.1 (fine facets), MFSF = 10
      - ✓ Action : PTF = 0.5, MFSF = 0.5 (Increase the contact nodes)

MFSF : Max. Facet Size factor

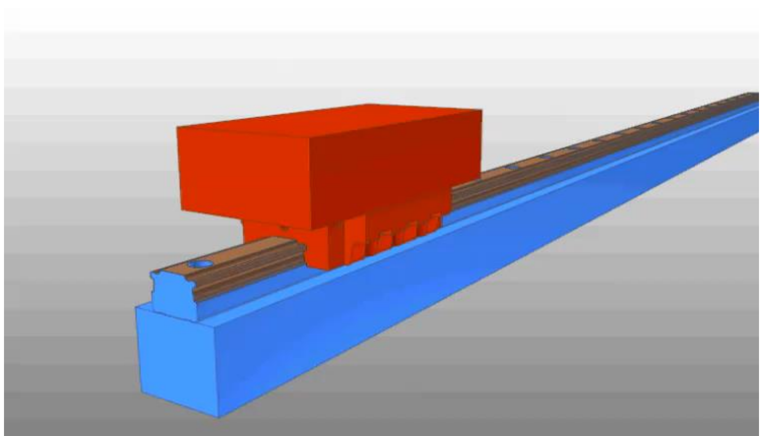
- Animation and Plot



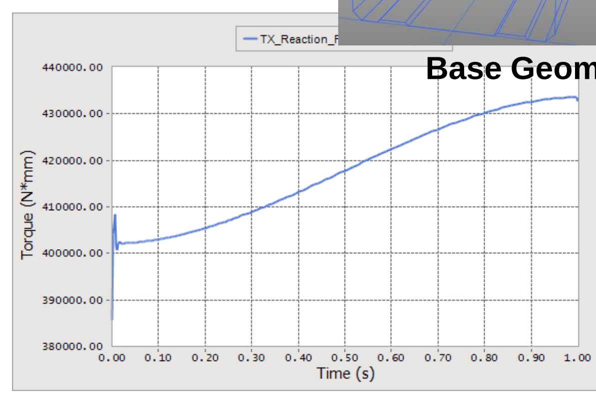
Action Geometry



Base Geometry



LM guide animation

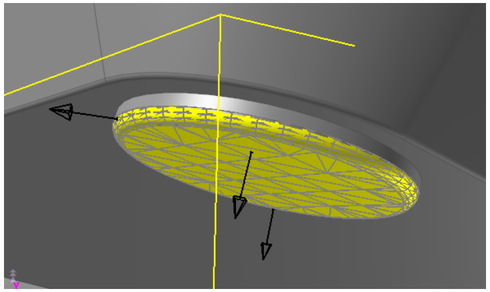


Hinge point reaction torque

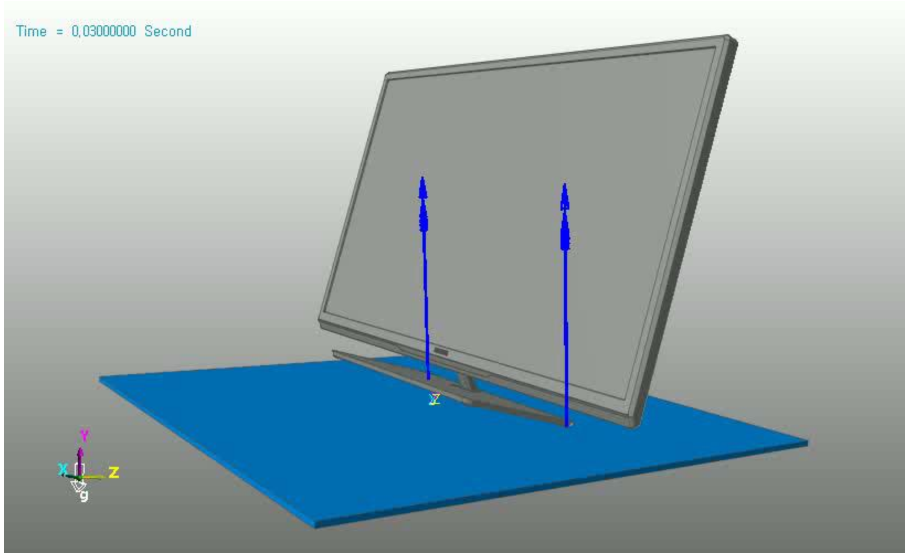
Stand wabble analysis

Sim time: 5sec, CPU time 16.2sec

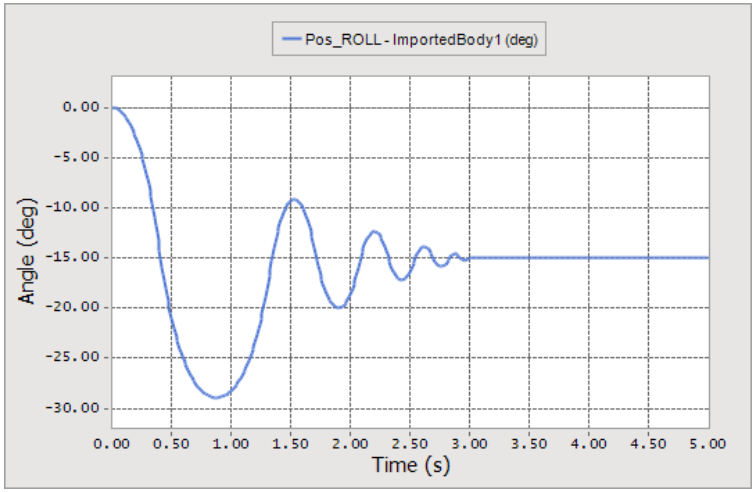
- Description
  - Simulation to analyze the stability of the TV stand
    - 1 Geo Surface Contact
    - Face surfaces are used
    - Max. Facet Size factor is used
    - CPM option is used
    - K = 10000 C = 100 Exp = 2.0 Fric = 1.0
    - Action : PTF = 3.0, MFSF = 0.1 (Increase the contact nodes)
    - Max Penetration = 5.0



Action Geometry



Wabble analysis animation

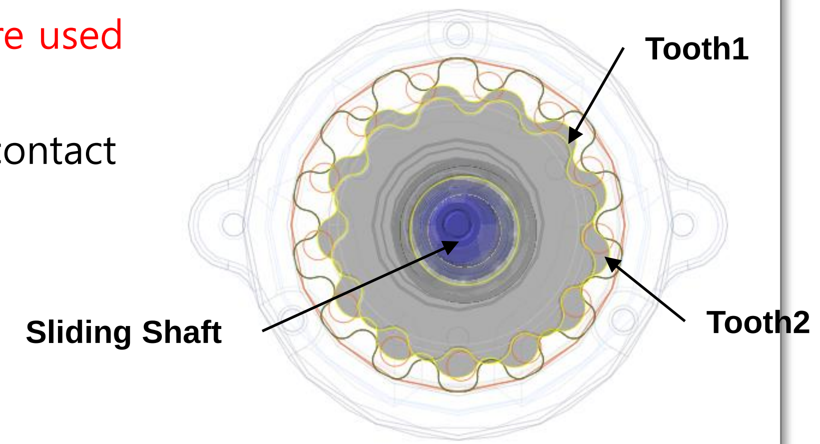


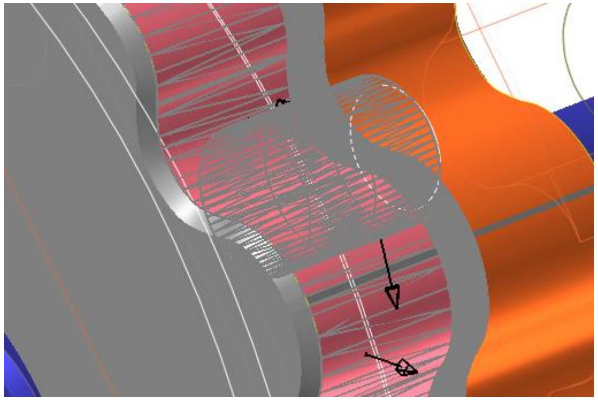
Pitch Angle

Cycloid drive

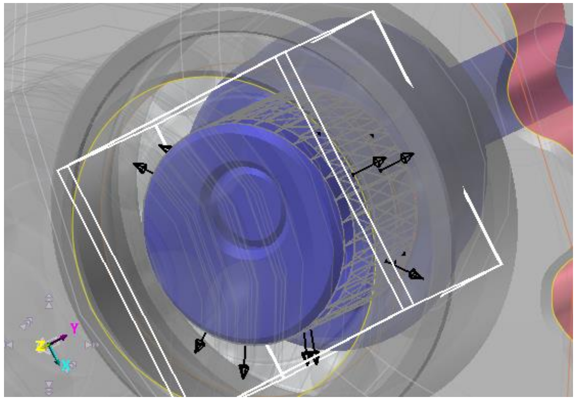
Sim time: 1sec, CPU time 26.5sec

- Description
  - A mechanism for reducing the spped of an input shaft by a certain ratio
    - 3 Geo Contacts
    - Face surfaces are used and finer facets are used
    - CPM option is NOT used
    - Smooth option is used for Sliding shaft contact
    - K = 10000 C = 1.0 Exp = 2.0 Fric = 0.01

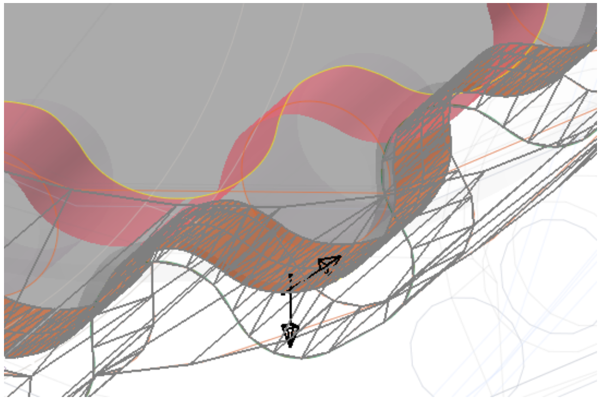




Tooth1 Contact



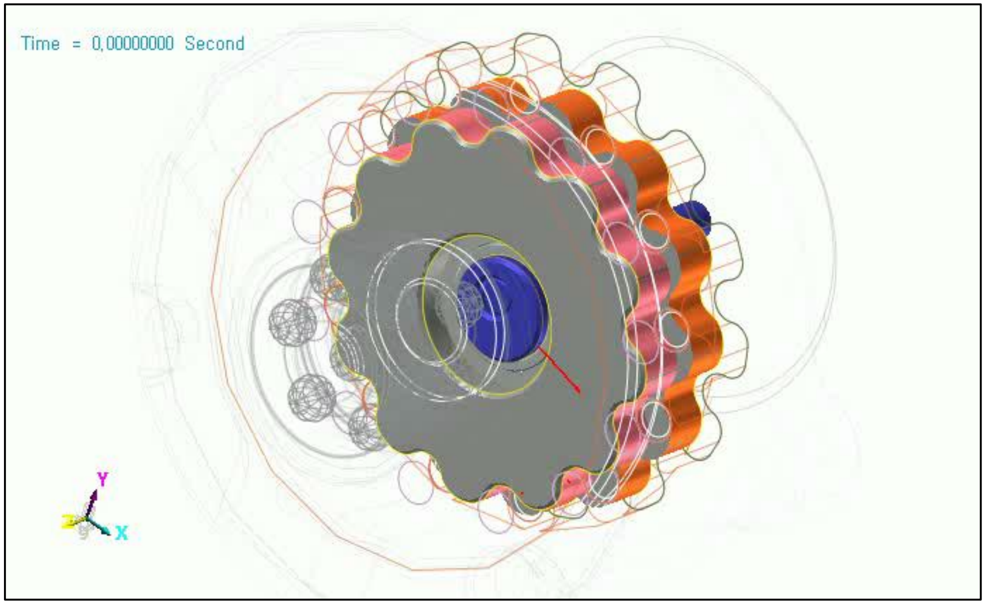
Sliding shaft contact



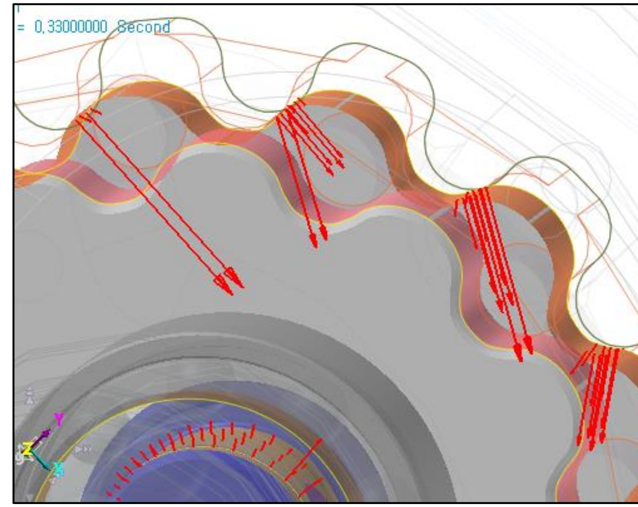
Tooth2 Contact

Cycloid drive

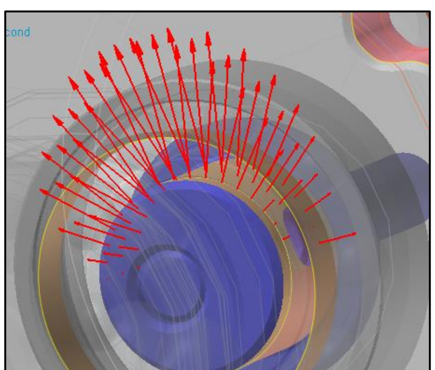
- Animation and Plot



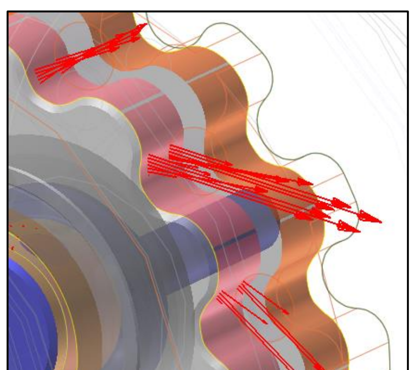
Cycloid Drive Animation



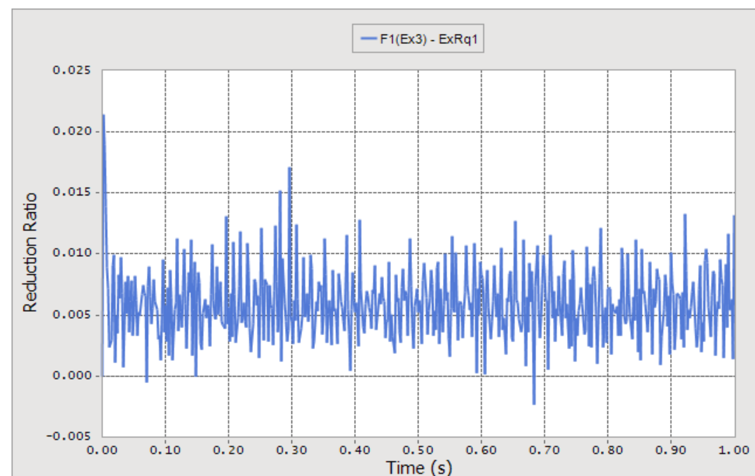
Tooth2 Contact



Sliding shaft contact



Tooth1 Contact

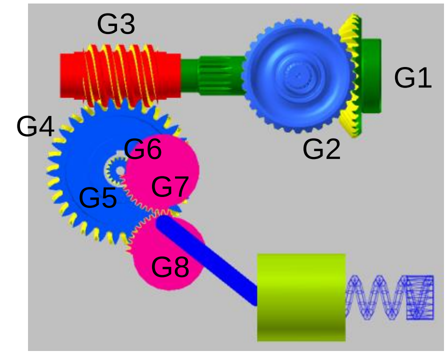


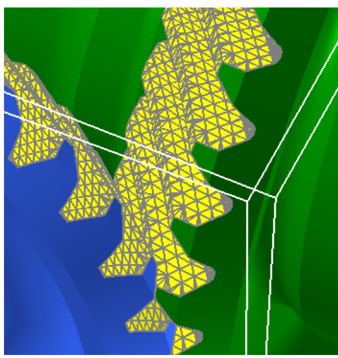
Reduction Ratio

Gear contact

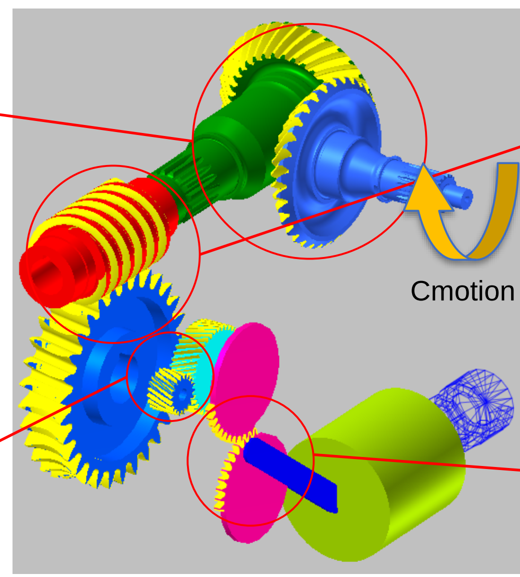
Sim time: 1sec, CPU time 2m 19sec

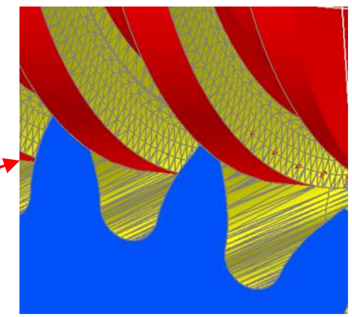
- Description
  - Gear system with various gear types
    - 5 Geo Contact
    - Face surfaces are used and finer facets are used
    - CPM option is used
    - K = 100000 C = 10 Exp = 2.0 Fric = 0.01



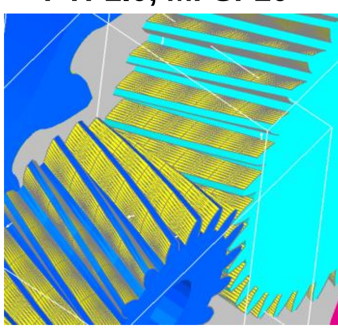


G1-G2 Contact(Bevel)
PTF1.0, MFSF10

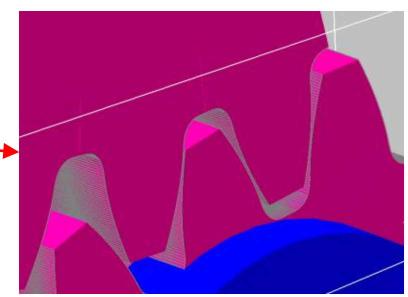




G3-G4 Contact(Worm)
PTF1.0, MFSF10



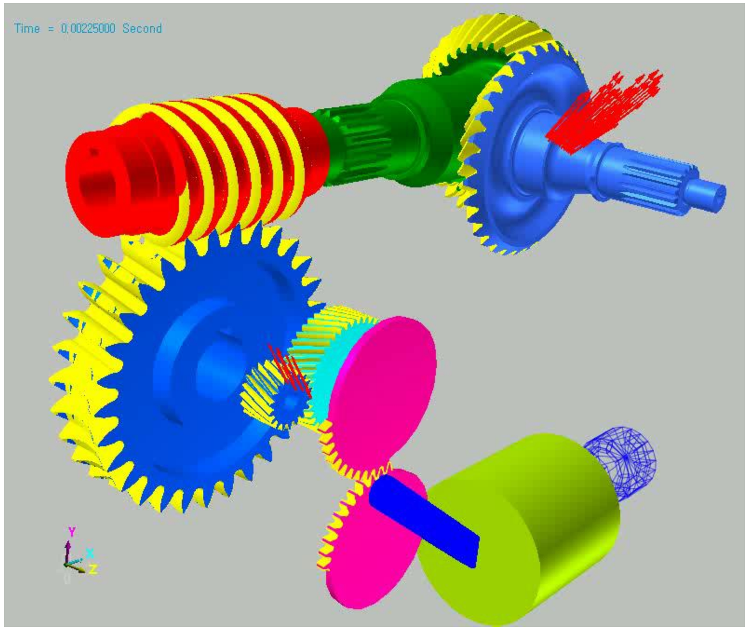
G5-G6 Contact(Helical)
PTF3.0, MFSF10.0



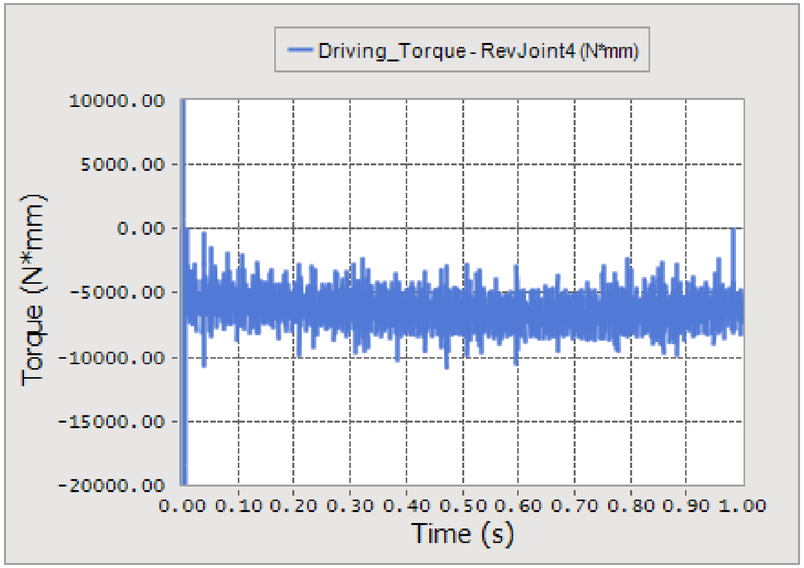
G7-G8 Contact(Spur)
PTF3.0, MFSF0.5

Gear contact

- Animation and Plot

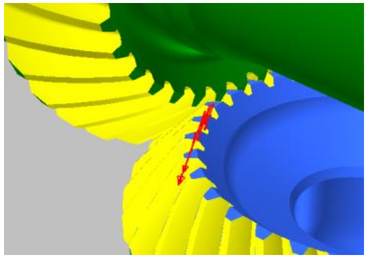


Gear contact animation

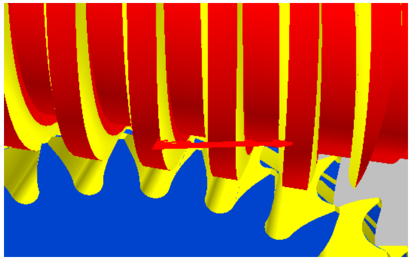


Driving torque variation

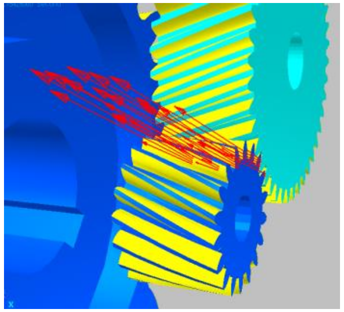
- Contact Shape



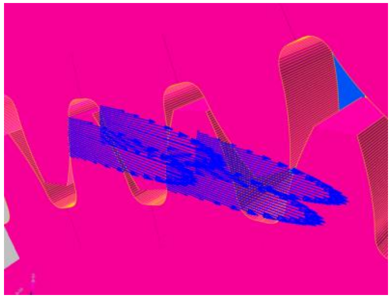
G1-G2 Contact(Bevel)



G3-G4 Contact(Worm)



G5-G6 Contact(Helical)



G7-G8 Contact(Spur)

Conclusion

Good contact modeling can reduce the simulation time and make the result more accurate

Lv1

Understanding theories on contact modeling

Lv2

Understanding the algorithm of contact force calculation

Lv3

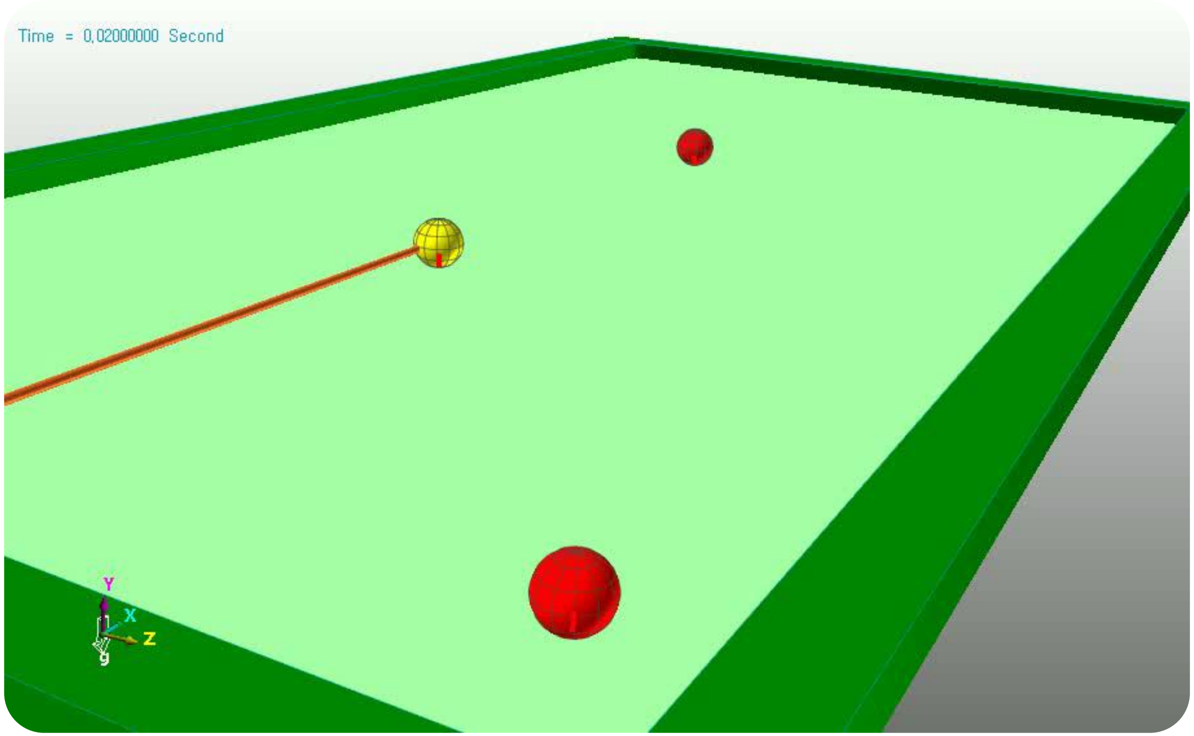
Understanding the various contact types of RecurDyn contact

Lv4

Understanding the model to be simulated

Conclusion

Contact!
You can use it well too!



Thank you

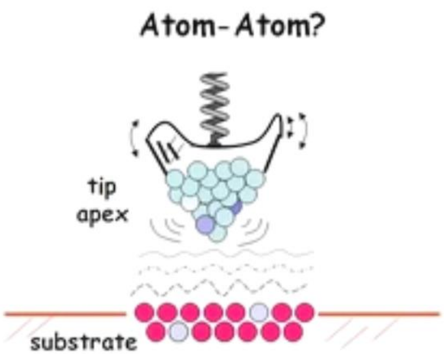
5F, Pangyo Seven Venture Valley 1 danji 2dong, 15, Pangyo-ro 228beon-gil,
Bundang-gu, Seongnam-si, Gyeonggi-do, 13487, Korea
Tel : +82-31-622-3700, Fax +82-31-622-3704, http://www.functionbay.co.kr

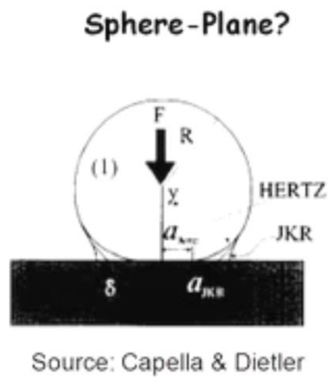
RecurDyn Contact 알고 쓰면 쉬워요!

Index

접촉 모델에 대해…

접촉해석에 대한 접근방법





미시적 접근법-DEM,FEM...

분석적 접근법-Hertz

Ueber die Berührung fester elastischer Körper.

(Von Herrn *Heinrich Hertz.*)

In der Theorie der Elasticität werden als Ursachen der Deformationen theils Kräfte, welche auf das Innere der Körper wirken, theils auf die Oberfläche wirkende Druckkräfte angenommen. Für beide Arten von Kräften kann der Fall eintreten, dass dieselben in einzelnen unendlich kleinen Theilen der Körper unendlich gross werden, so zwar, dass die Integrale der Kräfte über diese Theile genommen einen endlichen Werth behalten. Beschreiben wir alsdann um den Unstetigkeitspunkt eine geschlossene Fläche, deren Dimensionen sehr klein gegen die Dimensionen des ganzen Körpers sind, sehr gross hingegen im Vergleich zu den Dimensionen des Theils, in welchem die Kräfte angreifen, so können die Deformationen ausserhalb und innerhalb dieser Fläche ganz unabhängig von einander betrachtet werden. Ausserhalb hängen die Deformationen ab von der Gestalt des Gesammtkörpers, der Vertheilung der übrigen Kräfte und den endlichen Integralen der Kraftcomponenten im Unstetigkeitspunkte, innerhalb hängen sie nur ab von der Vertheilung der im Innern selbst angreifenden Kräfte. Die Drucke und Deformationen im Innern sind gegen die im Aeussern unendlich gross.

Im Folgenden wollen wir einen hierher gehörigen Fall behandeln, der praktisches Interesse hat*), den Fall nämlich, dass zwei elastische isotrope Körper sich in einem sehr kleinen Theil ihrer Oberfläche berühren, und durch diesen Theil einen endlichen Druck der eine auf den andern ausüben. Die sich berührenden Oberflächen stellen wir uns als vollkommen glatt vor, d. h. wir nehmen nur einen senkrechten Druck zwischen den sich berührenden Theilen an. Das beiden Körpern nach der Deformation gemeinsame Stück der Oberfläche wollen wir die Druckfläche, die Begrenzung

*) Vgl. *Winkler*, Die Lehre von der Elasticität und Festigkeit, Prag 1867; I, p. 43. *Grashof*, Theorie der Elasticität und Festigkeit, Berlin 1878; p. 49—54.

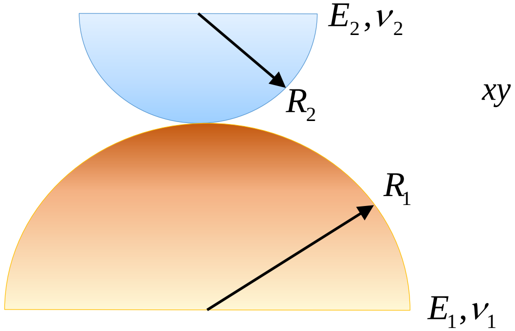
- 1881년 Heinrich Hertz에 의해 최초 제안 - 일반 형상과 응력 및 변형에 대한 해석적 접근
- 1932년 Bradley의 연구에 의해 두 강체 구의 접촉을 고려
- 1965년 Sneddon 에 의해 접촉 시 Half-space 탄성을 고려 하여 표면의 응력을 분석
- 1971년 Johnson-Kendall-Roberts에 의해 무른 소제의 접촉에서 발생하는 접착력(adhesion)고려
- 1975년 Derjahuin-Muller-Toporov에 의해 탄성 구와 강체 면의 접촉에 대하 van der Waals 힘을 고려
- 1992년 Maugis에 의해 기존의 점착력에 대한 연구를 향상하여 정확도를 높임

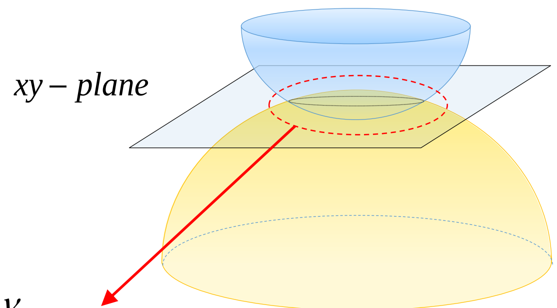
해석적 접근법은 최초 접촉이론이 개발된 이례로 기본적인 해석이론에 대해 큰 변화가 없으며 점착력이나 분자력과 같은 보다 미시적 현상에 대한 연구가 주로 이루어 졌음

※ Purdue University Lecture 8 Introduction to Contact Mechanics

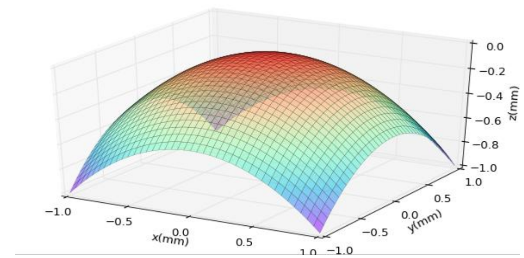
Hertz contact model

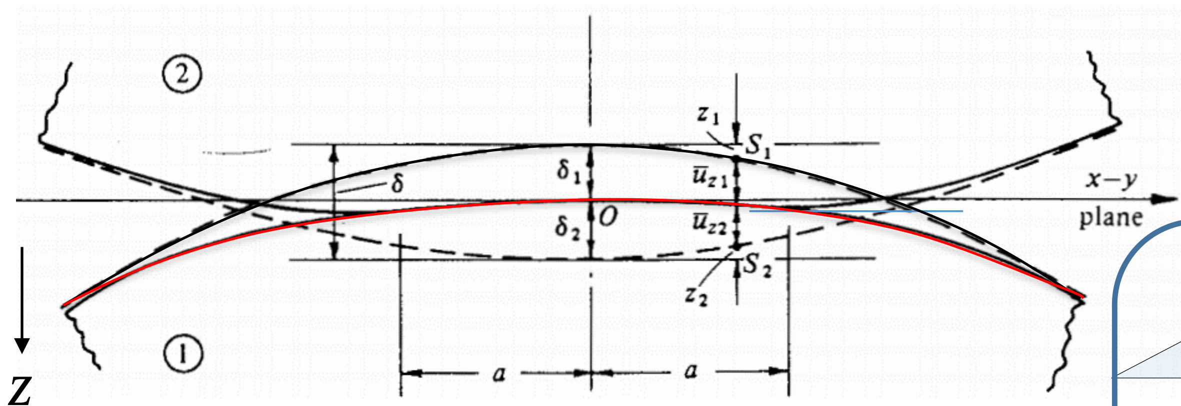
접촉상황 및 변형 형상에 대한 가정





Shape function of z



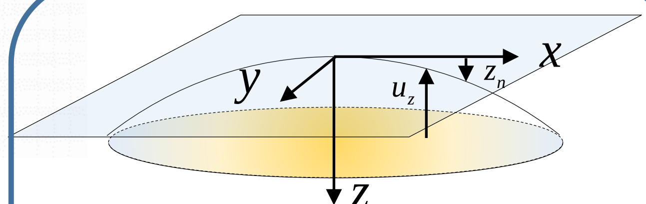


$$h = z_1 - z_2$$

$$\bar{u}_{z1} + \bar{u}_{z2} + h = \delta_1 + \delta_2$$

$$z_1 = \frac{1}{2R_1'}x^2 + \frac{1}{2R_1''}y^2$$

$$z_2 = -\left(\frac{1}{2R_2'}x^2 + \frac{1}{2R_2''}y^2\right)$$



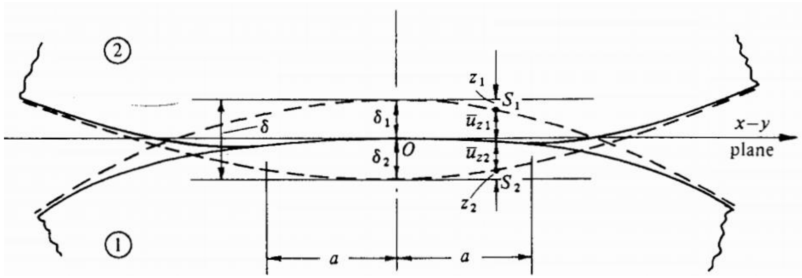
$$z_n = \frac{1}{2R'}x^2 + \frac{1}{2R''}y^2$$

R' : x방향의 곡률반경

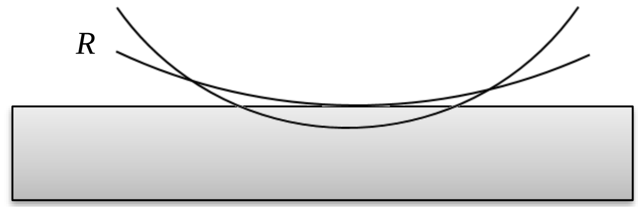
R'' : y 방향의 곡률반경

Hertz contact model

함수 h에 대한 단순화



단순화



$$h = Ax^2 + By^2 = \frac{1}{2R}x^2 + \frac{1}{2R}y^2$$

$$h = z_1 - z_2 = \frac{1}{2R_1'}x^2 + \frac{1}{2R_1''}y^2 + \frac{1}{2R_2'}x^2 + \frac{1}{2R_2''}y^2$$

$$\text{where, } R_1' = R'' = R_1, \quad R_2' = R_2'' = R_2$$

$$h = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)x^2 + \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)y^2$$

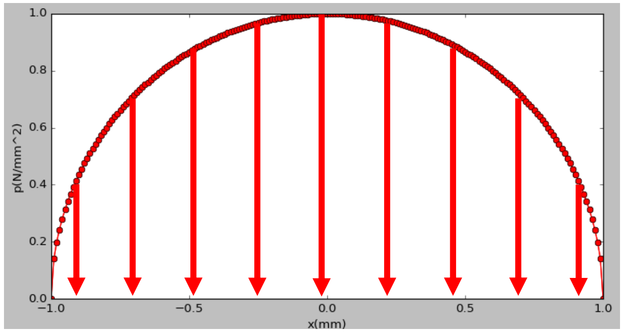
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

함수 h를 r-θ좌표계에 대해 표현

$$h = \frac{1}{2R}x^2 + \frac{1}{2R}y^2 \Rightarrow \frac{1}{2R}r^2 \quad (r - \theta\, coordinate)$$

Hertz contact model

접촉면의 압력형상 가정



압력의 분포가 반구형으로 작용한다고 가정

$$p(r) = p_0 \sqrt{a^2 - r^2} / a$$

압력의 분포가 반구형으로 작용한다고 가정했을 경우 반경 r에 대한 z변위의 계산식 (응력과 변형률 계산공식으로부터 도출)

$$\begin{cases} \bar{u}_{z1} = \dfrac{1-\nu_1^2}{E_1} \dfrac{\pi p_0}{4a} \left(2a^2 - r^2\right) \\ \bar{u}_{z2} = \dfrac{1-\nu_2^2}{E_2} \dfrac{\pi p_0}{4a} \left(2a^2 - r^2\right) \end{cases}$$

$$\bar{u}_{z1} + \bar{u}_{z2} = \delta_1 + \delta_2 - h$$

$$\bar{u}_{z1} + \bar{u}_{z2} = \delta - \frac{1}{2R} r^2 \quad (\delta = \delta_1 + \delta_2)$$

$$\frac{1-\nu_1^2}{E_1} \frac{\pi p_0}{4a} \left(2a^2 - r^2\right) + \frac{1-\nu_2^2}{E_2} \frac{\pi p_0}{4a} \left(2a^2 - r^2\right) = \delta - \frac{1}{2R} r^2 \quad (\delta = \delta_1 + \delta_2)$$

Hertz contact model

$$\frac{\pi p_0}{4a}\left(2a^2 - r^2\right)\left(\frac{1-\nu_1^{\,2}}{E_1} + \frac{1-\nu_2^{\,2}}{E_2}\right) = \delta - \frac{1}{2R}r^2$$

$$\frac{\pi p_0}{4aE}\left(2a^2 - r^2\right) = \delta - \frac{1}{2R}r^2$$

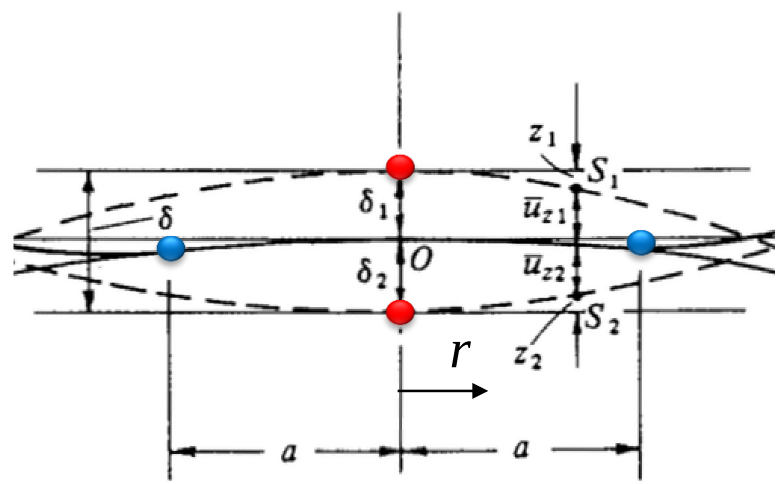
$$\left(\frac{1}{E} = \frac{1-\nu_1^{\,2}}{E_1} + \frac{1-\nu_2^{\,2}}{E_2}\right)$$

경계조건 적용

r이 0일 때 의 δ를 변형량으로 결정
r=a일 때 평형관계식을 통해 a를 결정

$$\text{where, } r = 0 \text{ than, } \delta = \frac{\pi p_0 a}{2E}$$

$$\text{where, } r = a, \delta = 0 \text{ than, } a = \frac{\pi p_0 R}{2E}$$



Hertz contact model

원인 접촉면에 반구 형상의 압력(p)이 가해질 경우 전체 하중 P계산

$$P = \int_0^a 2\pi r \cdot p(r) dr = \frac{2\pi p_0}{a} \int_0^a r\sqrt{a^2 - r^2} dr = \frac{2}{3}\pi p_0 a^2$$

$$P = \frac{2}{3}\pi p_0 a^2 \quad \Rightarrow \quad p_0 = \frac{3P}{2\pi a^2}$$

변형량과 접촉길이의 식에 P의 관계식 대입

$$\delta = \frac{\pi p_0 a}{2E}, \quad a = \frac{\pi p_0 R}{2E}$$

$$a = \frac{\pi p_0 R}{2E} = \frac{3PR}{4Ea^2} \quad \left(\text{where, } p_0 = \frac{3P}{2\pi a^2}\right)$$

$$\delta = \frac{a^2}{R} = \frac{1}{R}\left(\frac{3PR}{4E}\right)^{2/3} = \left(\frac{9P^2}{16RE^2}\right)^{1/3}$$

$$p_0 = \frac{3P}{2\pi a^2} = \left(\frac{6PE^2}{\pi^3 R^2}\right)^{1/3}$$

$$\therefore a = \left(\frac{3PR}{4E}\right)^{1/3}, \delta = \left(\frac{9P^2}{16RE^2}\right)^{1/3}, p_0 = \left(\frac{6PE^2}{\pi^3 R^2}\right)^{1/3}$$

Hertz contact model

Hertz Contact Formulation

$$P = \sqrt{\frac{16RE^2}{9}}\delta^{3/2} = K \cdot \delta^{1.5}$$

$$R = \frac{R_1 R_2}{R_1 + R_2} \qquad K = \sqrt{\frac{16RE^2}{9}}$$

$$E = \frac{E_1 E_2}{E_2\left(1-\nu_1^{\ 2}\right) + E_1\left(1-\nu_2^{\ 2}\right)}$$

RecurDyn Contact Formulation

$$F = K \cdot \delta^n$$

$$K = f\left(R_1, R_2, E_1, E_2, \nu_1, \nu_2\right)$$

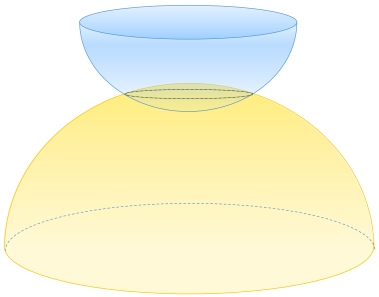
$$n = 1.5$$

References

- H. Hertz, “Über die Berührung fester elastischer Körper,” Gesammelte Werke (P. Lenard, ed.), Bd. 1,(J.A. Barth, Leipzig, 1895) pp. 155-173. Originally pub-lished in Journal f. d. reine u. angewandte Mathematik 92,156-171 (1881).
- ‘Contact mechanics’ in Wikipedia
- R S Dwyer-Joyce, “Tribological Design Data Part 3: Contact Mechanics” University of Sheffield
- K.L. Johnson, “Contact Mechanics” Cambridge University Press 1985 ISBN 0 521 347963
- Georges Cailletaud, St´ephanie Basseville1,Vladislav A. Yastrebov, “Contact mechanics I: basics”, EMESURF short course on contact mechanics and tribology, Paris, France, 21-24 June 2010
- https://woodem.org/theory/contact/hertzian.html

Hertz contact model – parameters

- 구와 구가 접촉하는 상황에 대해 다양한 반경 적용(Steel)



- E1,E2=210Gpa
- E = 115Gpa
- $\nu 1$, $\nu 2$=0.3

$$R = \frac{R_1 R_2}{R_1 + R_2} \quad K = \sqrt{\frac{16RE^2}{9}}$$

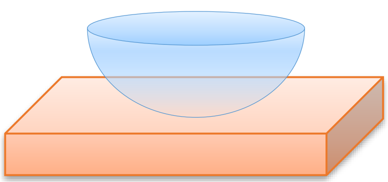
$$E = \frac{E_1 E_2}{E_2\left(1-\nu_1^2\right)+E_1\left(1-\nu_2^2\right)}$$

MMKS

R1(mm)	R2(mm)	R	K
0.5	1	0.333333333	88823
0.5	10	0.476190476	106163
0.5	100	0.497512438	108514
0.5	1000	0.499750125	108758
0.5	10000	0.499975001	108782
0.5	100000	0.4999975	108785
0.5	1000000	0.49999975	108785

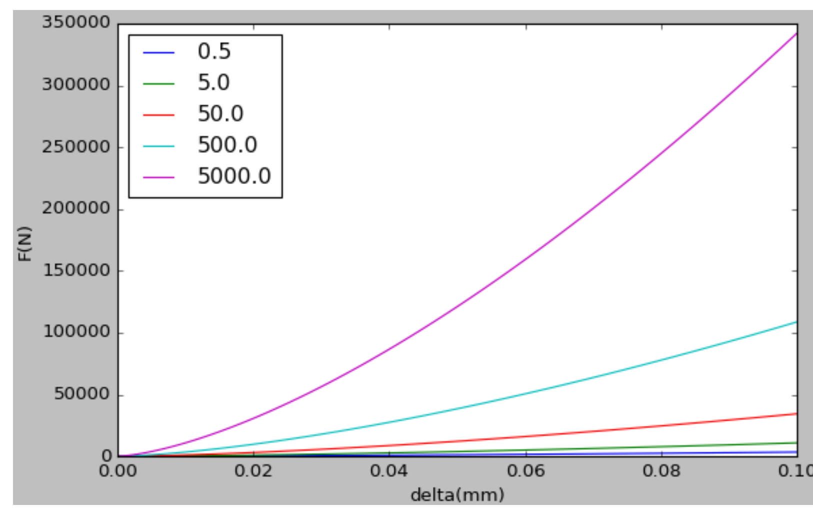
RecurDyn Default value = 100000

- 구와 평면이 접촉하는 상황에 대해 다양한 반경 적용(Steel)



- E1,E2=210Gpa
- E = 115Gpa
- $\nu 1$, $\nu 2$=0.3

R1(mm)	R2(mm)	R	K
0.5	500000	0.4999995	108785
5	500000	4.99995	344008
50	500000	49.9950005	1087802
500	500000	499.5004995	3438385
5000	500000	4950.49505	10824577



Hertz Contact FD curve

Hertz contact model – parameters

- 다양한 소재에 대한 접촉 물성치 적용

Material Properties

Material	E(Gpa)	ν
Steel	210.00	0.3
Aluminum	70.00	0.32
Bronze	120.00	0.34
Oak Wood	11.00	0.35
Plastic	2.40	0.39
Rubber(EPDM)	0.02	0.5

R1=0.5mm ,R2=500000mm

	Steel	Aluminum	Bronze	Oak Wood	Plastic	Rubber
Steel	108786	54955	80559	11210	2636	25
Aluminum		36763	46690	10182	2575	25
Bronze			63963	10819	2614	25
Oak Wood				5909	2177	25
Plastic					1334	25
Rubber						13

Contact Stiffness K for MMKS Model

- Conclusion
  - Hertz Contact모델을 이용한 접촉해석에서 Stiffness(K)의 값은 두 소재의 탄성계수(Young's Modulus)와 두 Solid의 접촉면에서 형상에 대한 곡률반경을 이용하여 구할 수 있다.

$$K = \sqrt{\frac{16RE^2}{9}}$$

$$\begin{cases} R = \dfrac{R_1 R_2}{R_1 + R_2} \\ E = \dfrac{E_1 E_2}{E_2\left(1-\nu_1^{\,2}\right) + E_1\left(1-\nu_2^{\,2}\right)} \end{cases}$$

RecurDyn Contact

RecurDyn Contact Computing process

Geometry 접근

Solver는 별도의 Action을 취하지 않음

Bounding buffer Cubic 침투

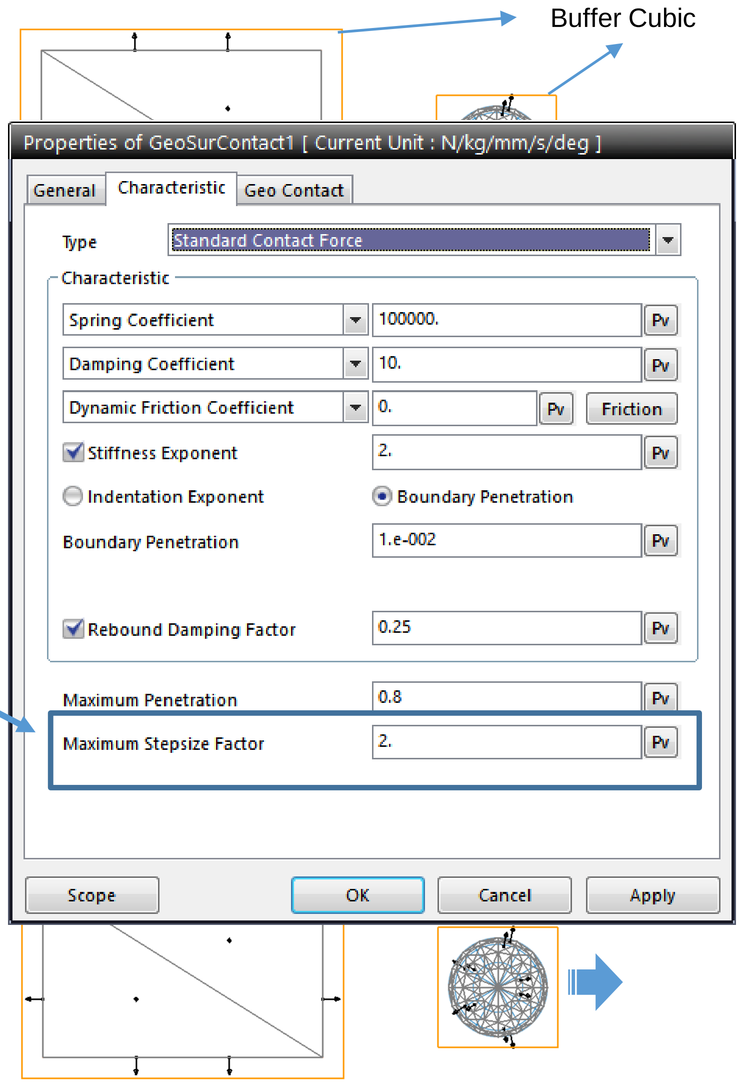
Buffer Cubic에 침투 시 Step Size Factor에 의해 Max. Step size의 값을 수정하여 적분

Contact 발생

Contact Event를 발생시켜 Contact Force를 계산하여 운동방정식에 적용

Geometry 이탈

반발 가속도에 의해 운동방향이 바뀌며 침투상황이 해제됨, Buffer Cubic을 이탈할 경우 Step Size Factor에 의한 Max.Step size의 수정 영향을 제거



RecurDyn Contact formula

- Normal Force

$$f_n = f_{ns} + f_{nd} \quad \begin{cases} f_{ns} : \text{stiffness force of contact} \\ f_{nd} : \text{damping force of contact} \end{cases}$$

- Stiffness Force: Hertz Contact이론에 기반한 수식 사용

$$f_{ns} = K \cdot \delta^{ms}$$

- Damping Force
  - Boundary Penetration Method

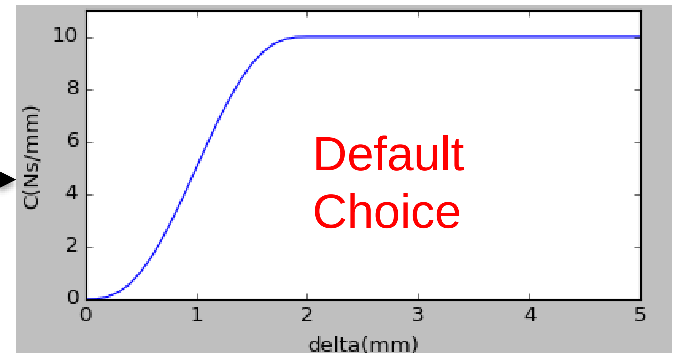
$$f_{nd} = step(\delta, 0, \delta_{\max}, C_{\max}) \cdot \dot{\delta}$$

  - Indentation Exponent Method

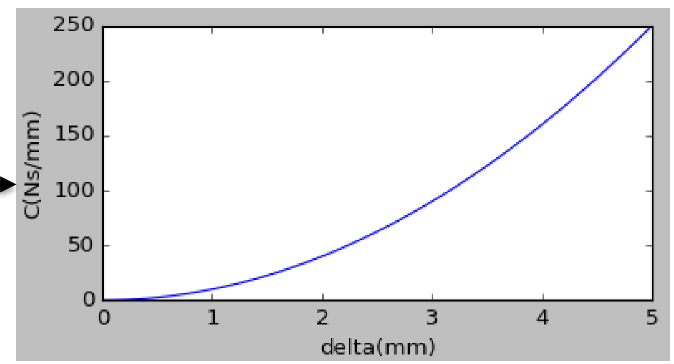
$$f_{nd} = C_{\max} \cdot \delta^{mi} \cdot sgn(\dot{\delta}) \cdot \dot{\delta}^{md}$$

$$\text{default parameters: } md = 1,\ mi = 2$$

$$f_{nd} = C_{\max} \cdot \delta^2 \cdot \dot{\delta}$$



δ – c curve of BPM

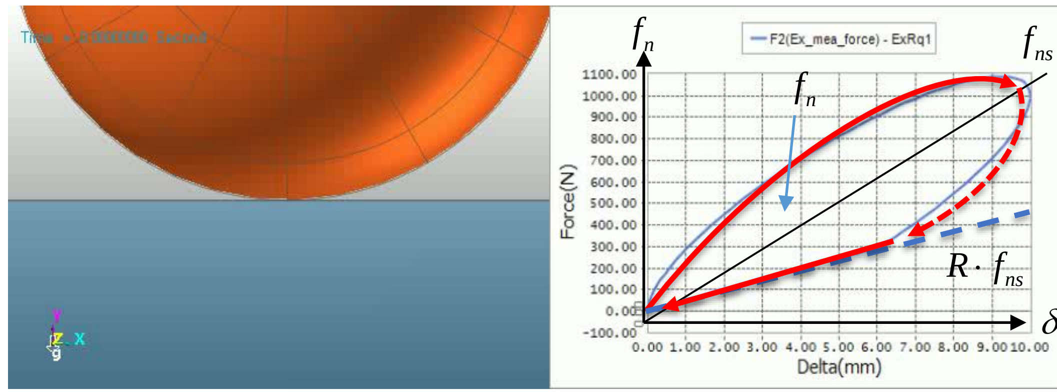


δ – c curve of IEM

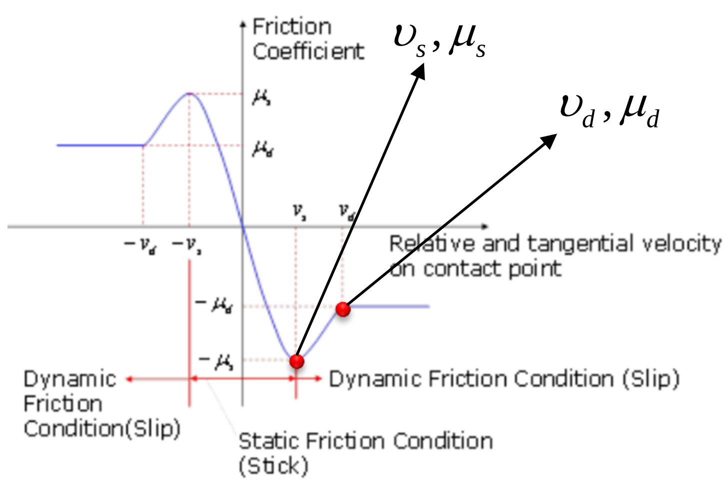
RecurDyn Contact formula

- Damping Force (Cont.)
  - Rebound Damping Factor
    - ✓ 반발력의 방향은 침투할 때 밀어내는 방향이지만 이탈할 경우 잡아 당기는 방향
    - ✓ 과도한 Damping이 작용할 겨우 fs보다 fd가 커지는 점착 상황 발생
    - ✓ 점착 상황을 방지하기 위해 Rebound Damping factor 사용

$$f_n = \max(f_n,\ R \cdot f_{ns})$$



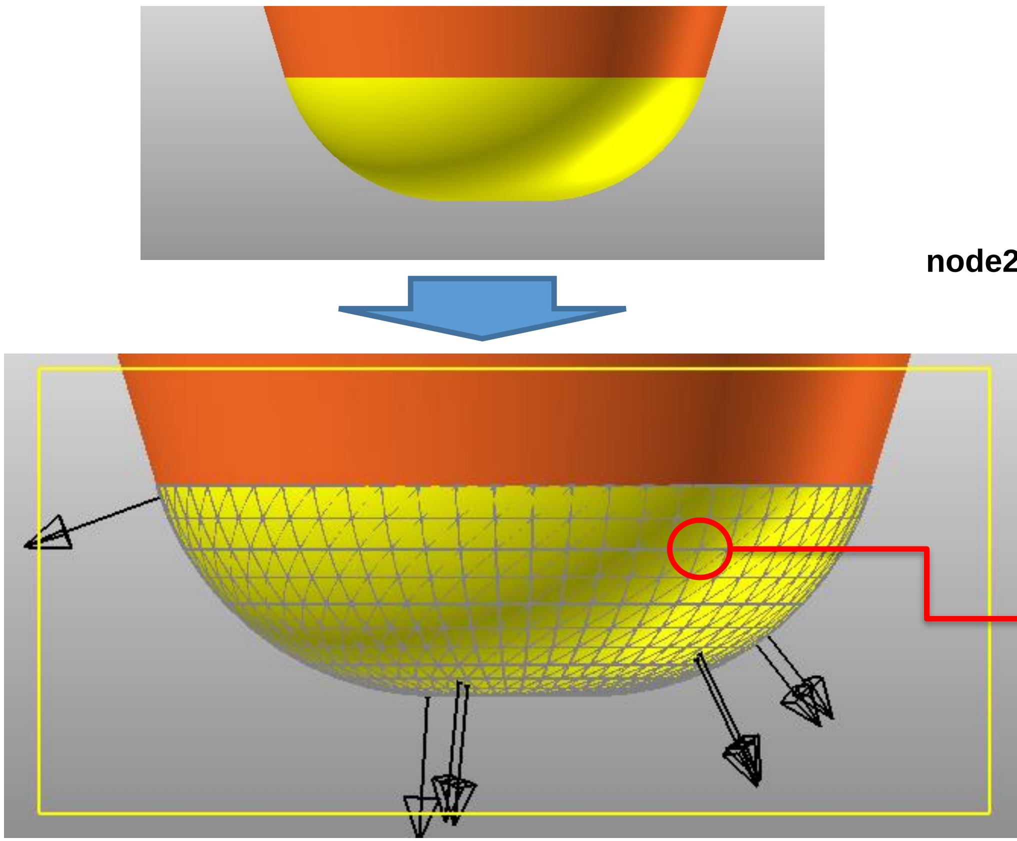
- Friction Force

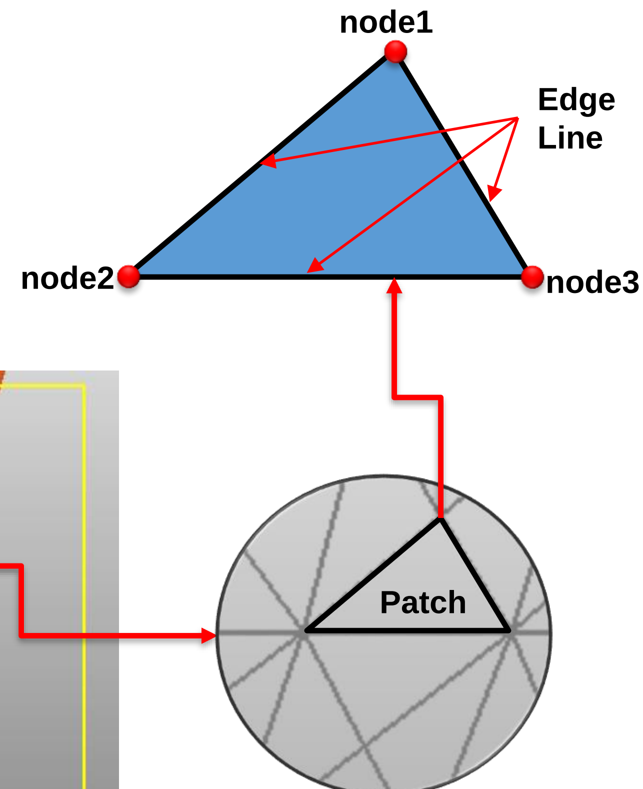


정마찰 및 동마찰 계수와 임계속도를
이용한 마찰특성그래프를 생성하고
이를 속도의 함수로 보간하여 사용

Faceting

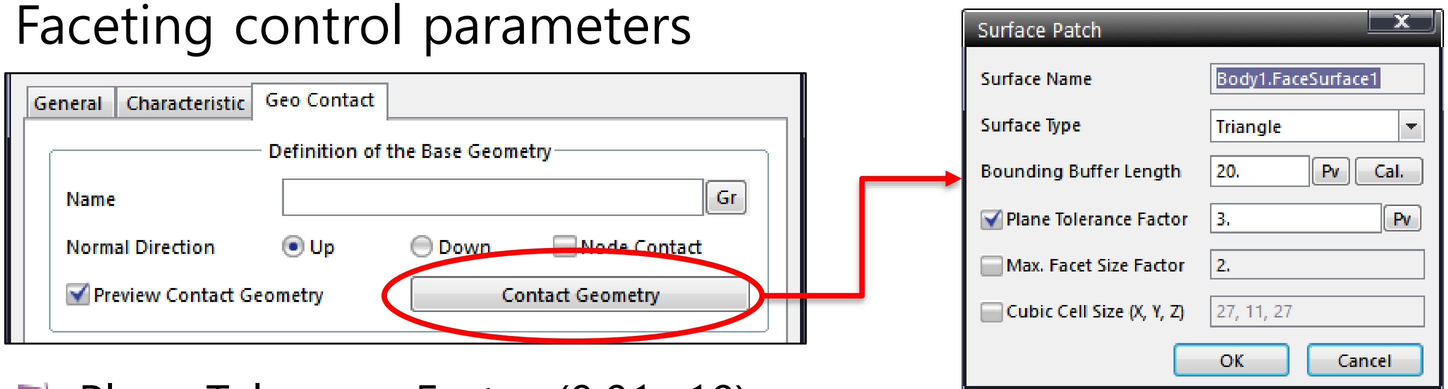
- Faceting
  - 자유곡면을 수학적 연산이 용이한 3각형 Polygon으로 분할하는 작업
    - ➢ 접촉연산을 수행할 때 곡면의 함수를 직접 이용할 경우 그 경우의 수와 함수의 복잡성으로 인해 계산속도가 급격하게 느려 질 수 있다. 이를 해결하기 위해 3각 Patch형태로 Geometry를 분할하여 계산에 활용





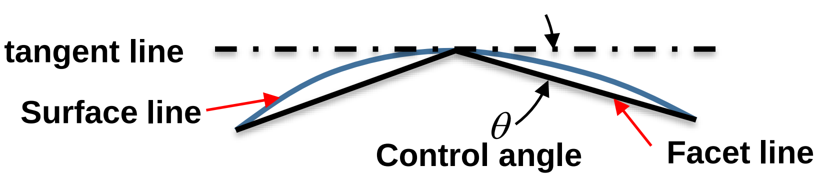
Faceting

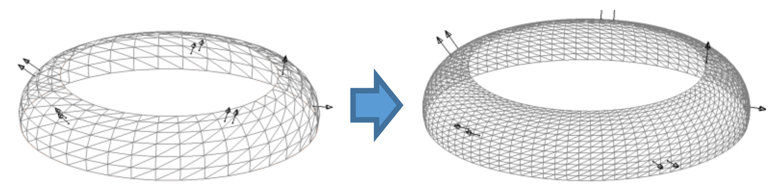
- Faceting control parameters



Plane Tolerance Factor (0.01~10)

- 곡률을 분할하는 정도로서 값이 작을 수록 곡면에서 Facet의 개수가 많아짐

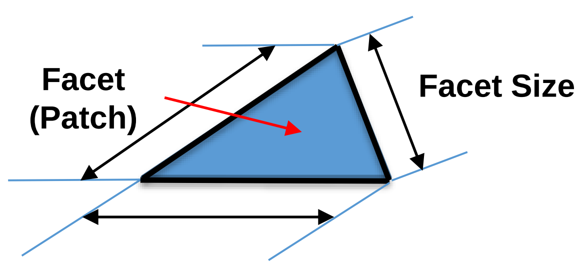


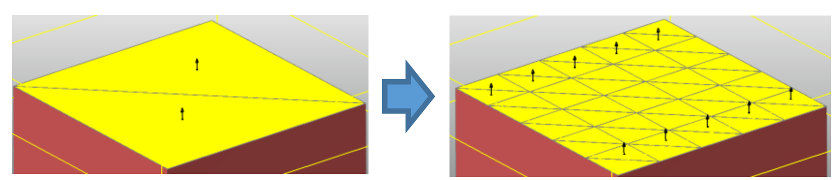


Plane Tolerance Factor 5 → Plane Tolerance Factor 2

Max. Facet Size Factor

- Facet의 크기를 제한하는 Factor로서 작은 값 일 수록 면의 Facet개수가 많아짐

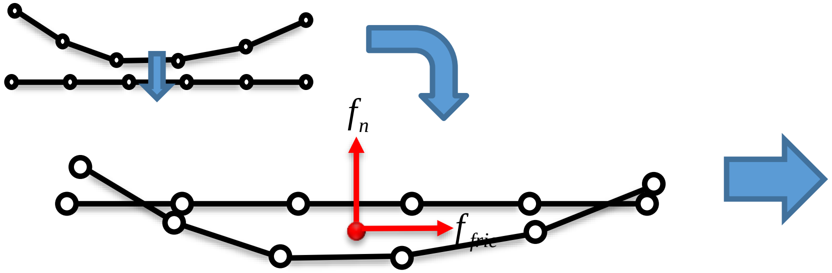


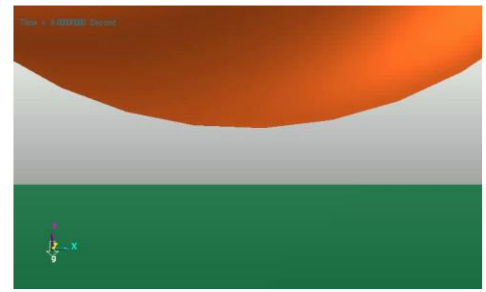


Max. Facet Size Factor 10 → Max. Facet Size Factor 2

Contact Event

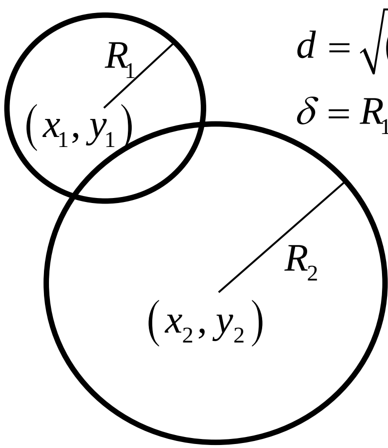
- Solid contact – (Solid contact)
  - Patch들이 침투한 상황에서 대표점(Geometry Center)에서 접촉발생





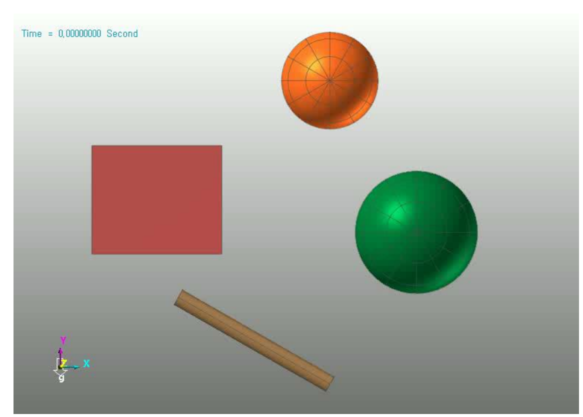
Simulation

- Analytical contact – (Primitive contact)
  - 미리 정의된 형상의 함수 식에서 접촉 위치를 계산하여 대표점에서 접촉
  - Faceting을 수행하지 않으며 Patch도 존재하지 않음



$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

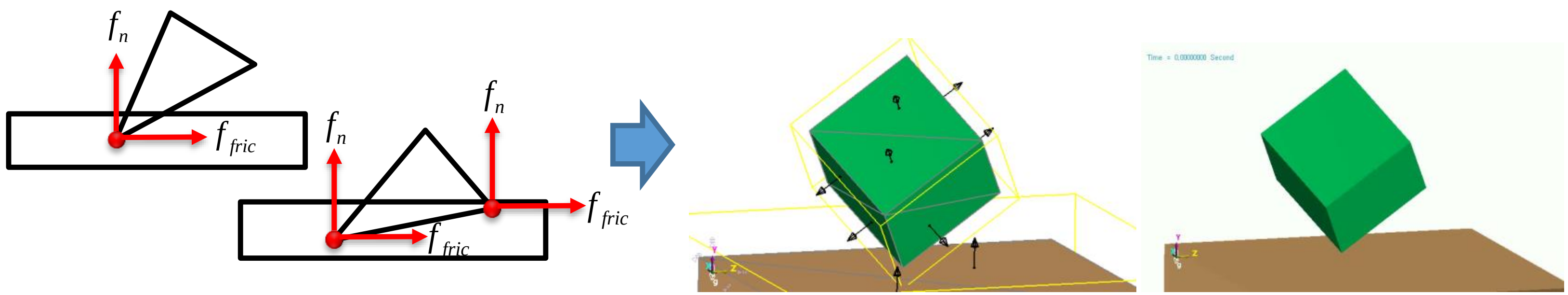
$$\delta = R_1 + R_2 - d$$



Simulation

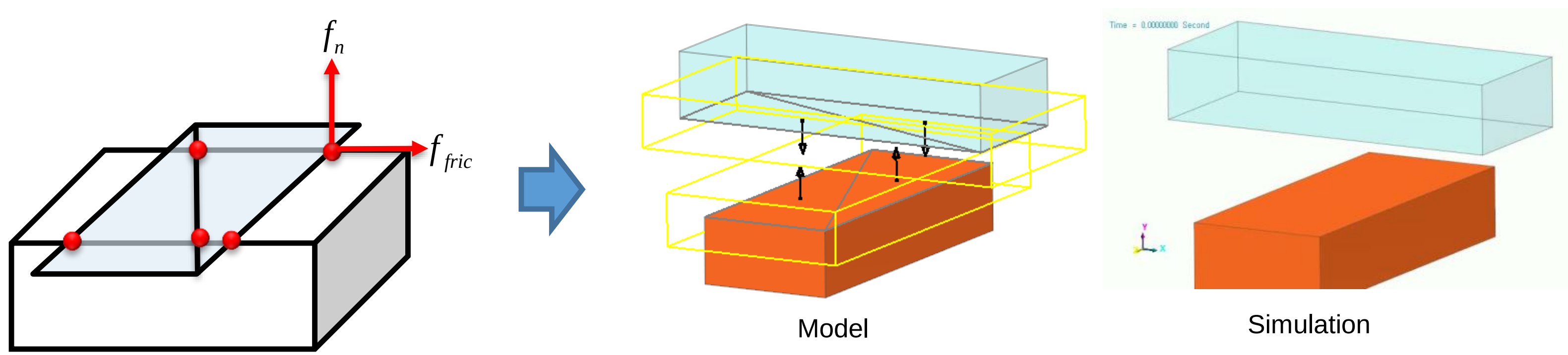
Contact Event

- Point(Node) contact – (Geo contact, Surface contact)
  - Node의 각 점이 상대 Geometry의 Patch면에 침투(Penetration) 할 경우 접촉발생
  - node에서 상대 Geometry의 Patch에 침투 발생시 개별적으로 Contact발생



Model Simulation

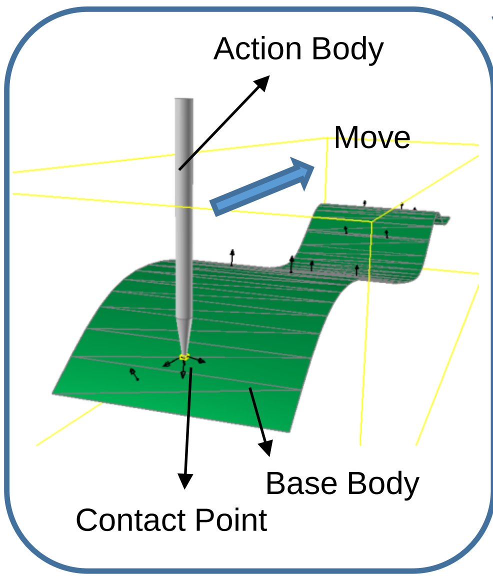
- Edge contact – (Geo)
  - Patch의 외각 선인 Edge Line이 상대Patch의 Edge Line과 교차점에서 침투 할 경우 접촉발생



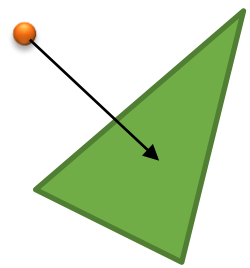
Model Simulation

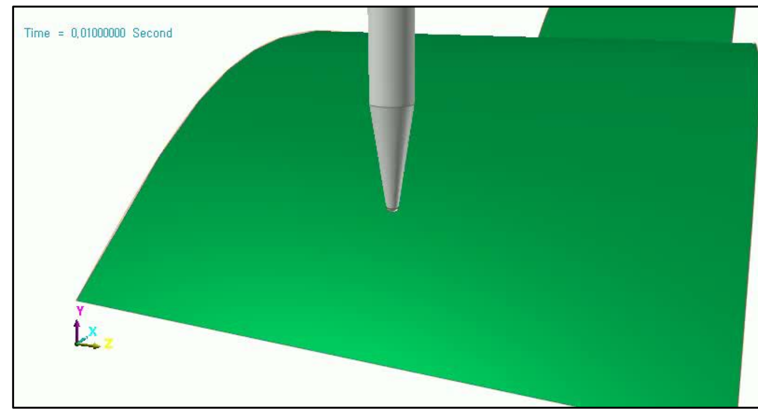
Smooth Contact – Geo contact

- Point contact event에서 Point의 상대 Patch의 면을 Hermite 곡면으로 변환하여 접촉을 계산하는 방법
  - Patch의 절점에서 불연속 면이 사라지는 효과
  - Geo Contact에서만 사용가능

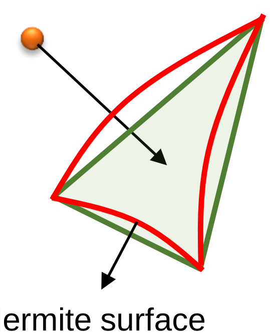


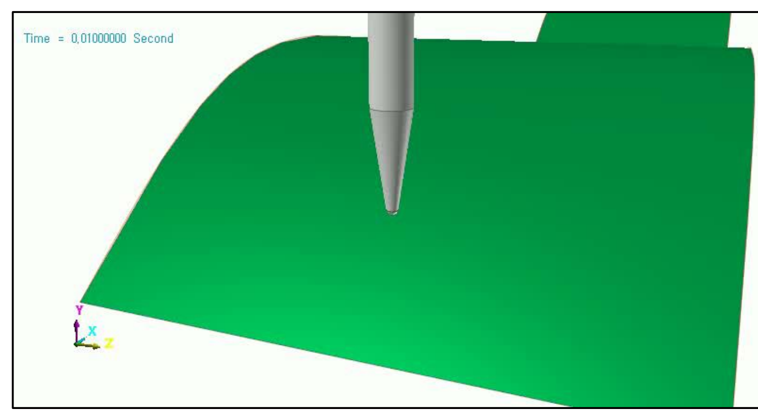
Non Smooth





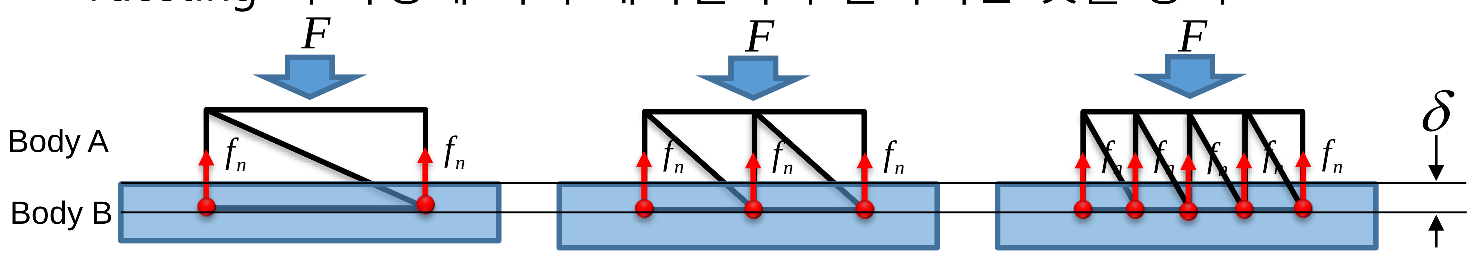
Smooth





CPM – Geo contact

- CPM(consistence penetration method)
  - 접촉 발생시 접촉 node수에 비례하는 강성 증가 효과를 제거 하기 위한 수치적 방법
  - Faceting 의 특성에 따라 해석결과가 달라지는 것을 방지



$$F = k\delta + k\delta \qquad F = k\delta + k\delta + k\delta \qquad F = k\delta + k\delta + k\delta + k\delta + k\delta$$

$$\delta = \frac{F}{2k} \neq \delta = \frac{F}{3k} \neq \delta = \frac{F}{5k}$$

  - 접촉점의 개수에 반비례하도록 k의 값을 수정하여 사용

$$k' = k / n \ (n: \text{contact point number})$$

$$F = k'\delta + k'\delta \qquad F = k'\delta + k'\delta + k'\delta \qquad F = k'\delta + k'\delta + k'\delta + k'\delta + k'\delta$$

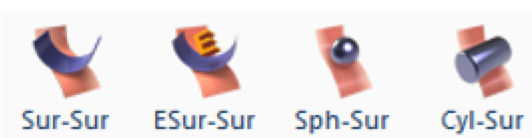
$$\delta = \frac{F}{k} = \delta = \frac{F}{k} = \delta = \frac{F}{k}$$

Consistence Penetration Method

Contact Entities- General 3D Contacts

- Solid Contact Event를 이용
- Rigid – Rigid
- 침투량(Penetration)작고, 곡률반경이 큰 형상에서 좋음

- Point Contact Event와 Edge Contact Event를 이용
- Rigid – Rigid, Rigid – FE, FE – FE
- 일반적인 형상에 대해 가장 좋은 해석 성능을 나타냄
- Geo Sph와 Geo Cyl의 경우 Analytical Contact의 기능 사용
- CPM(consistence penetration method 및 Smooth patch 기능 사용가능



- Geo contact개발 이전의 Point Contact Event만 적용된 Entity
- Rigid – Rigid
- 접촉점에서 contact force display가 표현되지 않음

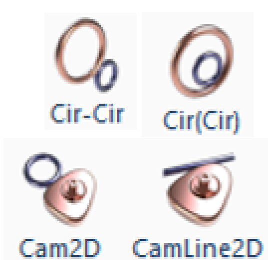
General Geometry Contact에 있어서 Geo Contact또는
Solid Contact을 사용하는 것이 바람직함

Contact Entities- Primitive 3D Contacts & 2D Contacts

- Analytical Contact Event를 사용
- Rigid – Rigid
- RecurDyn Geometry 만 사용가능
- 빠른 해석속도
- Parametric Value를 이용한 Geometry Size연결 및 수정가능

- Point Contact Event와 Edge Contact Event를 이용
- 2D Curve(Polyline, Spline, Circle, Arc, Edge Curve)를 사용
- Rigid – Rigid, Rigid – FE, FE - FE

- Point Contact Event만 사용
- 2D Curve(Polyline, Spline, Circle, Arc, Edge Curve)를 사용
- Rigid – Rigid



- Analytical Contact Event를 사용
- Rigid – Rigid
- Circle 또는 Edge Curve 및 Outline을 이용하여 모델링

합리적 접촉 모델링 과정

합리적 접촉 모델링 과정 개요

Step1
Geometry 및 접촉 형태에 따른 Contact Entity 선택

Step2
Base & Action Geometry의 선택

Step3
Contact Surface의 생성 및 Contact 생성

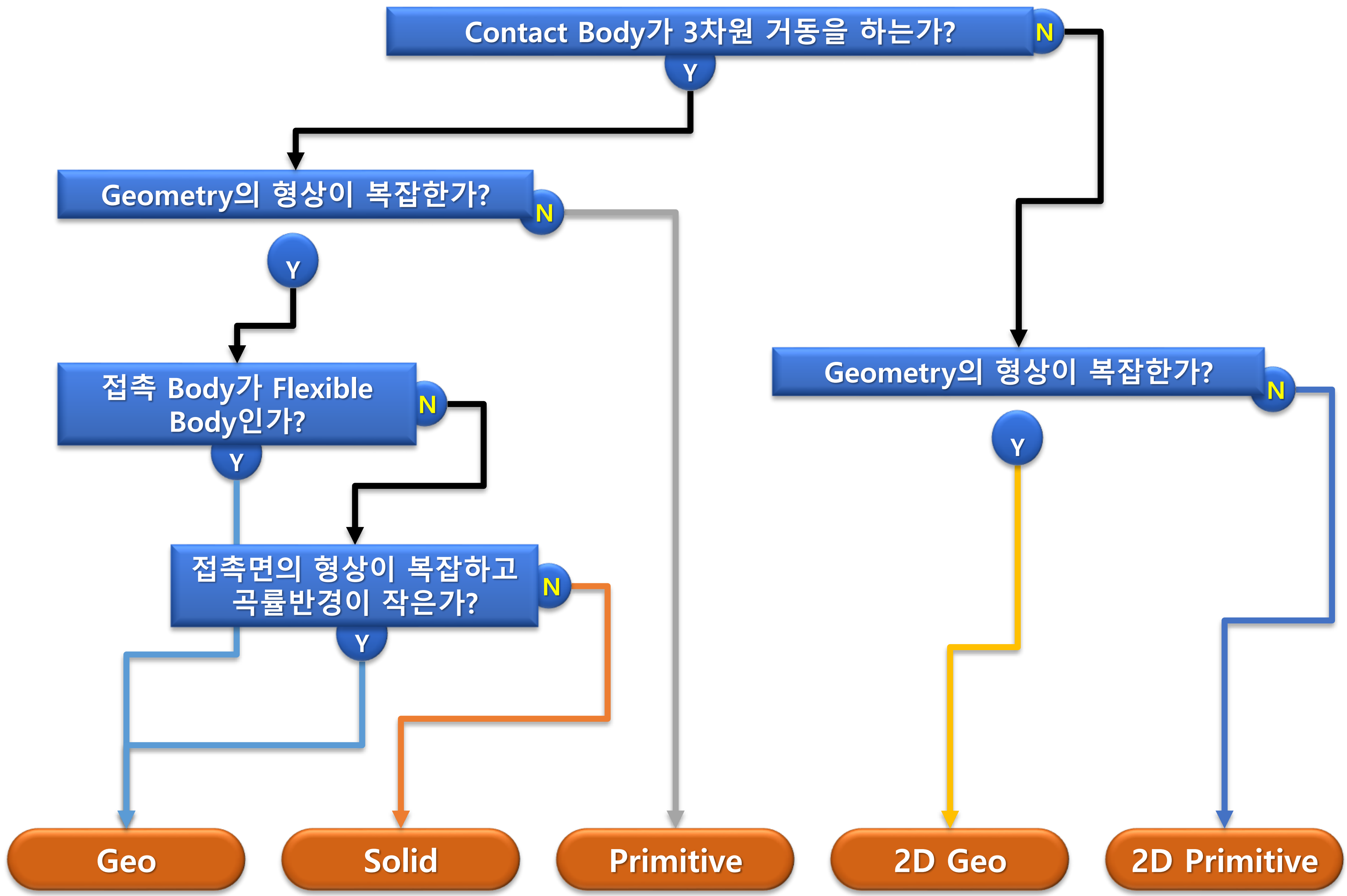
Step4
Contact Event에 따른 Faceting 정보 수정

Step5
Contact Parameter 입력

Step6
기타 옵션 설정

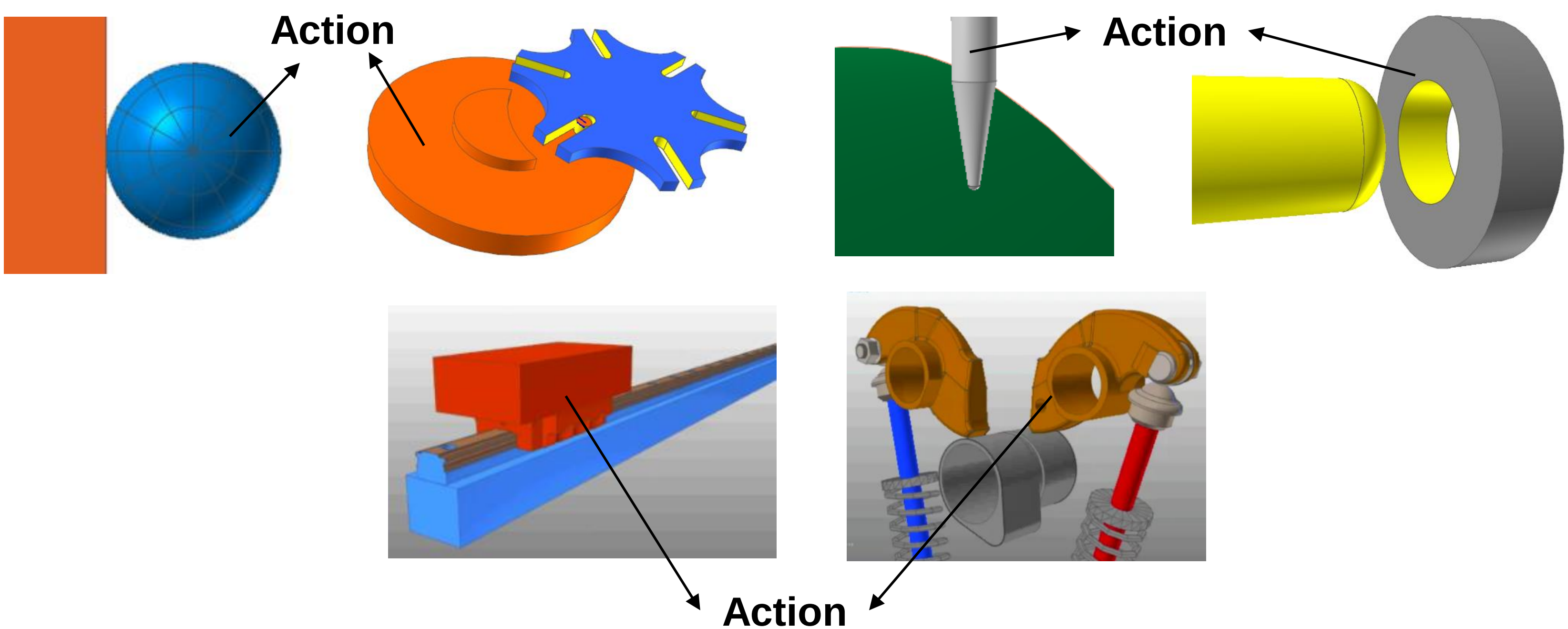
Step7
Simulation 수행 및 보정

Step1 Geometry 및 접촉 형태에 따른 Contact Entity 선택



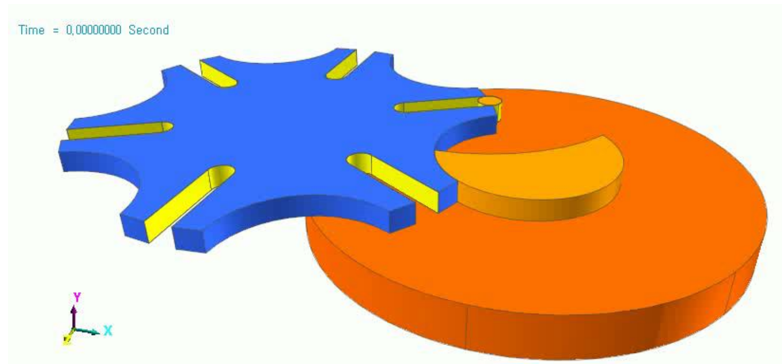
Step2 Base & Action Geometry의 선택

- 접촉면적이 작은 Geometry → Action으로
  - 접촉면적이 작은 쪽을 Geometry를 조밀하게 Faceting하여 부드러운 접촉 상황 발생에 유리
- 곡률반경이 작은 Geometry → Action으로
  - 큰 곡률의 Patch의 연결점을 지날 때, 접촉력의 불균일성이 작아짐
- 움직임이 큰 Body의 Geometry → Action으로
  - Action Body에 대한 계산의 효율성이 더 높게 프로그래밍되어 있음

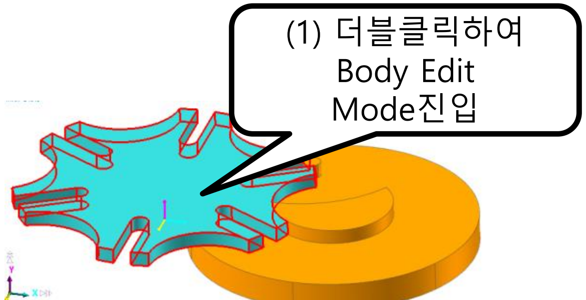


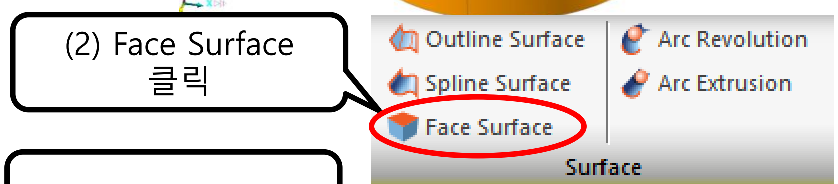
Step3 Contact Surface의 생성 및 Contact 생성

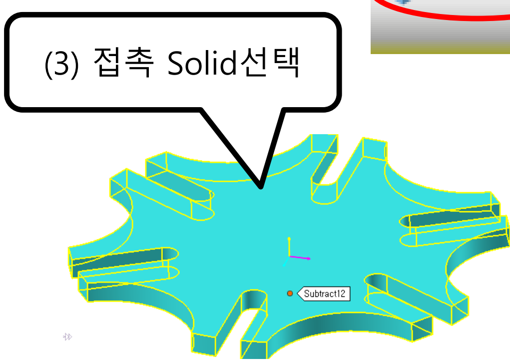
- General Contact은 모두 Solid 또는 Surface를 지정할 수 있지만, 접촉이 발생하는 특정 Surface만 접촉으로 지정하는 것은 Solver의 부담을 크게 줄여줌
  - Surface 생성과정

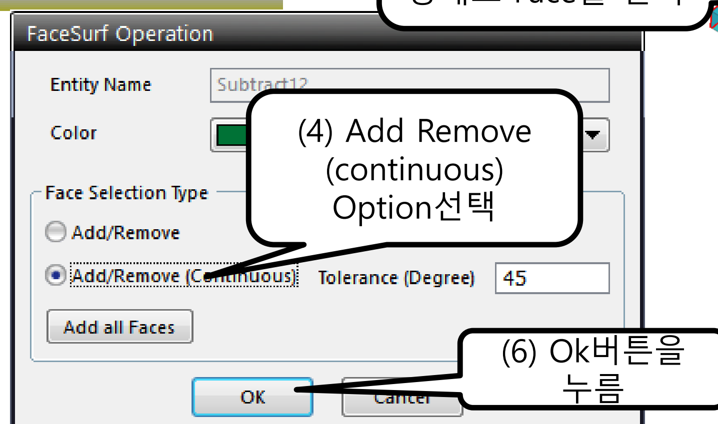


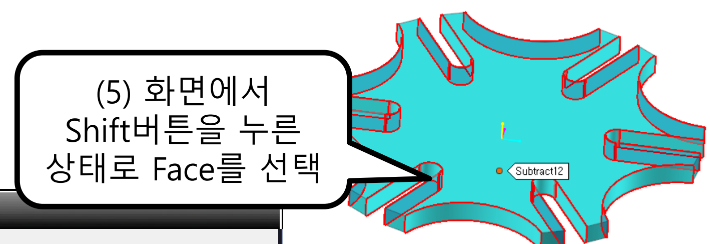
접촉 surface만 사용시 3배 이상 빠른 계산 가능

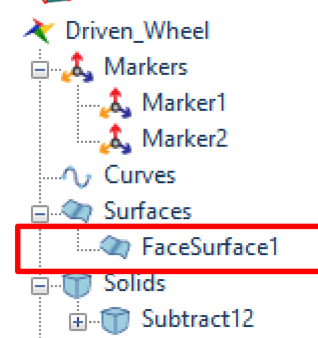






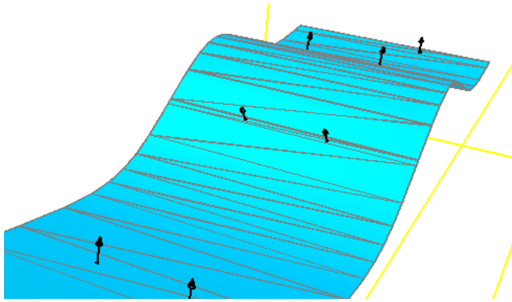




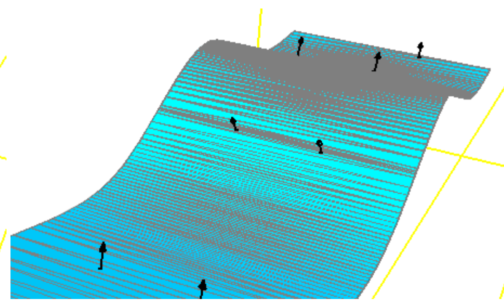


Step4 Contact Event에 따른 Faceting 정보 수정

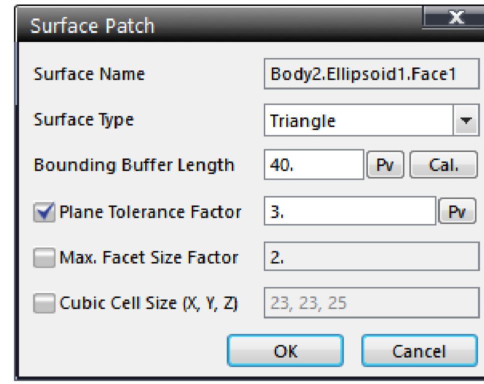
- Geo contact 및 Solid Contact의 경우 Faceting에 따른 해석의 정확도와 계산시간에 민감한 변화를 가져옴
  - Point가 접촉하는 Base Patch의 크기는 곡률을 충분히 나타낼 수 있도록 조밀하게 사용



Plane Tolerance Factor: 3.0

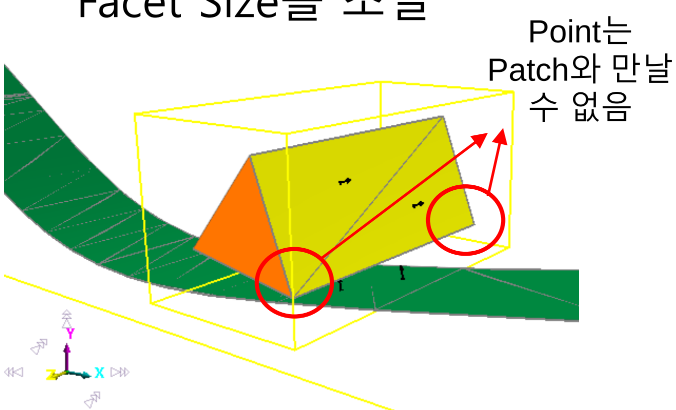


Plane Tolerance Factor: 0.2

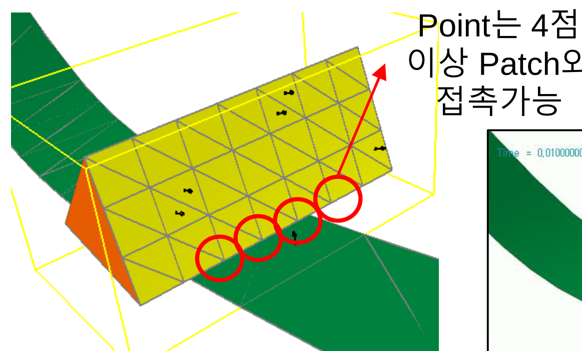


Default value of Faceting control

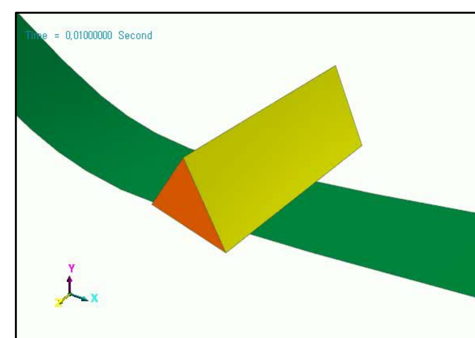
  - 접촉 Point(node)가 존재하는 Action Patch는 접촉상황이 발생할 수 있도록 Facet Size를 조절



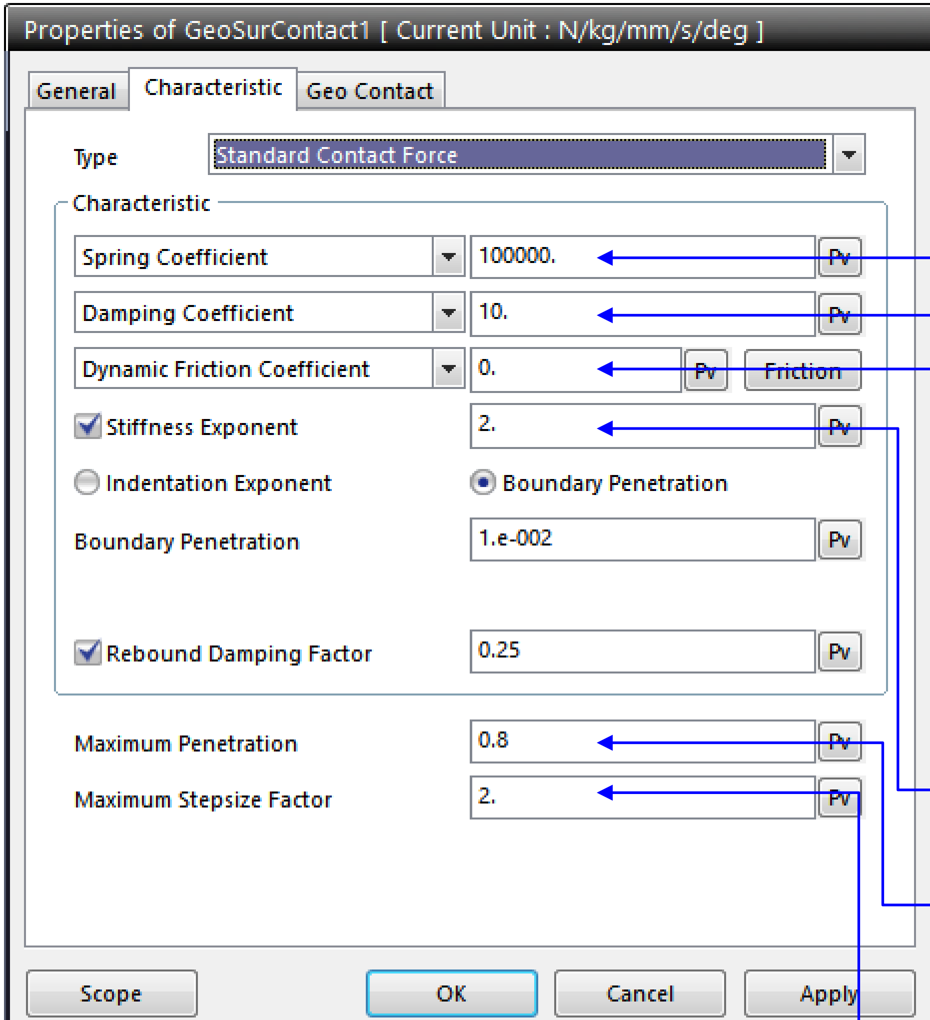
Max. Facet Size Factor: 10.0



Max. Facet Size Factor: 2.0



Step5 Contact Parameter 입력

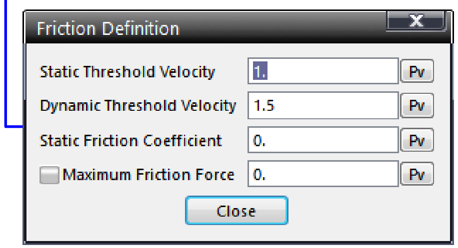


Hertz Contact Theory로 부터 계산식을 이용하여 K값 결정**(Tuning Point)**

$$K = \sqrt{\frac{16RE^2}{9}}$$

$$\begin{cases} R = \dfrac{R_1 R_2}{R_1 + R_2} \\ E = \dfrac{E_1 E_2}{E_2\left(1-\nu_1^2\right) + E_1\left(1-\nu_2^2\right)} \end{cases}$$

Damping Coefficient 입력: 보편적으로 **Stiffness의 1/10000정도 사용(Tuning Point)**



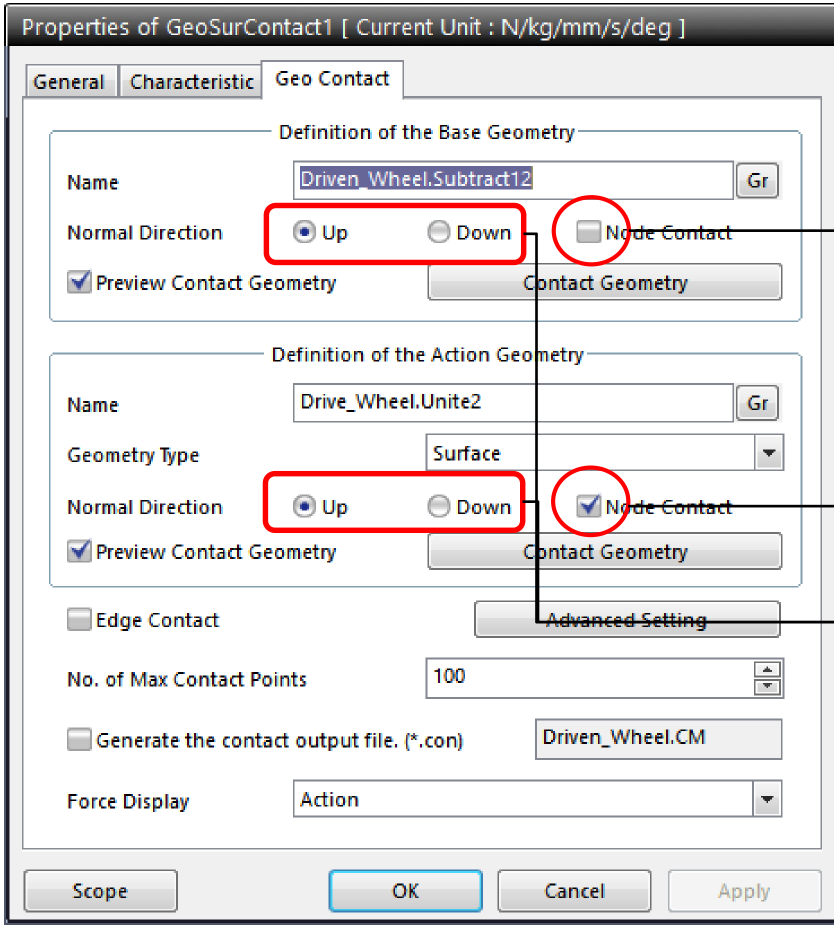
Friction Coefficient입력
정마찰 및 동마찰 계수는 실험이나 논문의 결과를 참조하여 입력
Threshold Velocity는 default로 사용

Stiffness Exponent는 Hertz Contact 이론에 따라 1.5로 사용**(Tuning Point)**

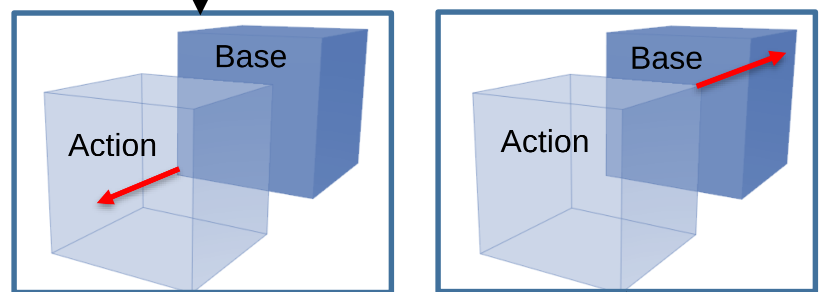
Maximum Penetration값은 접촉해제를 피하기 위해 **1mm**사용(해석상황에 따라 보고 보정)

원거리에서 접근하는 상황일 경우 10.0 사용
계속 붙어서 움직이는 접촉일 경우 **1.0** 사용

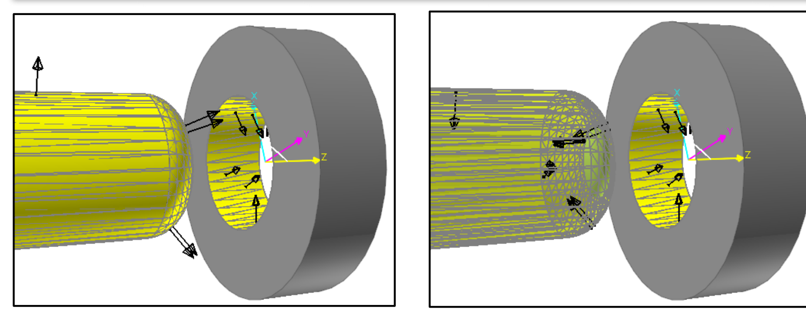
Step6 기타 옵션 설정



Node Contact옵션은 각 Geometry의 Point(Node)가 상대 Patch에 Contact Event를 발생시킬 것인지 결정하는 것로 가급적
Action Geometry의 Node Contact 만 Check



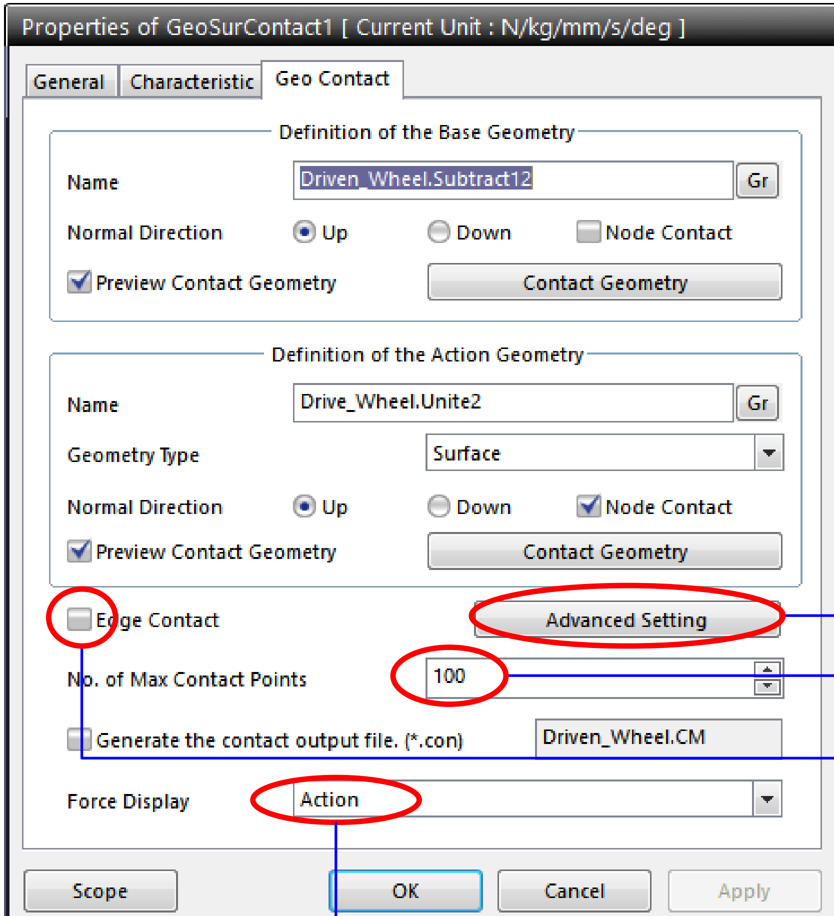
Normal Direction Check
Geometry의 Surface의 경우 접촉이 발생하는 방향벡터의 설정이 필요하며, Working Windows의 벡터 Icon을 통해 가시적으로 확인하면서 수정

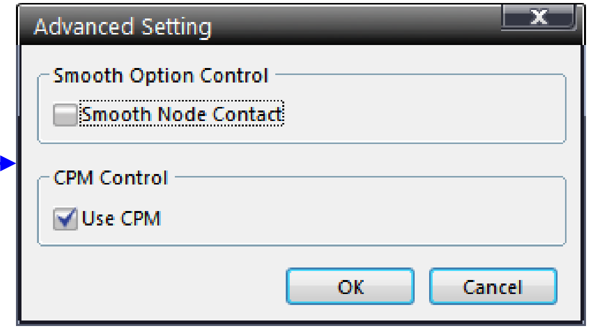


Base: up Action: up
Good!

Base: up Action: down
Wrong!

Step6 기타 옵션 설정





Smooth Option을 사용해야 할 경우 (가급적 Off)
- 중공형 Cylinder에 Shaft를 끼워 넣는 Contact
- 넓은 곡면을 소수의 접촉점이 지나가는 경우
- 곡률이 큰 곡면을 매끄럽게 미끄러져야 하는 경우

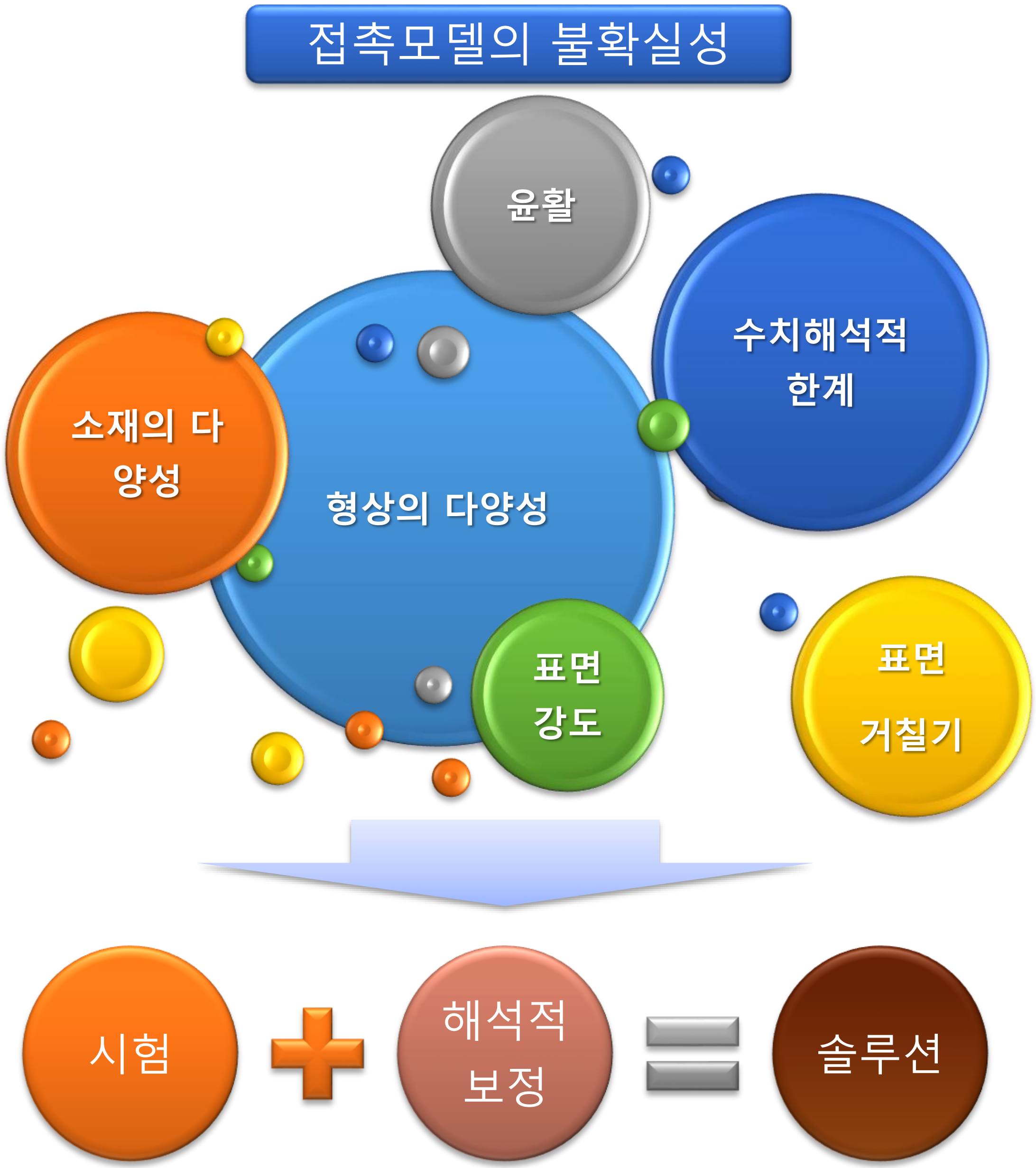
CPM Option을 꺼야 할 경우 (가급적 On)
- 중공형 Cylinder에 Shaft를 끼워 넣는 Contact
- 복잡한 형상의 Geometry 접촉 시 접촉위치가 다양하고 Normal Vector 각각 다른 경우

Edge Contact을 켜야 할 경우(가급적 Off)
- Geometry의 모서리만 접촉이 발생할 경우

No. of Max Contact Points :이 파라미터는 Display Point의 개수를 의미하므로 해석결과에 영향을 주지 않는다. 100정도 사용하면 무난함

Force Display: 주로 Action만 켜서 확인

Step7 Simulation 수행 및 보정



Step7 Simulation 수행 및 보정

- 해석수행 및 해석 결과와 해석 속도를 검토하여 각종 Parameter를 보정한다.
  - Check Point 1: 정성적 Contact 상황 발생유무
    - Contact이 통과하거나 비정상 위치에서 접촉이 발생 하지 않을 경우
      - ✓ Geometry간의 간격 확인 및 Facet Size 조밀하게 수정
      - ✓ Maximum Penetration값 증가
      - ✓ Normal Vector 방향 확인
  - Check Point 2: 침투량(Penetration)
    - 침투량이 지나치게 크거나 접촉상황이 발생하지 않고 통과할 경우
      - ✓ Stiffness coefficient 증가
      - ✓ Exponent 증가
      - ✓ CPM(consistence penetration method) off
    - 침투량 자체가 중요한 해석의 경우(MTT)
      - ✓ 하중을 미리 계산하여 침투량을 충족 시키는 Stiffness의 값을 계산하여 적용
  - Check Point 3: 반발특성
    - 반발특성이 거의 발생하지 않거나 너무 많이 튀는 경우
      - ✓ Stiffness coefficient 조절
      - ✓ Exponent 조절
      - ✓ Damping coefficient 조절(조금씩 변화하며 확인)
    - 실험에 의한 대수감쇠율을 알고 있을 경우
      - ✓ 반복적 해석을 통해 충족하는 Damping Coefficient값을 찾아야 함

Step7 Simulation 수행 및 보정

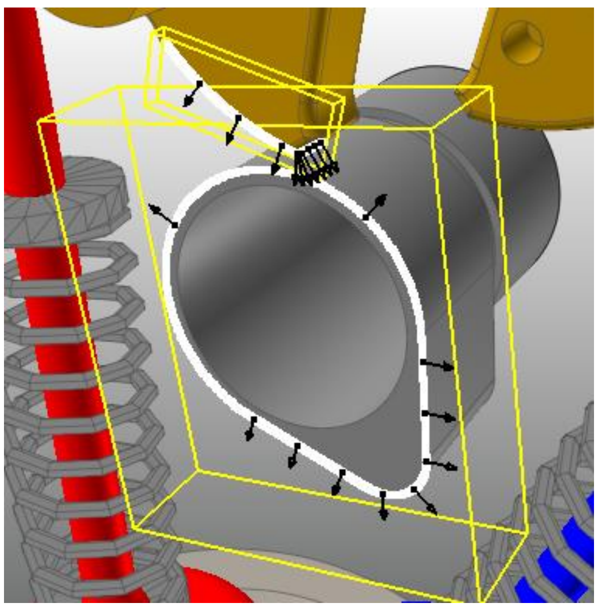
- Check Point 4: Solving Step Size
  - 접촉 해석상황이 지나치게 많은 해석시간을 소요할 경우 특히, Step Size가 매우 작아지는 경우
    - ✓ 반발특성과 침투량이 적절한 응답을 나타내는 범위에서 Stiffness 감소
    - ✓ 반발특성과 침투량이 적절한 응답을 나타내는 범위에서 Exponent 증가
    - ✓ 반발특성과 침투량이 적절한 응답을 나타내는 범위에서 Damping coefficient 조절
    - ✓ Contact모델이 있는 경우 Solver Option의 Maximum Step Size는 0.001이하의 값을 사용
- Check Point 5: Contact Force의 선형성
  - 두 Geometry가 서로 붙은 상태에서 이동하여 접촉위치가 지속적으로 변할 때 접촉하중이 불균일하게 나타나는 경우
    - ✓ Facet size 조밀하게 조정
    - ✓ Smooth contact 적용
    - ✓ Stiffness 감소 와 Exponent 증가를 동시에 진행하여 접촉 진동감소

Case study

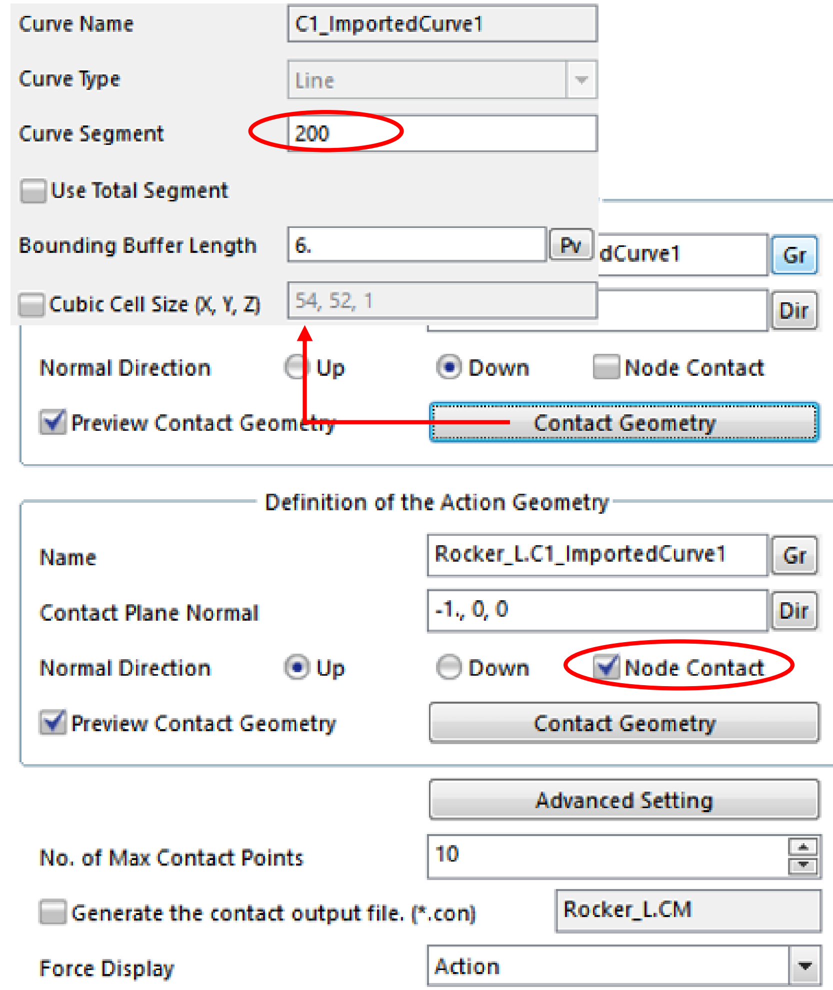
Cam System

Sim time: 2sec, CPU time 6.6sec

- 모델 설명
  - Cam Body, Rocker Body 및 Valve가 서로 접촉하면서 메커니즘을 만들어냄
    - 총 4개의 GeoCurveContact사용
    - 2D GeoCurveContact 사용
    - CPM, Smooth 사용
    - Curve Segment 200개 사용
    - K:100000 C:10 Exp:1.5 Fric:0.1

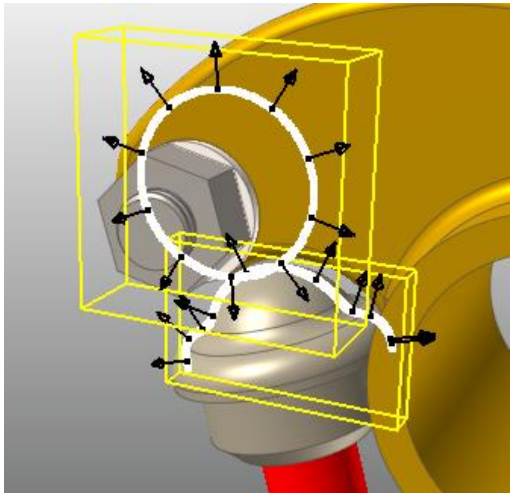


Cam to Rocker

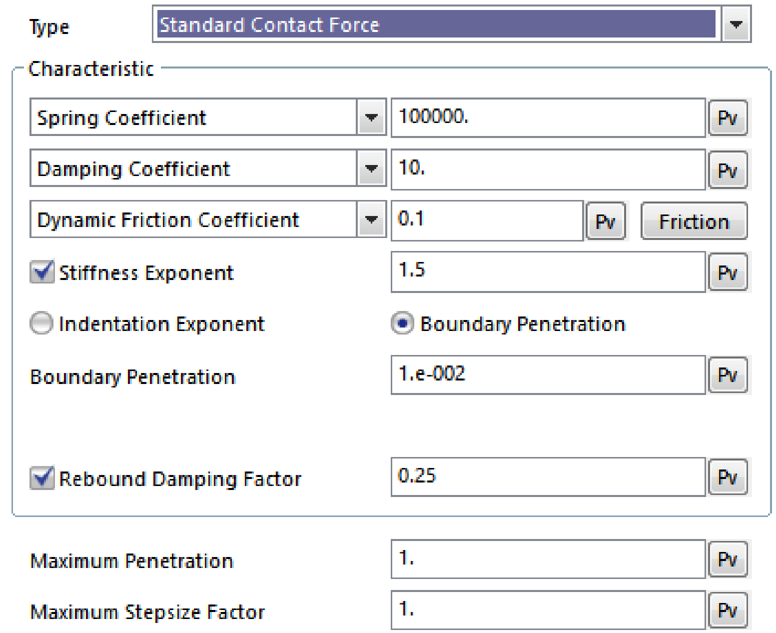


GeoCurve Dbox

Cam System

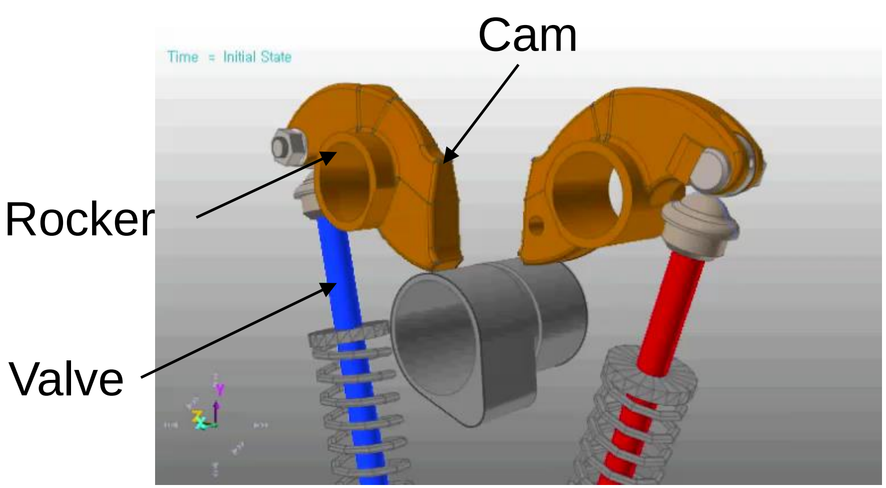


Cam to Rocker

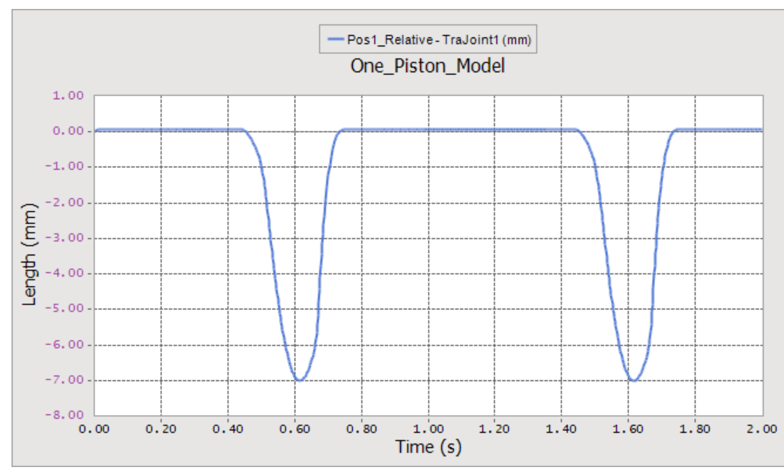


Characteristic Dbox

- Animation and Plot



Cam working animation

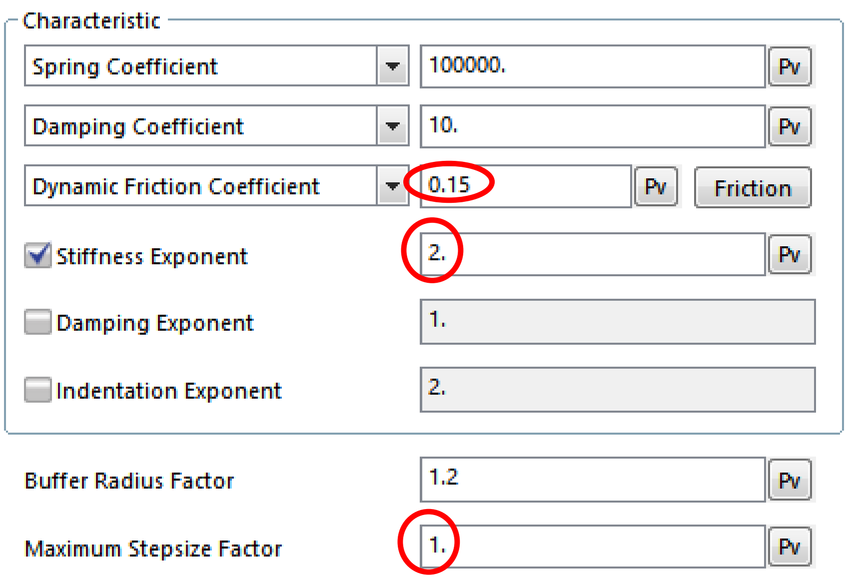


Valve displacement

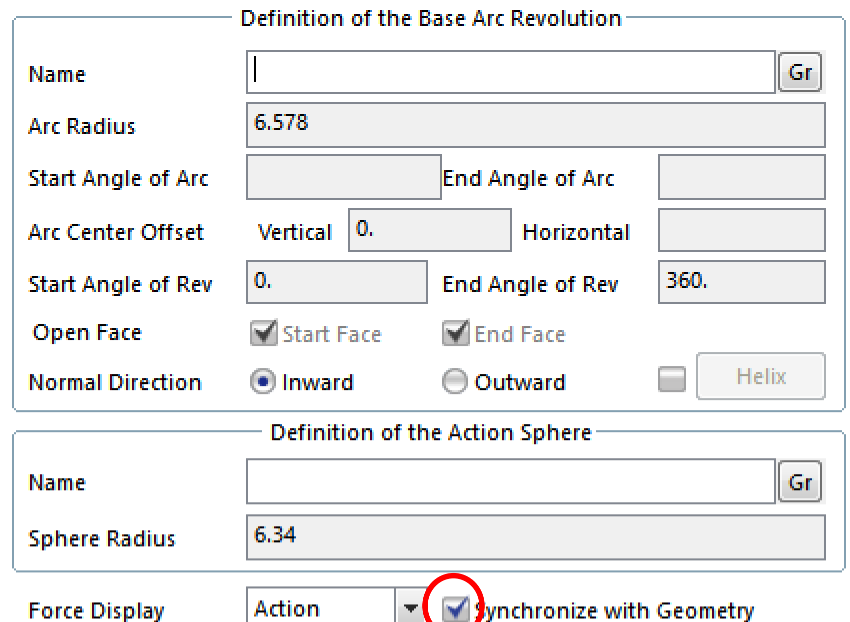
Ball Bearing

Sim time: 4sec, CPU time 6.4sec

- 모델설명
  - Ball과 Arc Revolution Geometry의 접촉에 의해 작동
    - 총 40개의 SphereToArcRevolution Contact사용
    - Face surface추출 및 Faceting 최적화
    - K:100000 C:10 Exp:2.0 Fric:0.15



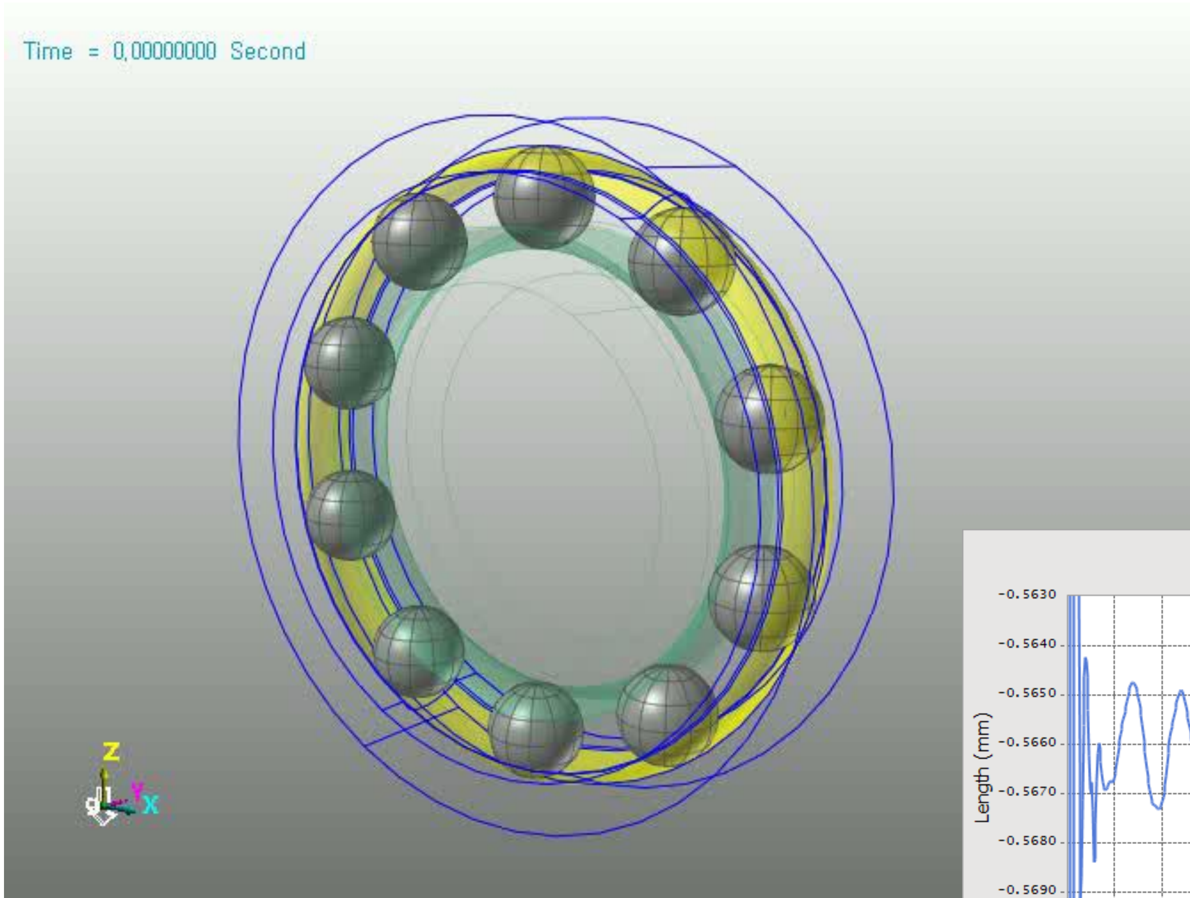
Characteristic Dbox



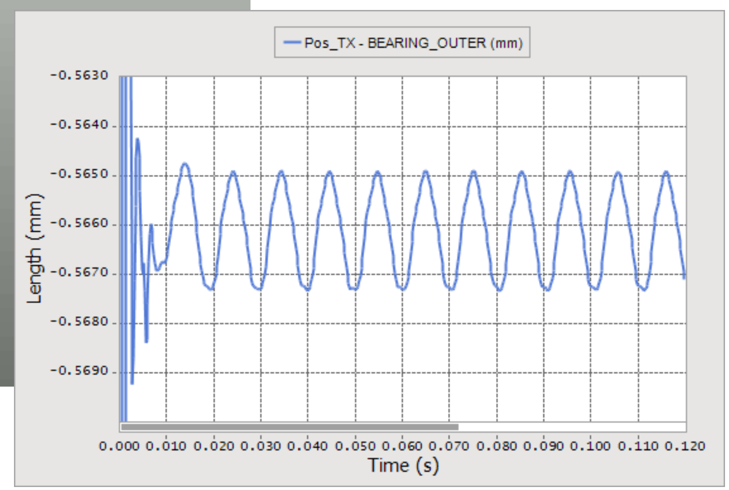
SphereToArcRevolution Dbox

Ball Bearing

- Animation and Plot



Ball bearing animation



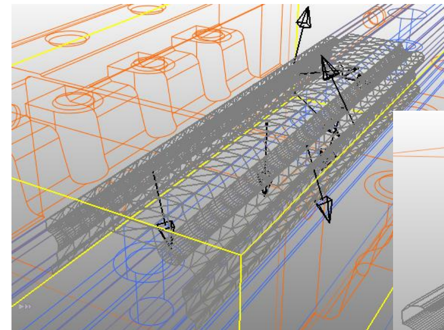
Outer ring vertical displacement

Linear guide modeling

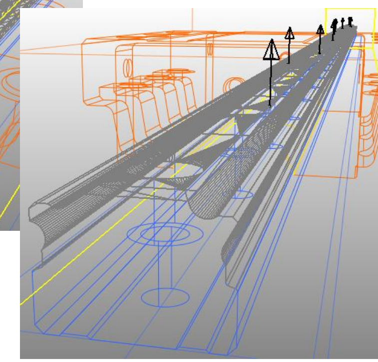
Sim time: 1sec, CPU time 6.4sec

- 모델 설명
  - Steel Rail위를 LM Guide가 면접촉을 하며 직선운동을 하는 메커니즘
    - 1개의 GeoSurface Contact사용
    - Face surface추출 및 Faceting 최적화
    - CPM 사용안함
    - K:1000 C:0.1 Exp:2.0 Fric:0.1
    - Faceting을 최적화
      - ✓ Base:PTF0.1(단면형상 곡면표현), MFSF10
      - ✓ Action:PTF0.5, MFSF0.5(접촉node증가)

MFSF : Max. Facet Size factor

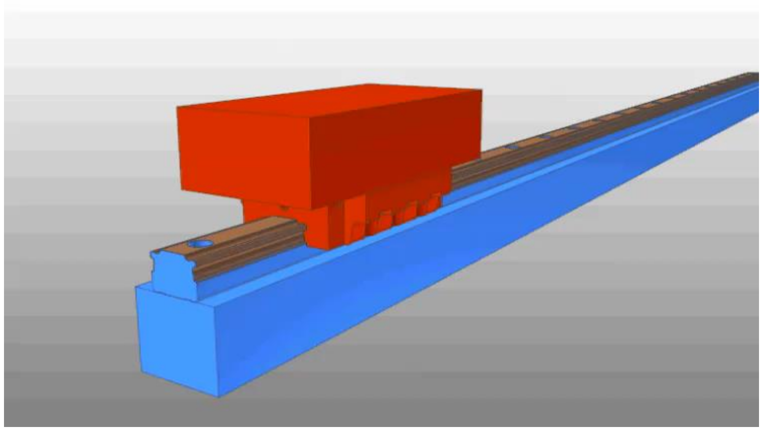


Action Geometry

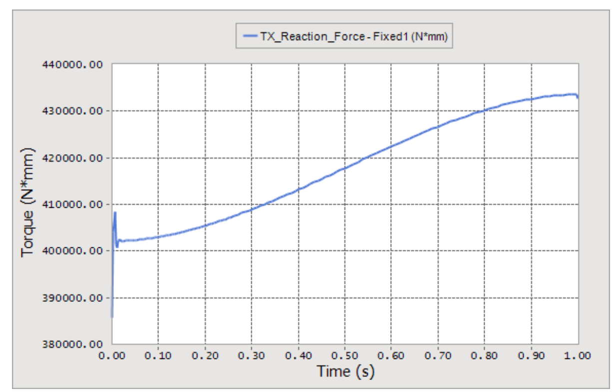


Base Geometry

- Animation and Plot



LM guide animation

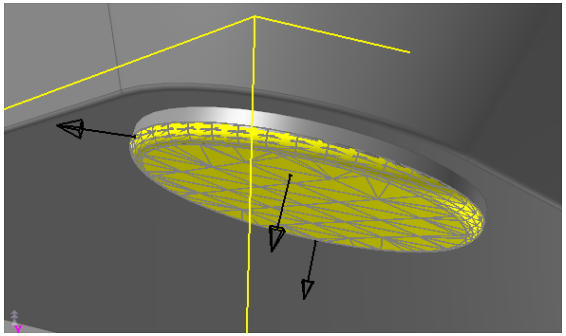


Hinge point reaction torque

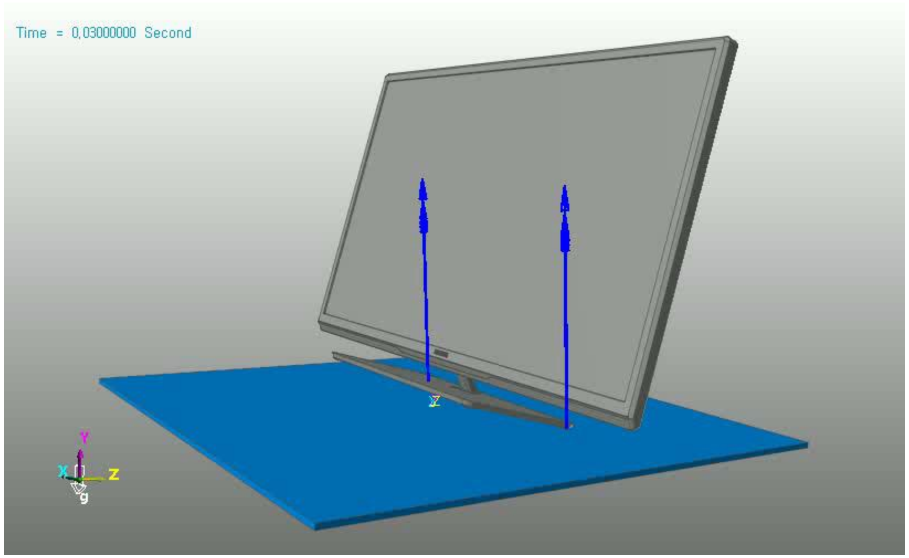
Stand wabble analysis

Sim time: 5sec, CPU time 16.2sec

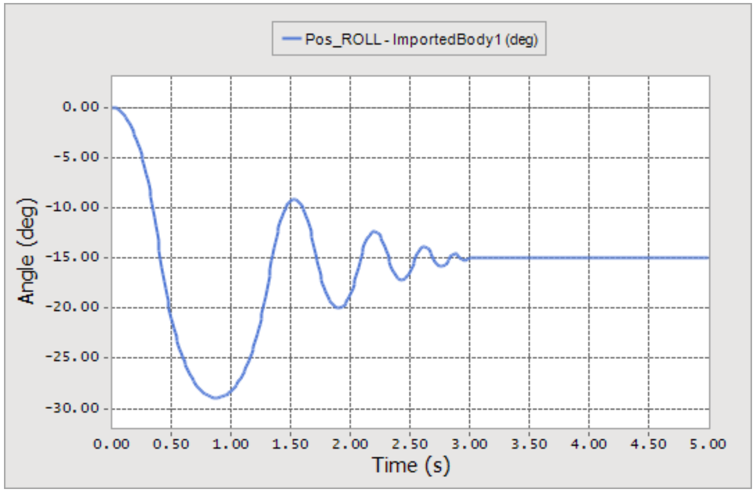
- 모델설명
  - 접촉에 의해 자세를 유지하는 제품에 자세 안정성을 검토하는 해석
    - 1개의 GeoSurface Contact사용
    - Face surface추출 및 Faceting 최적화
    - CPM 사용
    - K:10000 C:100 Exp:2.0 Fric:1.0
    - Faceting을 최적화
      - ✓ Action:PTF3.0, MFSF0.1(접촉node증가)
    - Max Penetration : 5.0



Action Geometry



Wabble analysis animation

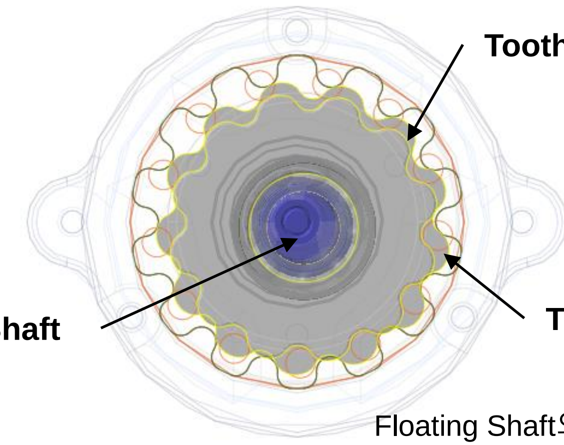


Pitch Angle

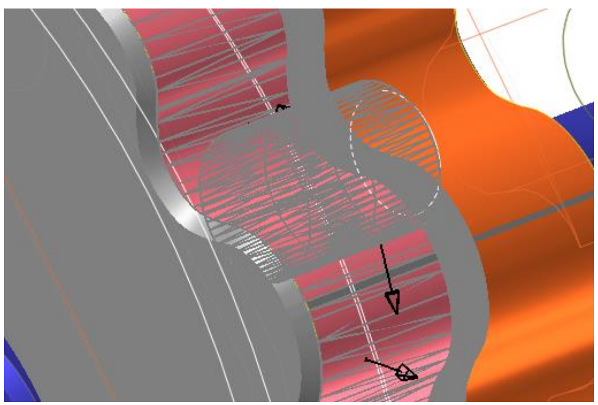
Cycloid drive

Sim time: 1sec, CPU time 26.5sec

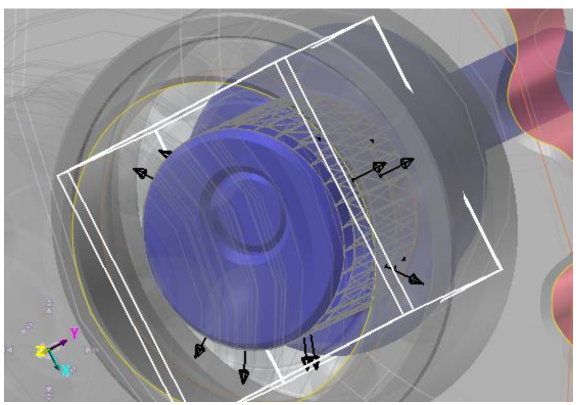
- 모델설명
  - 내측기어의 형태를 2가지로 구성하여 다른 회전 중심으로 회전하며 접촉하여 높은 기어비를 생성하는 감속기, 완전히 접촉에 의한 메커니즘
    - 3개의 Geo Contact사용
    - Face surface추출 및 Faceting 최적화
    - CPM 사용안함
    - Sliding shaft contact에서 smooth사용
    - K:10000 C:1.0 Exp:2.0 Fric:0.01



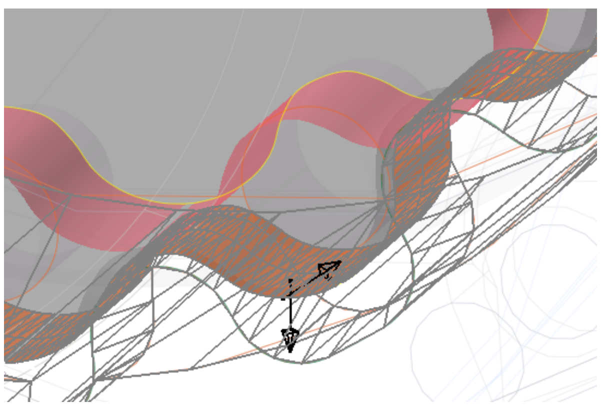
Floating Shaft의 세차운동에 의해 기어비가 만들어짐



Tooth1 Contact



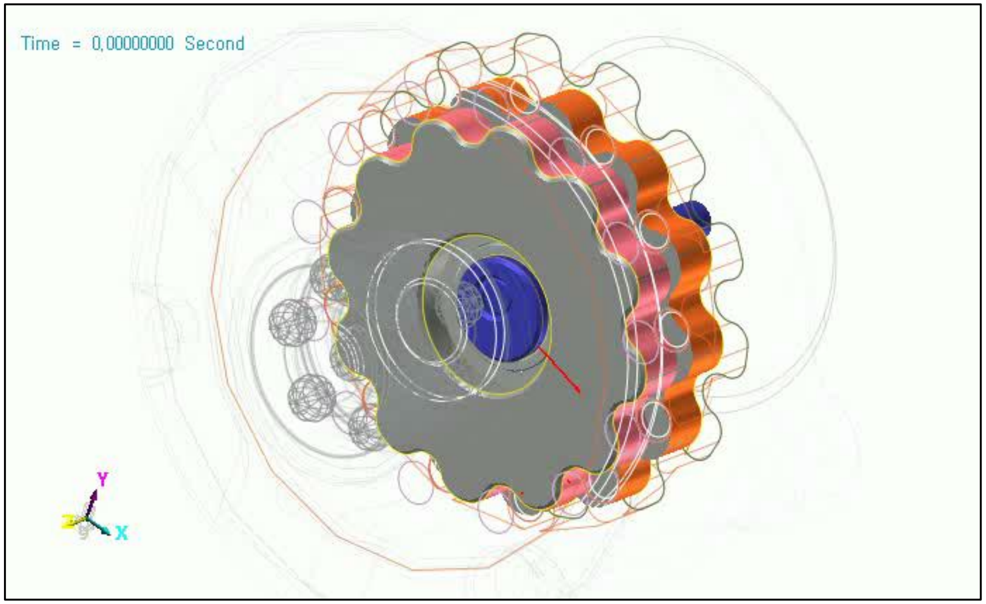
Sliding shaft contact



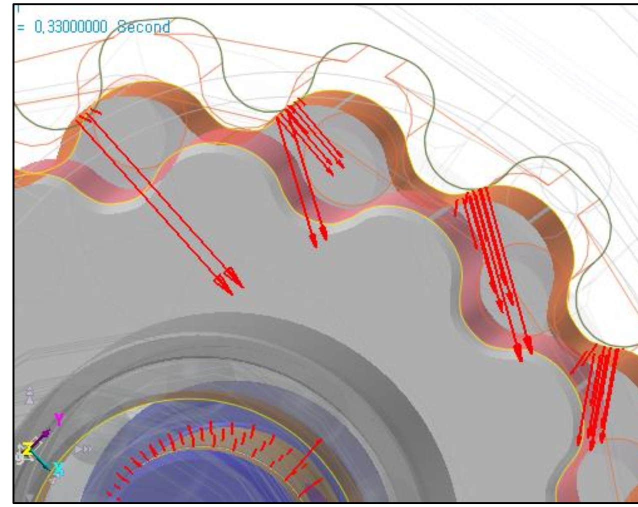
Tooth2 Contact

Cycloid drive

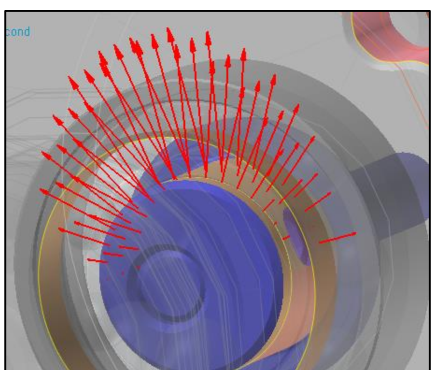
- Animation and Plot



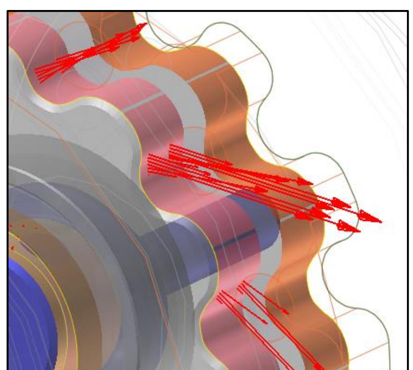
Cycloid Drive Animation



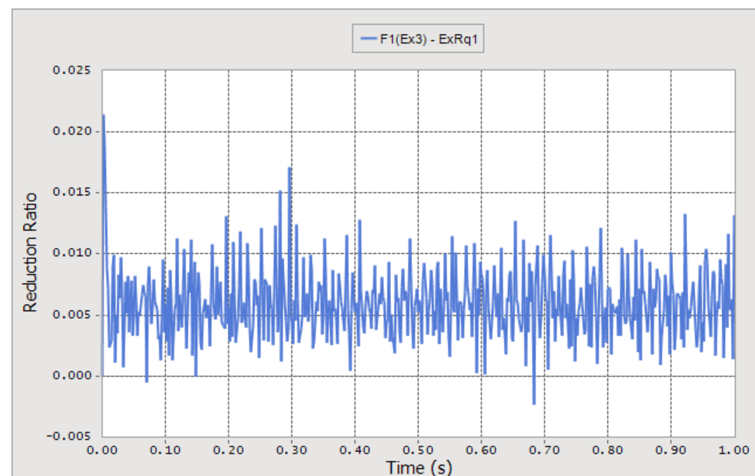
Tooth2 Contact



Sliding shaft contact



Tooth1 Contact

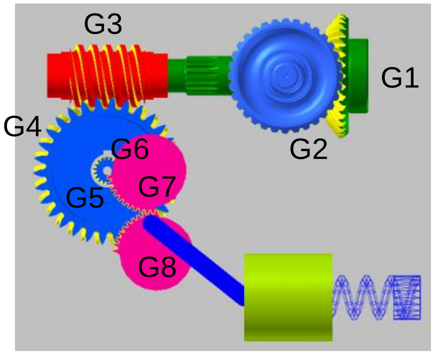


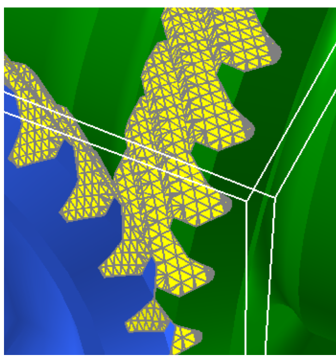
Reduction Ratio

Gear contact

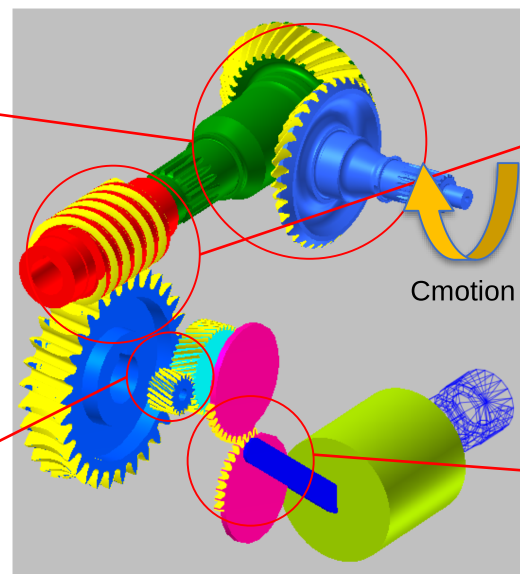
Sim time: 1sec, CPU time 2m 19sec

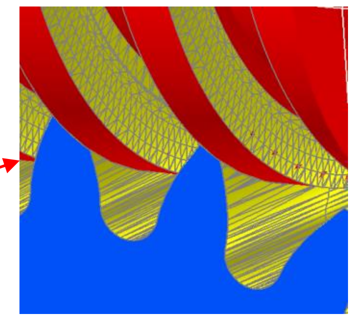
- 모델설명
  - 광범위하게 사용되고 있는 기어 시스템의 접촉 모델링
    - 5개의 Geo Contact사용
    - Face surface추출 및 Faceting 최적화
    - CPM 사용
    - K:100000 C:10 Exp:2.0 Fric:0.01



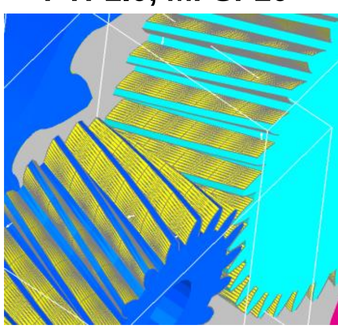


G1-G2 Contact(Bevel)
PTF1.0, MFSF10

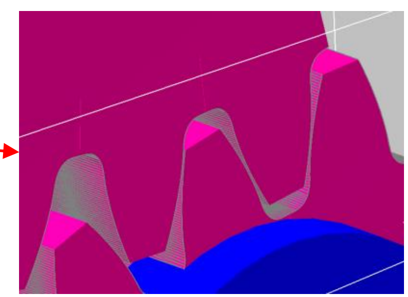




G3-G4 Contact(Worm)
PTF1.0, MFSF10



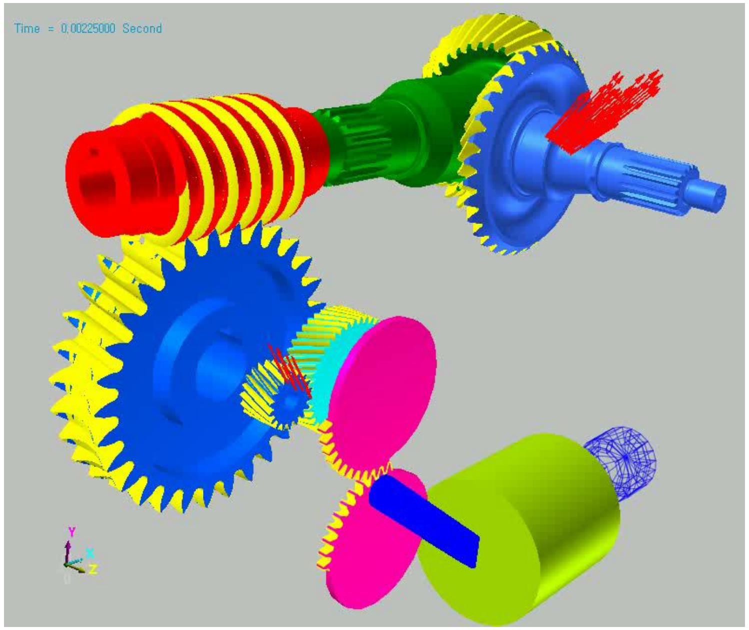
G5-G6 Contact(Helical)
PTF3.0, MFSF10.0



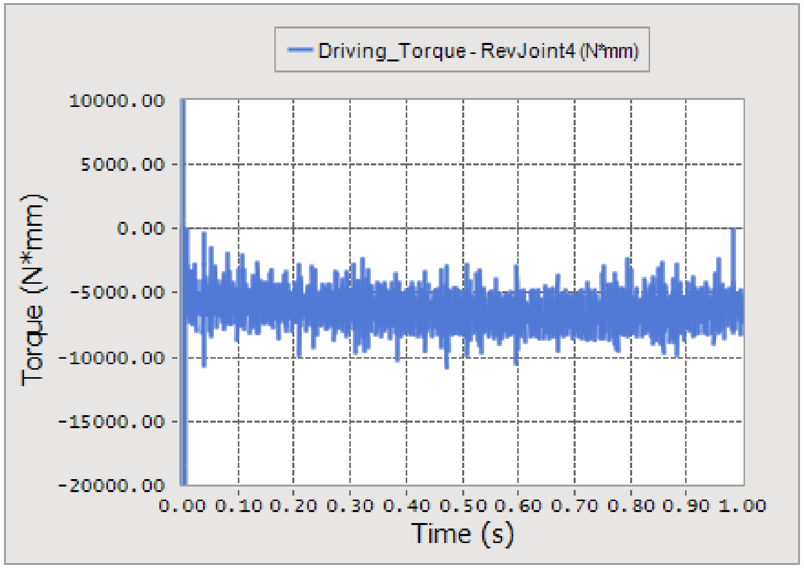
G7-G8 Contact(Spur)
PTF3.0, MFSF0.5

Gear contact

- Animation and Plot

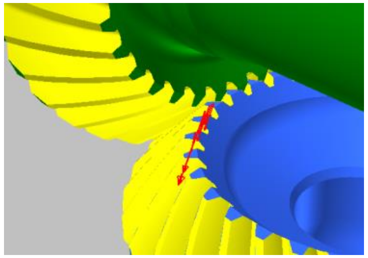


Gear contact animation

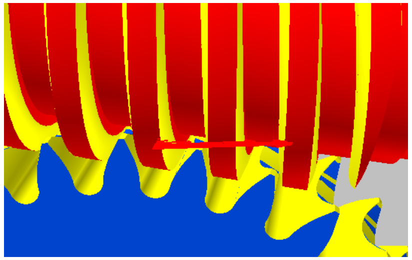


Driving torque variation

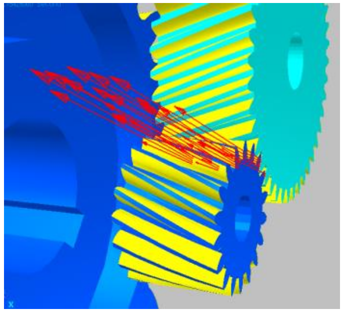
- Contact Shape



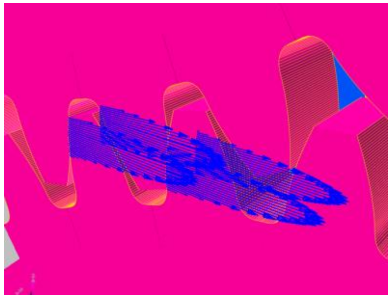
G1-G2 Contact(Bevel)



G3-G4 Contact(Worm)



G5-G6 Contact(Helical)



G7-G8 Contact(Spur)

Conclusion

합리적 방법을 통해 접촉 모델링을 통해 보다 빠르고 정확한 솔루션 획득할 수 있습니다.

Lv1

접촉모델에 대한 이론적 배경 이해

Lv2

접촉 점의 계산방법에 대한 알고리즘적 이해

Lv3

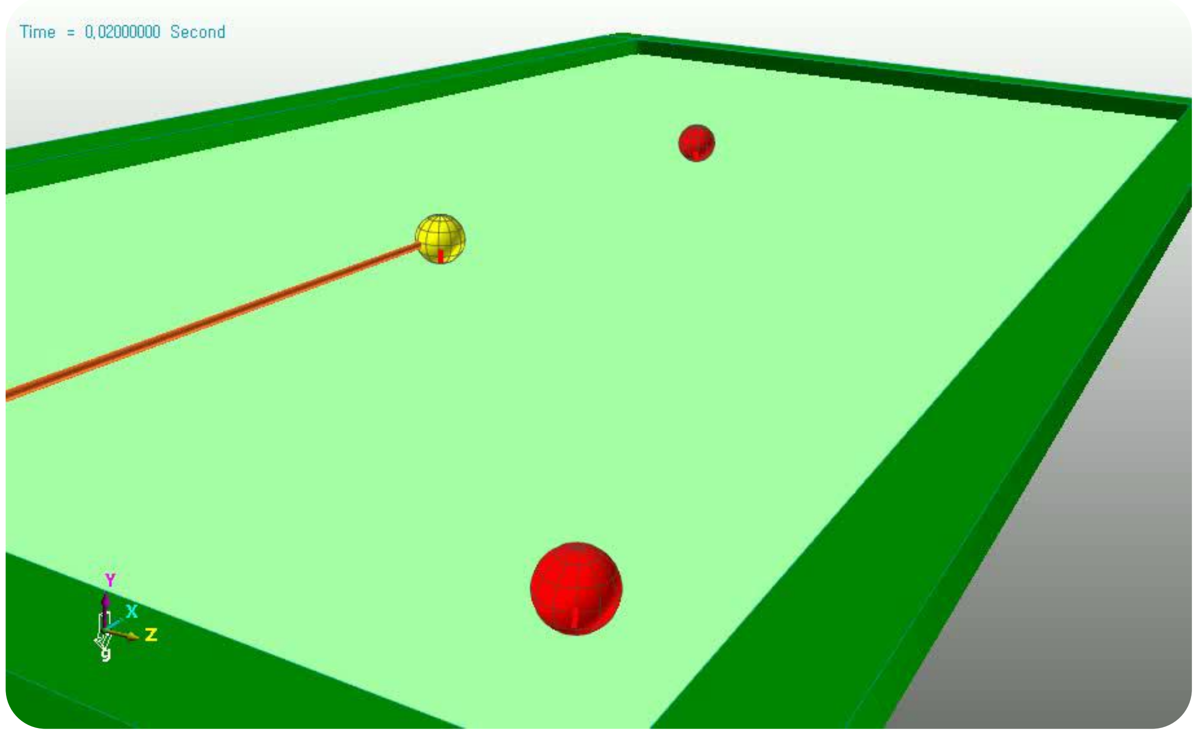
RecurDyn의 Entity의 다양성과 효과적 적용방법에 대한 이해

Lv4

해석하고자 하는 제품에 대한 접촉상황에 대한 이해

Conclusion

Contact !
이제 어려워하지 마세요!



감사합니다.

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