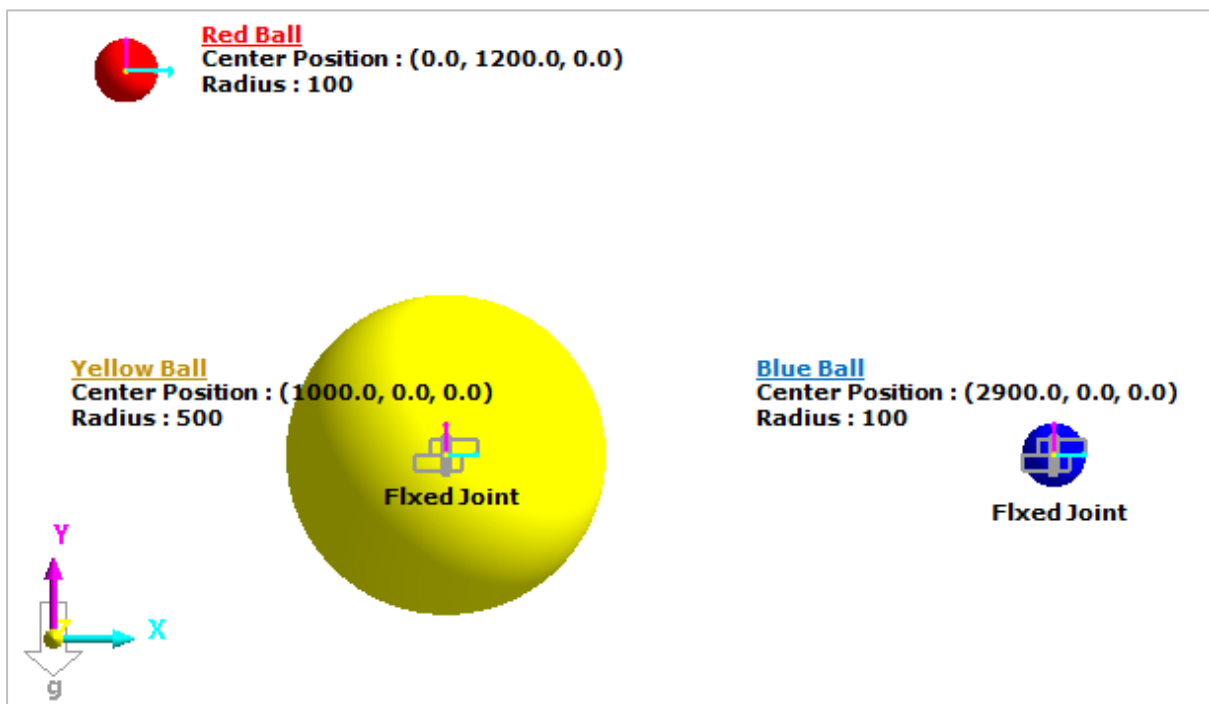




Three-Ball Contact Tutorial (AutoDesign)



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Edition Note

This document describes the release information of **RecurDyn V9R4**.

Table of Contents

Outline of Tutorial Sample A	4
Three-Ball Contact Problem	5
Model Definition	6
Design Parameter Definition.....	8
Analysis Response Definition	11
Design Study	14
Basic Procedure for Design Study	15
Effect Analysis	18
Screening Variables	19
Correlation Analysis	22
Design Optimization.....	24

Outline of Tutorial Sample A

Model	Description
Sample A	<p>Three-Ball Contact Problem:</p> <p>This problem explains the design process from making analysis model to formulating design optimization problem. This sample can help the beginners to understand a design optimization process in the AutoDesign.</p> <p>Key Point:</p> <p>Study the design formulation for representing contact phenomenon from the viewpoint of optimization.</p>



Three-Ball Contact Problem

To explain the basic function of **AutoDesign**, let's solve a simple design problem. The design model consists of three balls. The yellow and the blue ball are fixed on ground. When the red ball is thrown with an initial velocity, the red ball should be contacted with the yellow ball and go through the blue ball as near as possible.

1. **Model Definition**
2. **Design Parameter Definition**
3. **Analysis Response Definition**
4. **Design Study**
5. **Design Optimization**

Next, the refined optimization is explained to find more accurate results. This design uses the simulation results to solve the former design problem.

6. **Refining the Design Formulation**

Open files related in Sample-A	
Sample	<InstallDir>\Help\Tutorial\AutoDesign\ThreeBallContact\Examples\Sample_A.rdyn
Solution	<InstallDir>\Help\Tutorial\AutoDesign\ThreeBallContact\Solutions\Sample_A.rdyn

Note: If you change the file path at discretion, it can be located in any folder that you specify.

Model Definition

The contact between the red ball and the yellow ball is defined but is not done between the red ball and blue ball, because the blue ball is just the target point. The design variables are the initial velocity of red ball along x-direction and the contact stiffness coefficient in the contact force between the red and the yellow balls. Now, for the red ball to pass the nearest way to the center of the blue ball, what can you define as the design objective and constraints?

To do this, the design system is modeled as follows:

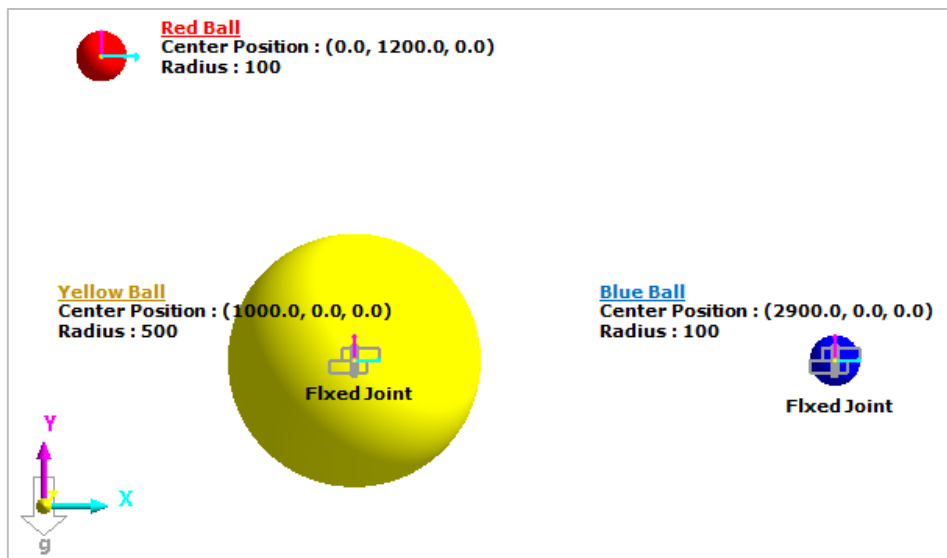
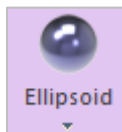


Figure A-1-1 MBD Model of the ball contact design problem

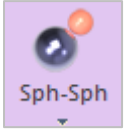
The below is the procedure for defining the balls, joint and contact force shown in Figure A-1-1.



1. Make balls using '**Ellipsoid**' icon in the body module folder.



2. Fixed the Yellow ball and the Blue ball with ground using the '**Fixed**' joint in the joint module folder.

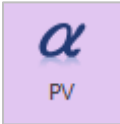


3. Define the contact force between the red ball and the yellow ball using the '**Sphere To Sphere**' contact in the contact module folder.

Chapter
2

Design Parameter Definition

Let's study the procedure for defining design parameters:



1. Define parametric values shown in Figure A-2-1.

Parametric Value List

No	DP	Name	Value	Comment
1	<input checked="" type="checkbox"/>	InitialVX	2700. E	
2	<input checked="" type="checkbox"/>	K	10. E	

Figure A-2-1 Parametric value definition

2. Link the 'InitialVX' with the x direction initial velocity of the red ball body shown in Figure A-2-2.

Properties of Red_Ball [Current Unit : N/kg/mm/s/deg]

General | Graphic Property | Origin & Orientation | **Body**

Material Input Type: Library
Material Type: Steel

Mass: 32.8820031075732

lxx: 131528.012430293 | lxy: 0.
lyy: 131528.012430293 | lyz: 0.
lzz: 131528.012430293 | lzx: 0.

Volume: 4188790.20478639 | Show Property

Center Marker: CM

Inertia Marker: Create | IM

Initial Condition: **Initial Velocity**

Body Initial Velocity

Translational Velocity

InitialVX | Pv
 Y | 0. | Pv
 Z | 0. | Pv

Reference Marker: Ground.InertiaMarker | M

Rotational Velocity

X | 0. | Pv
 Y | 0. | Pv
 Z | 0. | Pv

Reference Marker: Red_Ball.CM | M

Figure A-2-2 Link the 'InitialVX'

- Link the 'K' with the stiffness coefficient of the contact force between the red ball and the yellow ball shown in Figure A-2-3.

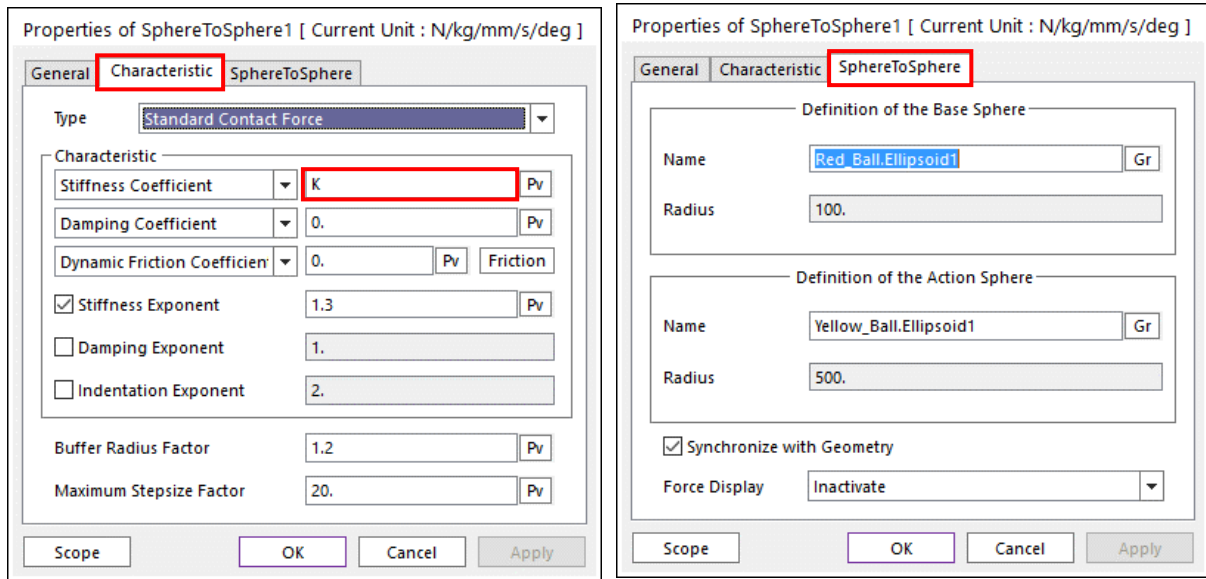
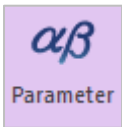


Figure A-2-3 Link the stiffness 'K'



- Define the design parameters from parametric values using the 'Design Parameter' command in the 'AutoDesign' toolkit shown in Figures A-2-4 and A-2-5. First, you push 'Create' button to define the design parameters as Figure A-2-4. In Figure A-2-5, you should link the design parameters to the parametric values that were defined in Figure A-2-1. The initial values are the current parametric values defined in Figure A-2-1. You should define the lower and the upper bounds on the design variable. This represents that the optimization process should change the design values within these bounds during iterations. After you create the design parameters, you check the active design parameters for this design problem.

Design Parameter List

№.	Name	Type	Prop.	Descripti...	Curr...	LB	UB	Design Cost...	DP Form	DV
1	DP1	Direct		Initial VX	2700.	15...	50...	0.	Value	<input checked="" type="checkbox"/>
2	DP2	Direct		Stiffness K	10.	1.	20.	0.	Value	<input checked="" type="checkbox"/>

Figure A-2-4 Check 'DV' check box

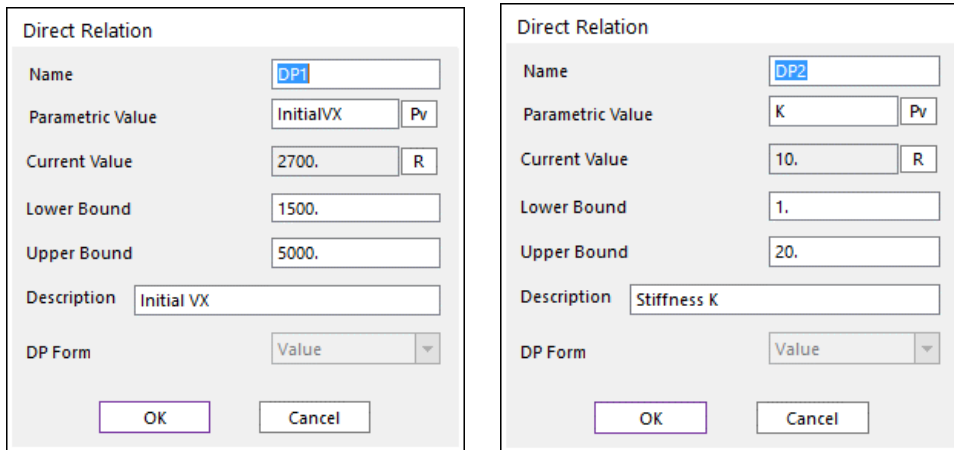
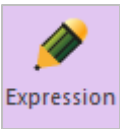


Figure A-2-5 Define 'DP1' and 'DP2'

Chapter
3

Analysis Response Definition

The design goal is that the center of the red ball passes the nearest way from the center of the blue ball, the target point. You need to define the performance indexes for solving the optimization problem. In **AutoDesign**, performance indexes are objectives and constraints in design optimization, which are composed of analysis responses. Then, in order to define the performance index, analysis responses are defined first. The procedure of defining analysis responses is explained as:



Define **Expressions**. Each expression is defined shown in the Figures A-3-2, A-3-3, and A-3-4, sequentially.

Expression List

No	Name	Expression	Value	Comment
1	Ex1	DM(1,2)	E 3138.47	
2	Ex2	CONTACT(1,0,1,2)	E 0	
3	Ex3	DM(1,2)-600	E 962.05	

Figure A-3-1 Expression List

Expression

Name: Ex1

DM(1,2)

Available

- Function expressions
- Fortran 77 Functions
- Simulation constants
- Displacement
- Velocity
- Acceleration
- Generic force
- Specific force
- System element

Argument List

ID	Entity
1	Red_Ball.Marker1
2	Blue_Ball.Marker2

Buttons: Add, Delete, OK, Cancel, Apply

Figure A-3-2 Detailed Definition of Expression Ex1

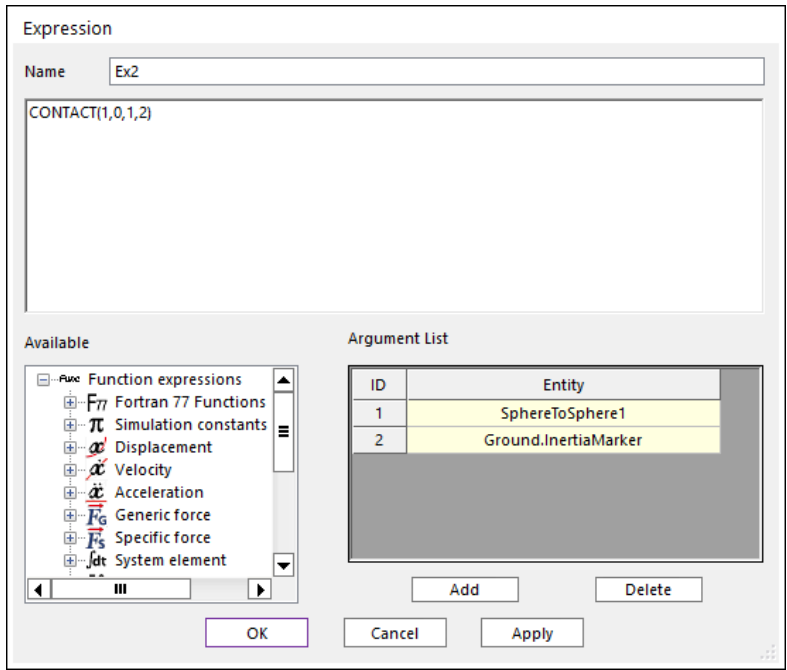


Figure A-3-3 Detailed Definition of Expression Ex2

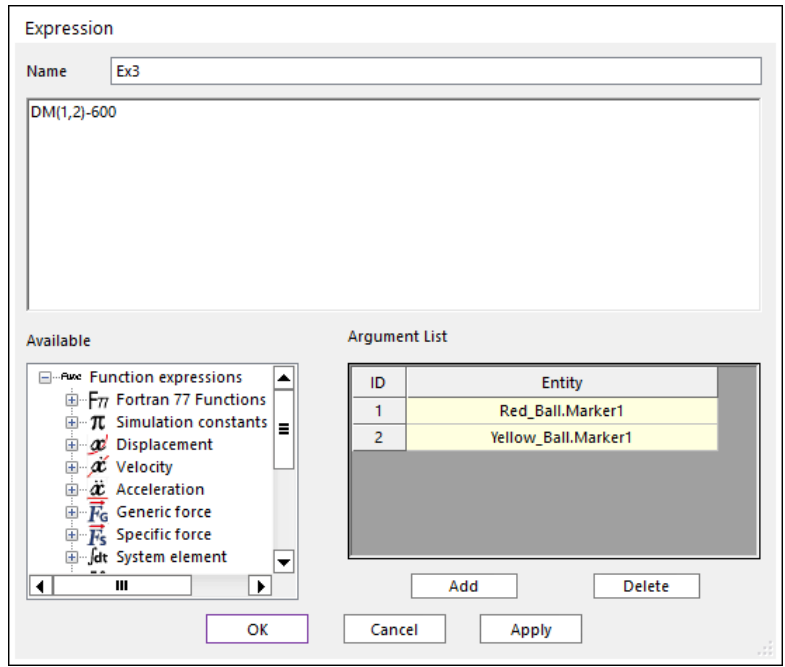
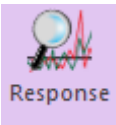


Figure A-3-4 Detailed Definition of Expression Ex3



Register expressions for analysis response shown in Figure A-3-5. Other figures are representing the dialogue of each analysis response. Define the **Analysis Response** using the '**Analysis Response**' command in the '**AutoDesign**' toolkit. The detailed information for each analysis response is shown in Figure A-3-6. Also, their physical relations are shown in Figure A-3-7.

Analysis Response List

No	Name	Type	Pr...	Description	Treatment	PI
1	AR1	Basic		Distance between Red Ball & ...	Min Value	<input checked="" type="checkbox"/>
2	AR2	Basic		Contact Force between Red B...	Max Value	<input checked="" type="checkbox"/>
3	AR3	Basic		Distance between Red BALL &...	Min Value	<input checked="" type="checkbox"/>

Figure A-3-5 Analysis Response List

Analysis Response - Basic

Name:

Result Output:

Treatment:

Description:

Analysis Response - Basic

Name:

Result Output:

Treatment:

Description:

Analysis Response - Basic

Name:

Result Output:

Treatment:

Description:

Figure A-3-6 The detailed information for three analysis responses

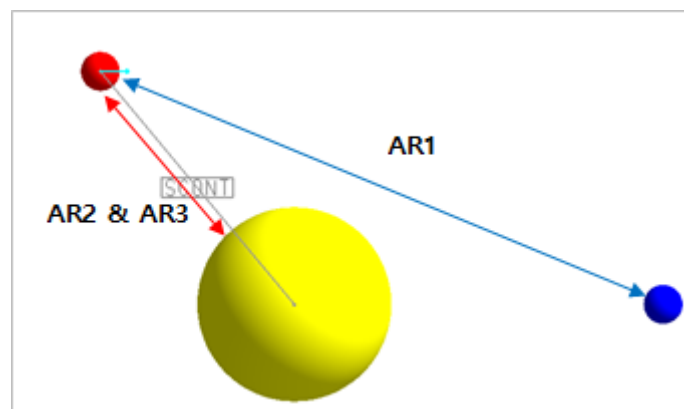


Figure A-3-7 Three analysis responses in the model

Chapter

4

Design Study

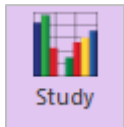
Before you start to solve this optimization problem, it needs to know the relationship between design variables and analysis responses or the correlation between analysis responses. To get that kind of information, you need the effect analysis from design of experiments.

AutoDesign provides such functions as effect analysis, correlation analysis and even design variable screening in Design Study menu. Design Study is composed of six sub-menus listed in Table A-4-1.

Design Variables	Select DOE method and define the level for variable
Performance Index	Show the ARs checked in Analysis Response menu
Simulation Control	Define the solving option of RecurDyn solver
Effect Analysis	Perform the effect analysis from the analysis results
Screening Variables	Screening procedure from the effect analysis results
Correlation Analysis	Perform the correlation analysis from analysis results

Table A-4-1 Description of sub-menu in Design Study

Basic Procedure for Design Study



In order to design study such as effect analysis, screening variables and correlation analysis, you select the DOE method and define the level for each variable and perform the simulation of **RecurDyn**. First, these procedures are explained as:

1. In the sub-menu of design variables, select '**Bose's Orthogonal Design**' in DOE methods, and set the level of the study as '**5**'. Then, one defines the required runs as 25. This method is a strength-II orthogonal array design. For more information, one may refer to the theoretical manual of **AutoDesign**.

Design Study

Design Variable Performance Index Simulation Control Effect Analysis Screening Variables Correlation Analysis

Method Bose's Orthogonal Array

DV	DP	Description	Level	Lower	Mid1	Upper
1	DP1	Initial VX	5	1500.	0	5000.
2	DP2	Stiffness K	5	1.	0	20.

Number of Trials 25 R

All Level Set 5 Set Default

OK Cancel Apply

Figure A-4-1 Define DOE method for design study

2. Confirm the Performance index that is checked in Analysis Responses.

Design Study

Design Variable Performance Index Simulation Control Effect Analysis Screening Variables Correlation Analysis

PI	AR	Description
1	AR1	Distance between Red Ball & Blue Ball
2	AR2	Contact Force between Red Ball & Yellow Ball
3	AR3	Distance between Red Ball & Yellow Ball

Figure A-4-2 The selected PI list for design study

3. In the sub-menu of simulation control, define analysis setting shown in Figures A-4-4 and A-4-5. This setting is the same as that in RD analysis. If you increase the accuracy of effect analysis and optimization results, it is recommended that the **plot multiplier factor** should be '1.0' and increase the number of steps. After setting the options, push the **OK** button. After setting them, push the Execution button. Then, **RecurDyn** is analyzed for the given number of trials.

Design Study

Design Variable Performance Index Simulation Control Effect Analysis Screening Variables Correlation Analysis

Simulation Type: Dynamic/Kinematic

Save Results effect_base\

Number of Trials: 25

Analysis Setting Execution

Figure A-4-3 Simulation Control page

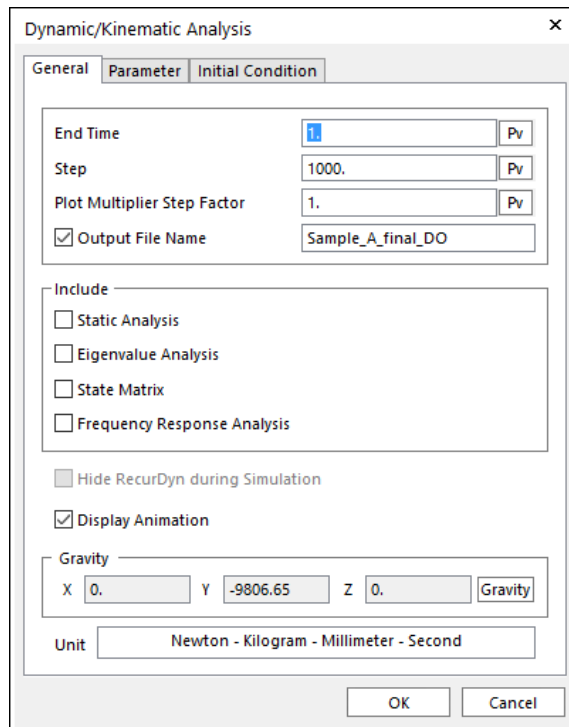


Figure A-4-4 General analysis setting

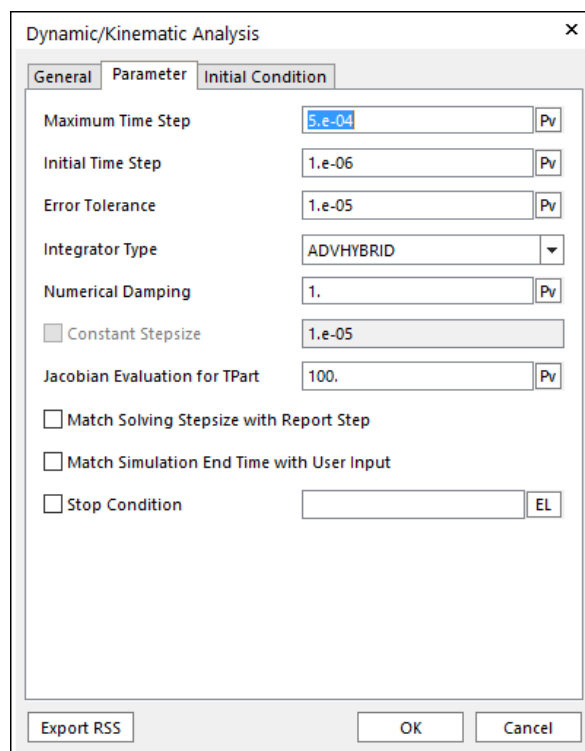


Figure A-4-5 Integrator parameter setting

4. After all analyses are completed, one can select the effect analysis, correlation analysis and screening design variables.
5. Now, select the effect analysis menu. Effect analysis gives the relation between one performance index and all design variables.

Effect Analysis

Figure A-4-6 shows the effect analysis menu. Let's study the effect analysis procedure.

Select the performance index in PI row. Then check the design variables to see the effect analysis for the selected PI. Then, push DRAW button. Figure A-4-7 shows the effect analysis between PI_1 and design variables. This shows that DV1 is more nonlinear than DV2 in the distance between red ball and blue ball.

Design Study							
Design Variable	Performance Index	Simulation Control	Effect Analysis	Screening Variables	Correlation Analysis		
PI: 1 : AR1(DM(1,2))							
Effect Values and Variation Draw							
DV	Level1	Level2	Level3	Level4	Level5	Variation	Effect Value
1	2.208152655...	1.358839406...	0.487655979...	0.652289790...	0.293062168...	<input type="checkbox"/>	<input checked="" type="checkbox"/>
2	0.808903863...	1.036337385...	1.051277050...	1.052378731...	1.051102968...	<input type="checkbox"/>	<input checked="" type="checkbox"/>

Figure A-4-6 Sub-menu for effect analysis

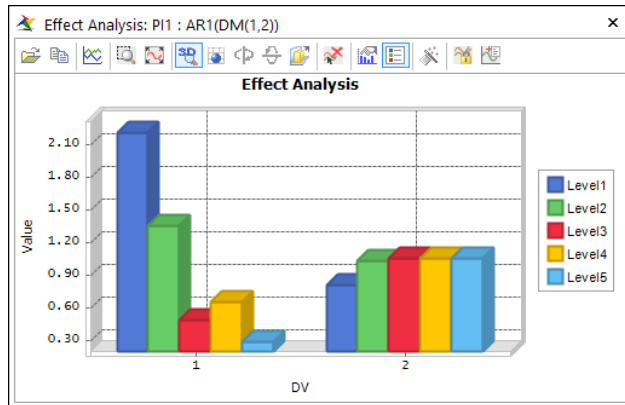


Figure A-4-7 Effect analysis result for the first PI

Similarly, you can see the effect analysis for PI_2, which is shown in Figure A-4-8. For the 4th and 5th levels of DV1, the contact forces are 'zero'. This represents that two balls are not contacted for those cases. It is noted that this discontinuity makes the accuracy of meta-model to be worse.

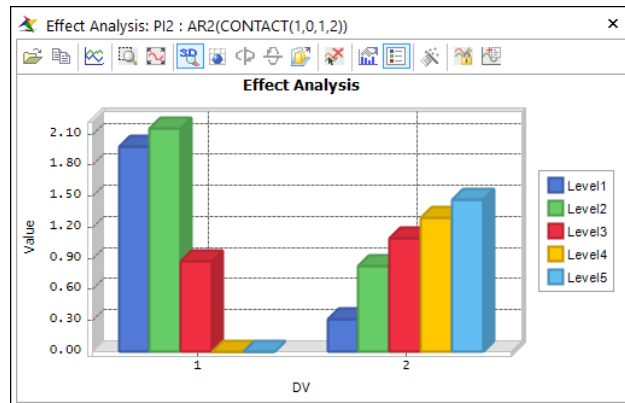


Figure A-4-8 Effect analysis result for the second PI

Finally, you can see the effect analysis for PI_3, which is shown in Figure A-4-9. This represents the distance between red and yellow balls. Unlike Figure A-4-8, this shows a continuous result even though two balls didn't contact for 4th and 5th levels of DV1. This represents that PI_3 is suitable to define the contact constraint in the design optimization.

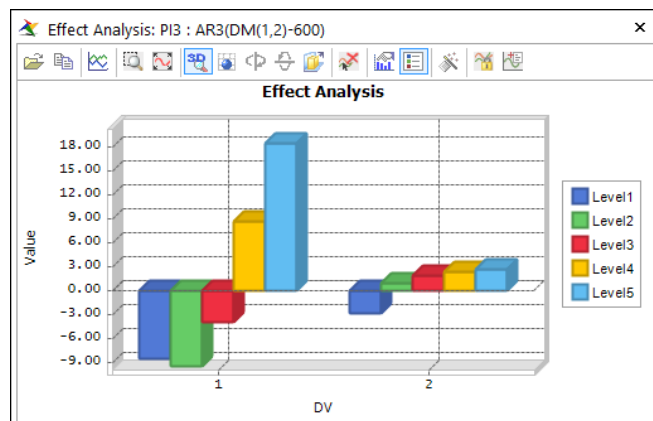


Figure A-4-9 Effect analysis result for the third PI

The explanation of effect analysis is completed. However, you have a question for the minimization or maximization combinations shown in Figure A-4-10.

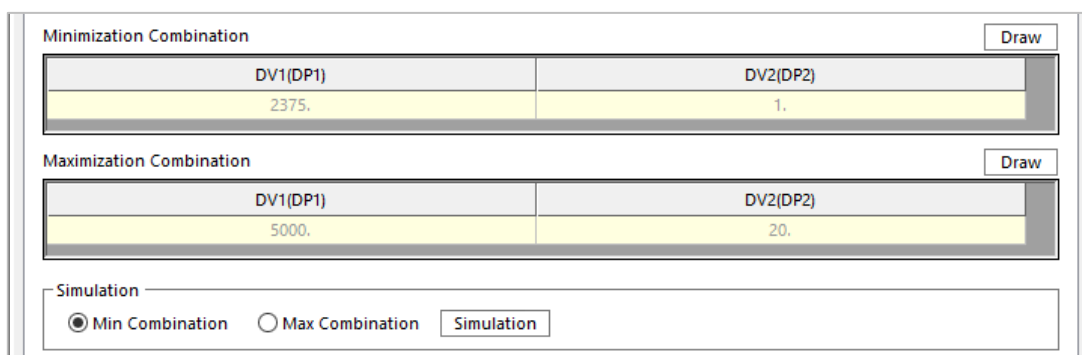


Figure A-4-10 Selection of minimization or maximization combination

Suppose that you select the third PI. Then, you see the effect analysis result shown in Figure A-4-9. Then, Figure 4-10 shows the design variable combination for minimizing PI_3 and maximizing PI_3. If you need the confirmation for minimum or maximum set, then select one of them and push simulation button in Figure A-4-10 menu.

Screening Variables

Figure A-4-11 shows the menu for screening variables. First, you can see the scatter points. This represents the design variables. In this problem, there are only two design variables. Thus, variable screening is not required but we study only the screening variable method.

1. First, select the first performance index, **PI_1**. Figure A-4-11 shows that two design variables have severely different effectiveness. Now, you need to know which variable is effective for PI_1.

- Define the cutoff values as 1.0 and push **Apply** button. You can see Figure A-4-12. Then, push the **Screening DV** button. Figure A-4-13 shows the screening result. It shows that design variable DV1 (or DP1) is more effective than DV2.

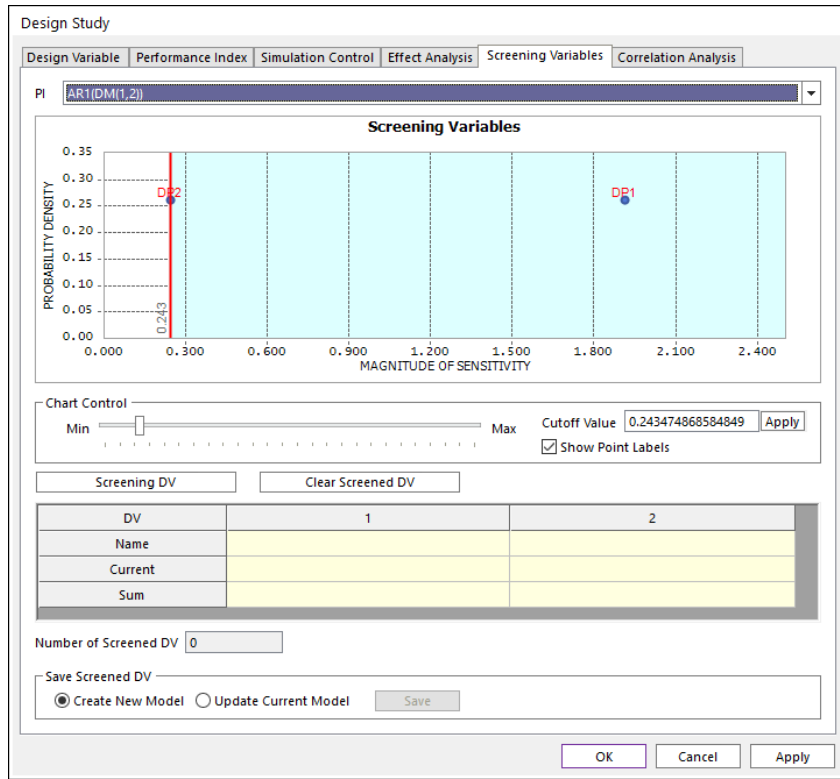


Figure A-4-11 Sub-menu for screening variables

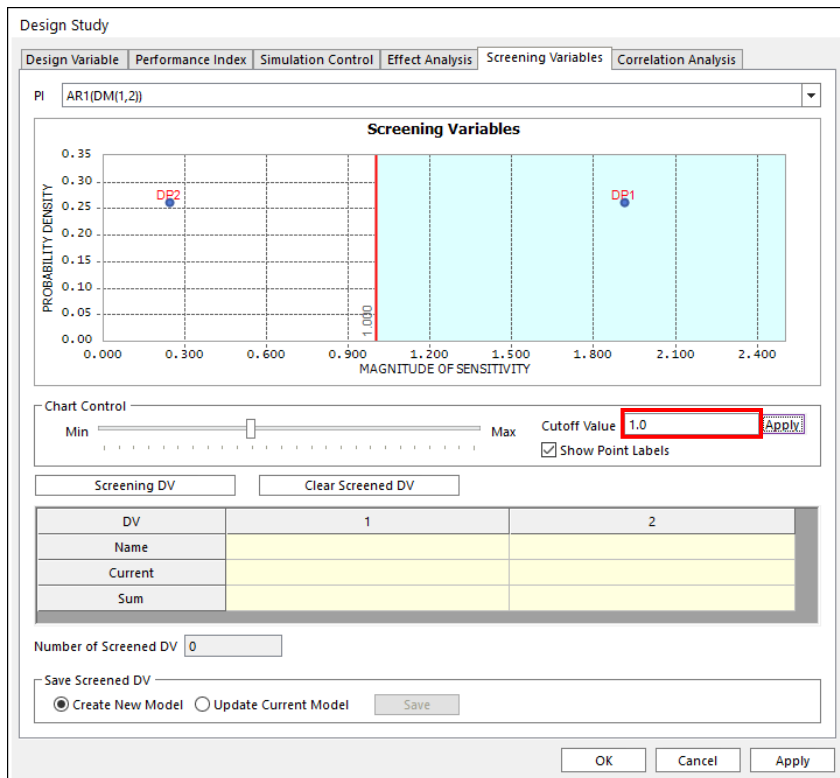


Figure A-4-12 Defining the cutoff value for screening variables

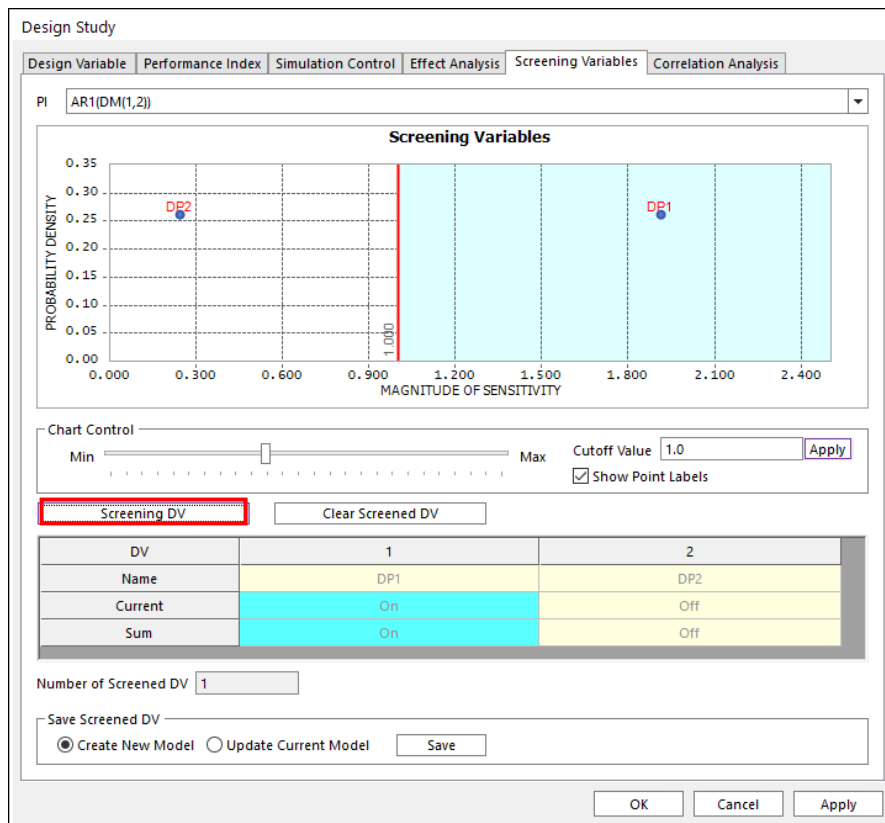


Figure A-4-13 Screened result for the first performance index

- Next, change the performance index **AR3**. Then, define the cutoff value as 12. Perform the similar procedure in step 2. Then you can see the result shown in Figure A-4-14. In the figure, Current represents the screening results for PI_3. Total represents the union of screening results for PI_1 and PI_3. If you push **Save** button, only active design variables (marked 'on') are remained in New Model or Current Model.

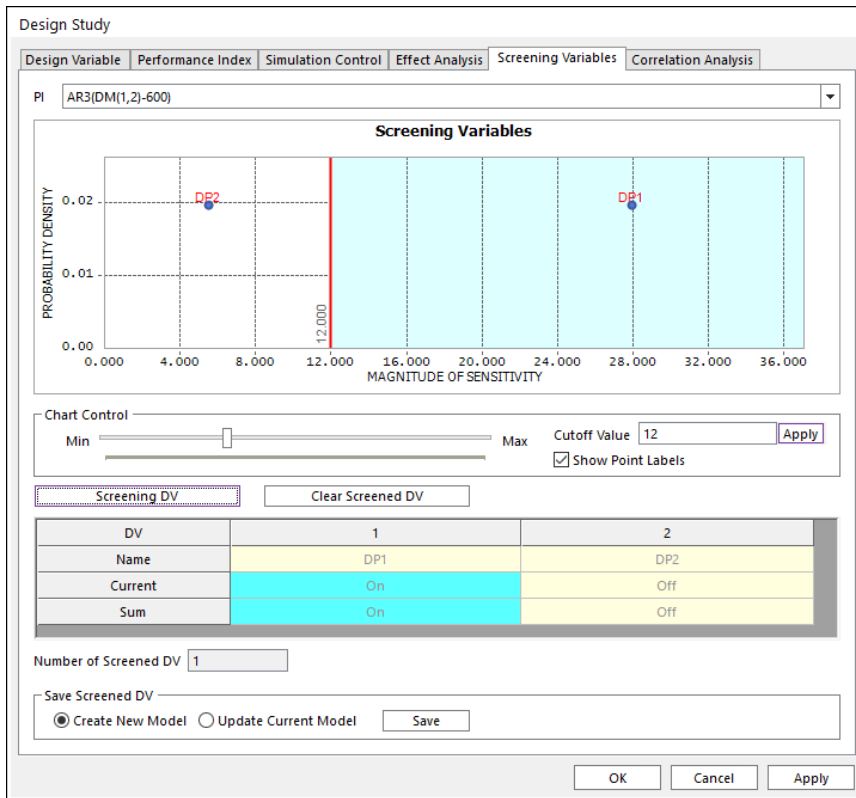


Figure A-4-14 Screened result for the third performance index

Correlation Analysis

Figure A-4-15 shows the menu for correlation analysis. This shows the relation between two selected ARs from the analysis results. If you see the relation between the first PI and the third PI, check Horizontal Axis as PI_1 and Vertical Axis as PI_3 and push Draw button. Then, you can see the correlation result shown in Figure A-4-16. Figure A-4-16 shows that they have no trend or slightly reverse trend.

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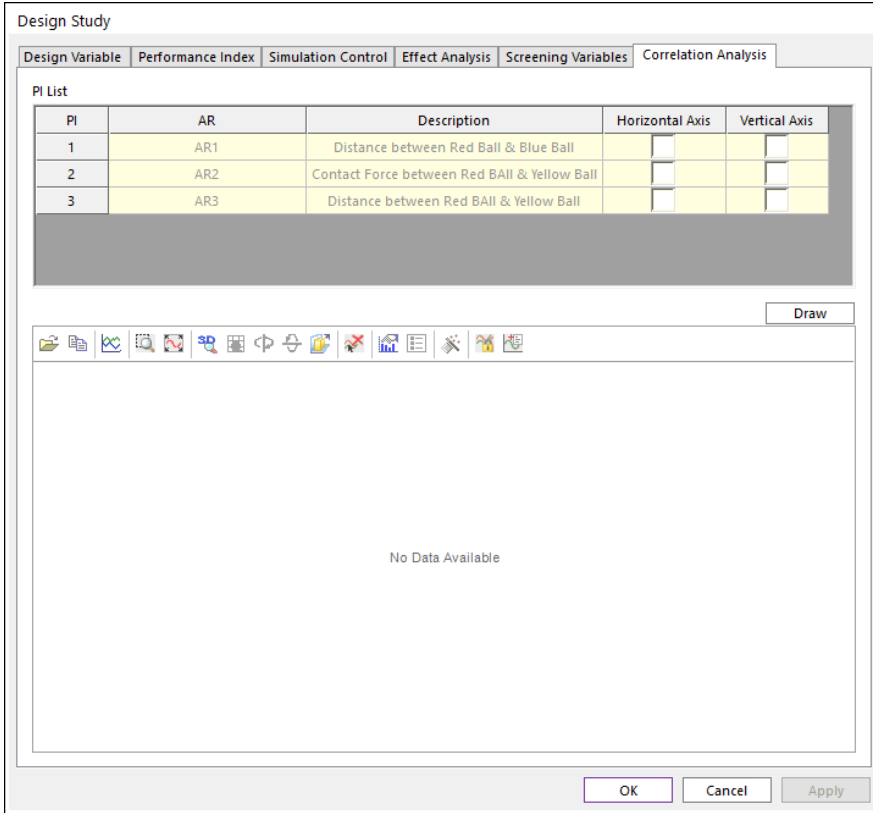


Figure A-4-15 Sub-menu for correlation analysis

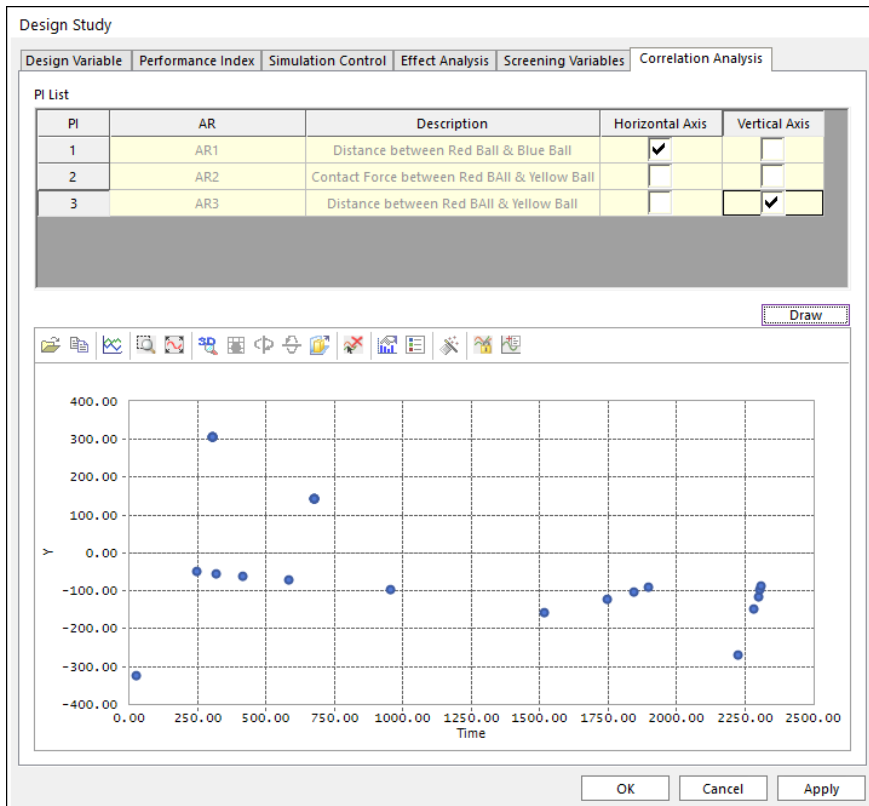
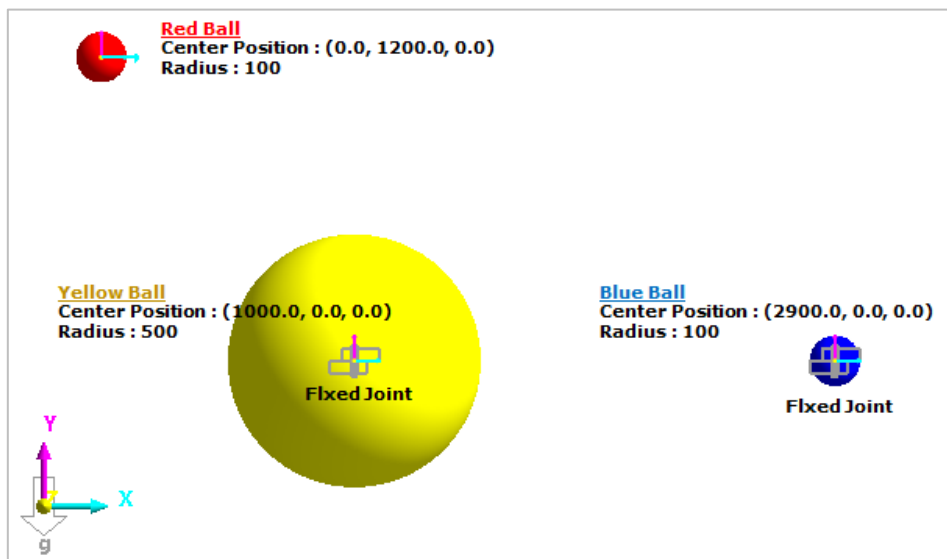


Figure A-4-16 Correlation result between PI_1 and PI_3

Design Optimization

Let's remind the following design problem:

Find the initial velocity of red ball along x-direction and the contact stiffness between red and yellow balls for red ball to hit the blue ball after red ball hit yellow ball.



Next process is for defining the design option and executing the optimization analysis. The first step is to define the design variables shown in the Figure A-5-1. This can start using the '**Design Optimization**' command in the '**Auto Design**' toolkit.



1. In **Design Variable** menu, the selected DPs are listed. In this menu, DP can be design variable or constant during optimization process. If you define a DP as constant, you should define its constant value.

Design Optimization							
Design Variable							
DV	DP	Description	Current	LB	UB	Type	Value
1	DP1	Initial VX	2700.	1500.	5000.	Variable	0.
2	DP2	Stiffness K	10.	1.	20.	Variable	0.

Figure A-5-1 Definition of design variables

2. The next process is to define the performance indexes in Figure A-5-2, which is named as 'performance index' of the dialog of Figure A-5-1. **Performance Index** is a design optimization formulation part. Figure A-5-3 shows the mathematical definition for design optimization. Let's discuss the optimization formulation in Figure A-5-2. In the first performance index, choose **AR1** and define it as objective. Also, select the design goal as minimization and define its weighting coefficient as **1.0**. In the second performance index, add one inequality constraint as '**AR1** =< **100**'. In the third performance index, add one inequality constraint as '**AR3** =< **0**', In the last performance index, choose **AR2** and define it as objective. Unlike AR1, the design goal is defined as maximization and its weight coefficient is defined as **1**.

Design Optimization							
Performance Index							
PI	Use	AR	Description	Definition	Goal	Weight/Limit Value	
1	<input checked="" type="checkbox"/>	AR1	Distance between R...	Objective	MIN	1.	
2	<input checked="" type="checkbox"/>	AR1	Distance between R...	Constraint	LE	100.	
3	<input checked="" type="checkbox"/>	AR3	Distance between R...	Constraint	LE	0.	
4	<input checked="" type="checkbox"/>	AR2	Contact Force betw...	Objective	MAX	1.	

Figure A-5-2 Definition of performance indexes

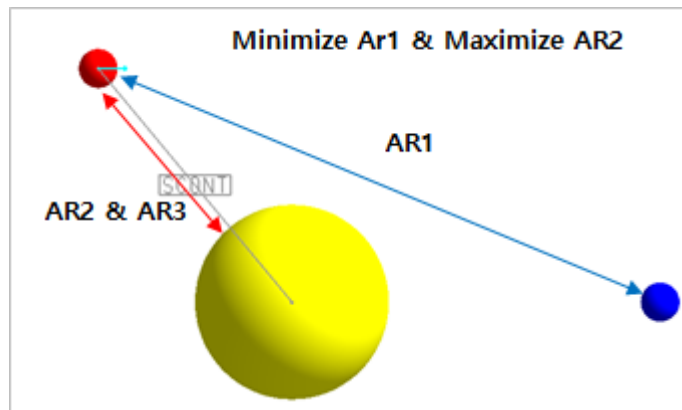
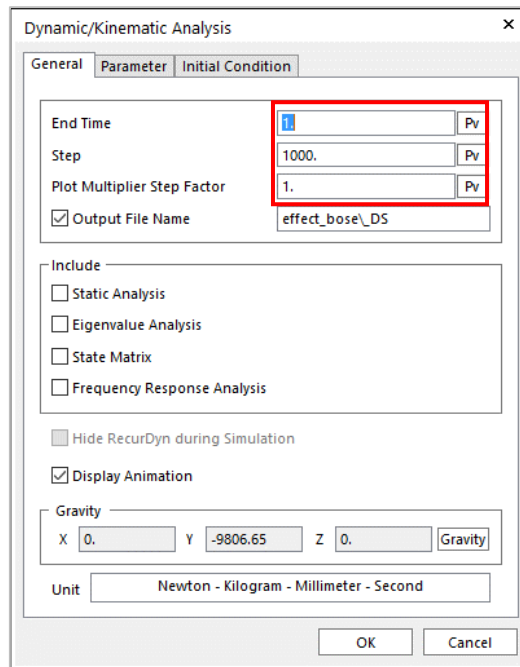


Figure A-5-3 Design optimization formulation

- Check the analysis setting by clicking the **Analysis Setting** button. In order to reduce the numerical error, we increase the number of time steps shown in right. If you increase the resolution of optimization solution, then increase the number of steps. In refining the design optimization, we will show more accurate design by only increasing the value.



- Define the option of optimization control and execute analysis shown in the Figure A-5-4. The analysis setting is the same that of Design Study. Finally, if you push the optimization button, you can see the summary of the design optimization formulation shown in Figure A-5-5. Then, check your formulation. If you see some mistakes, then push the **Cancel** button and correct the mistakes. Otherwise, push the **Execution** button. Then, **AutoDesign** runs until convergence criteria are satisfied or maximum iteration is reached. During optimization process, you can see the analysis results in the **Simulation History** menu.

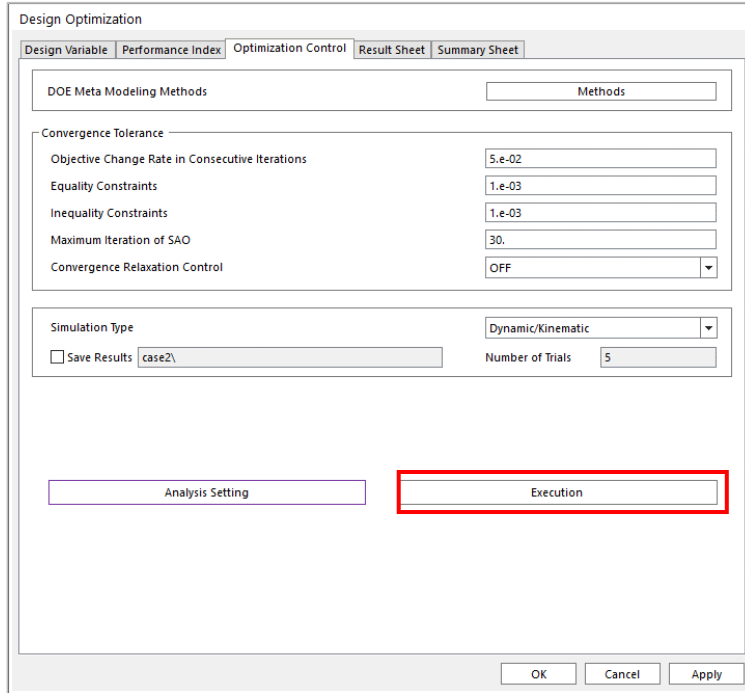


Figure A-5-4 Control option definition for optimization and analysis

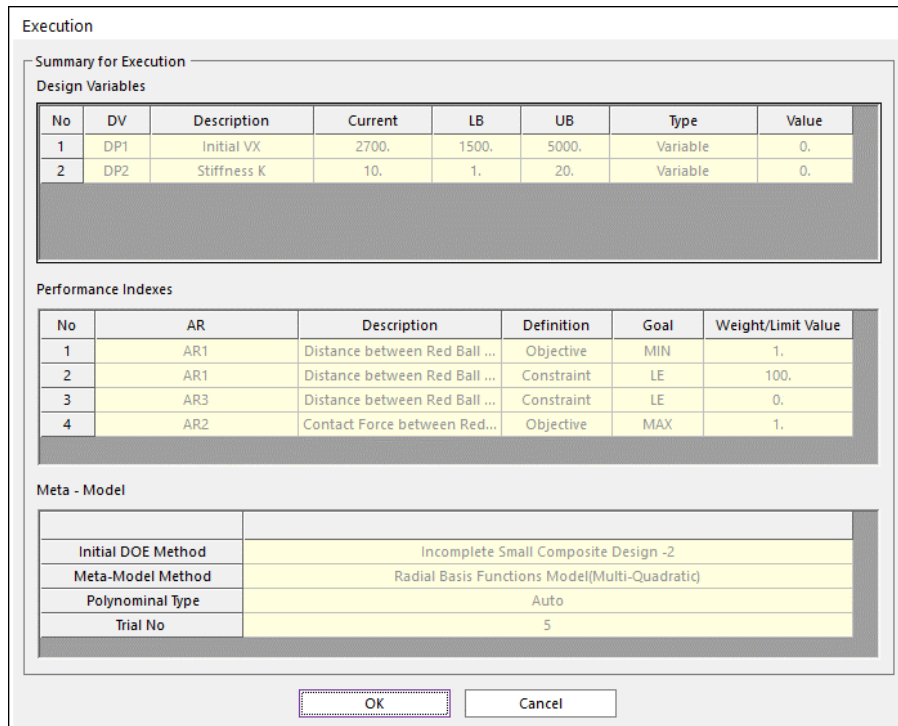


Figure A-5-5 Summary of design optimization formulation

- If **AutoDesign** is completed, then you can see the convergence results in **Result Sheet**. Figure A-5-6 shows the optimization results. In **RecurDyn**, the final value of AR1 is **0.732(mm)** after **8** iterations. Figure A-5-7 shows the trajectory of red ball for **SAO 8**.

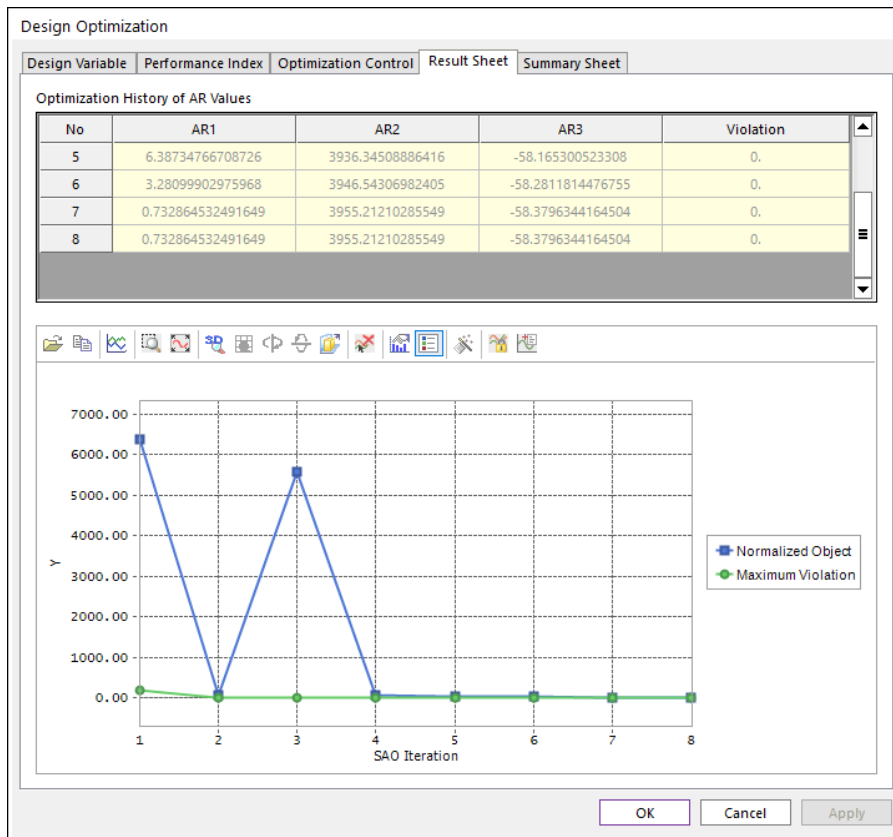


Figure A-5-6 Convergence history

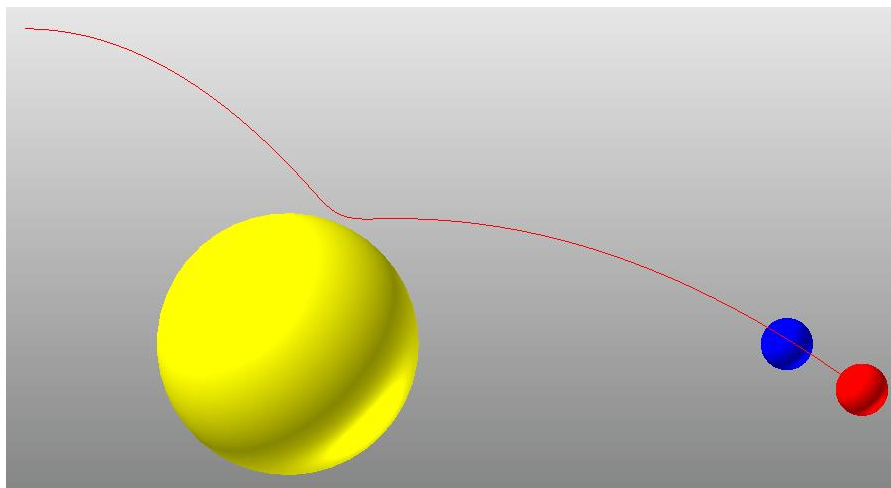


Figure A-5-7 Animation of the final design

Thanks for participating in this tutorial!