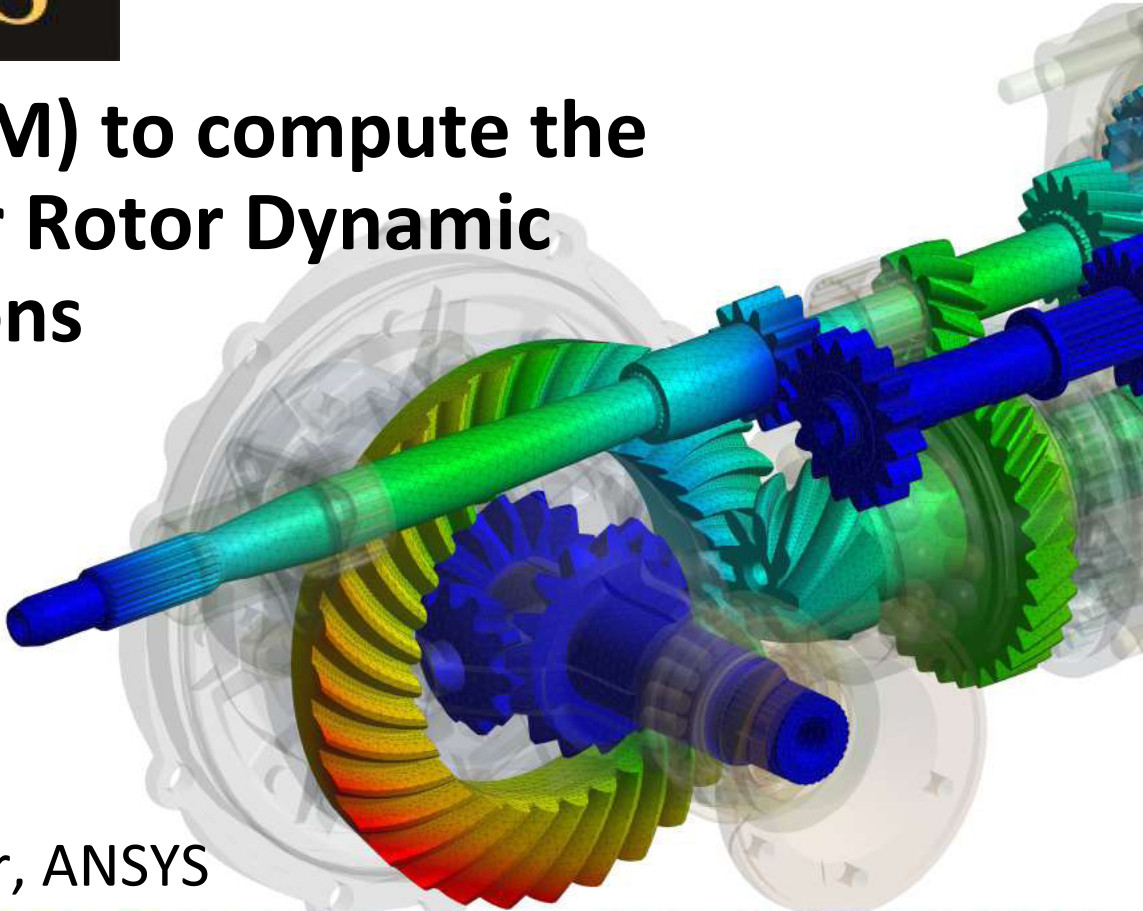




Meta-Model Method (ROM) to compute the Bearing Coefficients for Rotor Dynamic Applications

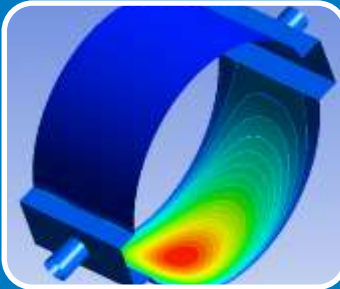


Johannes Einzinger, ANSYS

Agenda



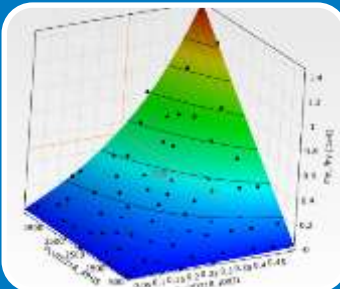
Application Areas of Fluid Film Bearings



Modelling

3D Navier-Stokes (CFD)

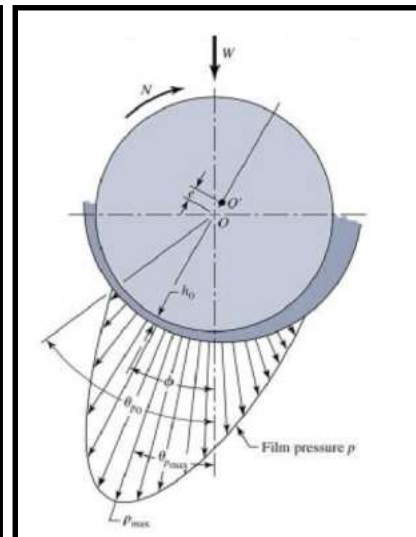
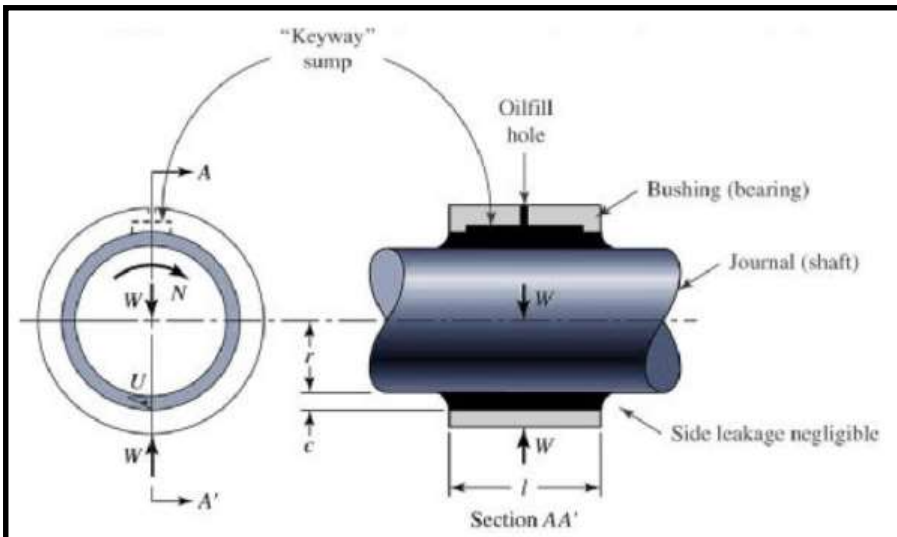
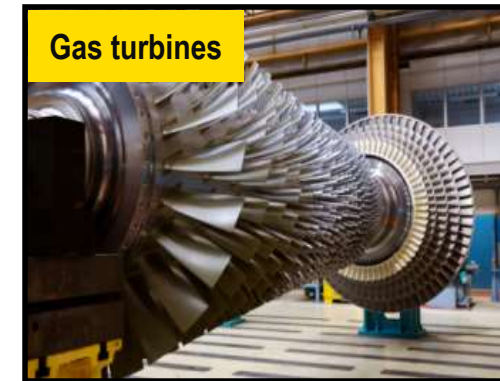
Reynolds Equation (Mechanical)



Reduced Order Model

Application Areas of Fluid Film Bearings

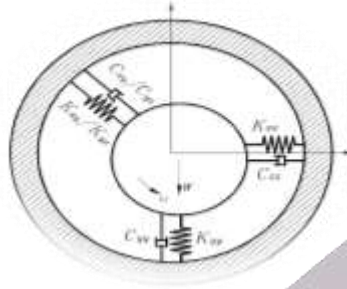
- Why Fluid Film Bearings?
 - Simple Construction
 - Good Damping Characteristics
 - High Load and Speed
 - High Precision Applications
- Critical to Machines overall Reliability!!



Modelling – Overview

Accuracy and Usability

$$\begin{bmatrix} C_{xx} & C_{xy} \\ C_{yx} & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} + \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} u_x \\ u_y \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_y \end{Bmatrix}$$



Spring & Damper
 Efficient Coupling with Rotor Dynamics
 How to compute the Coefficients???

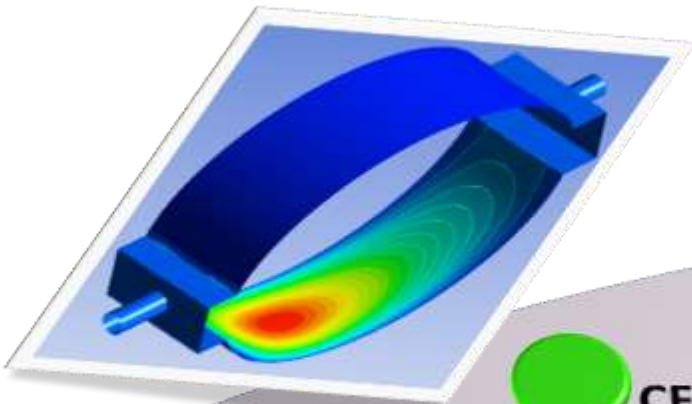
Reynolds Equation
 Simplified Navier-Stokes Equation
 Limited Modelling

3D CFD
 Full Navier-Stokes Equation

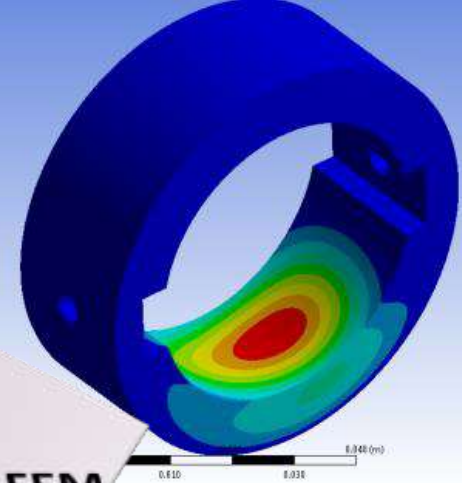
CFD&ROM
 CFD and ROM for
 Mechanics, Rigid Body

CFD&FEM
 Non-Linear
 Fluid-Structure
 Interaction

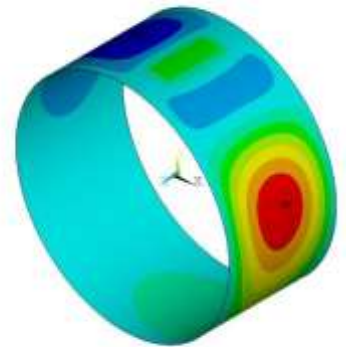
Computational Effort



Thermal and
 Mechanical
 Deformation



$$\frac{\partial}{\partial x} \left(\frac{h^3}{12\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{12\mu} \frac{\partial p}{\partial z} \right) = \frac{U}{2} \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t}$$



Simulation Procedure

- Stiffness and Damping is wrt to Equilibrium Position:

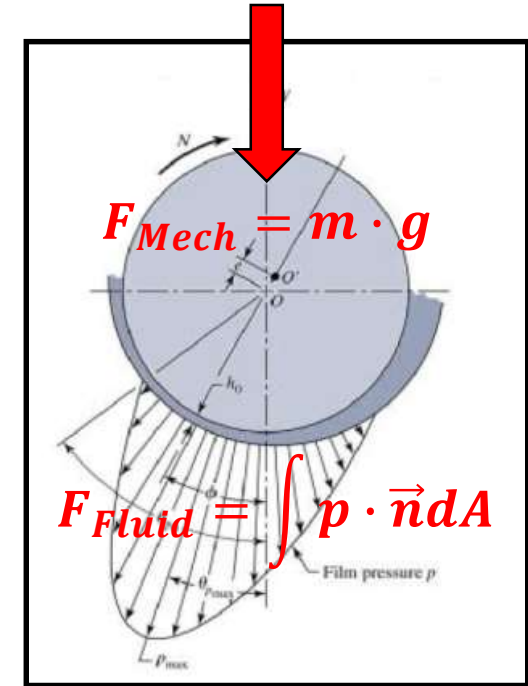
Calculate Equilibrium Position

- Stiffness Coefficient:
$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} \end{bmatrix}$$

Repeat Simulation with varied Position $\rightarrow K = \frac{\Delta F}{\Delta x}$

- Damping Coefficient:
$$\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial \dot{x}_1} & \frac{\partial F_1}{\partial \dot{x}_2} \\ \frac{\partial F_2}{\partial \dot{x}_1} & \frac{\partial F_2}{\partial \dot{x}_2} \end{bmatrix}$$

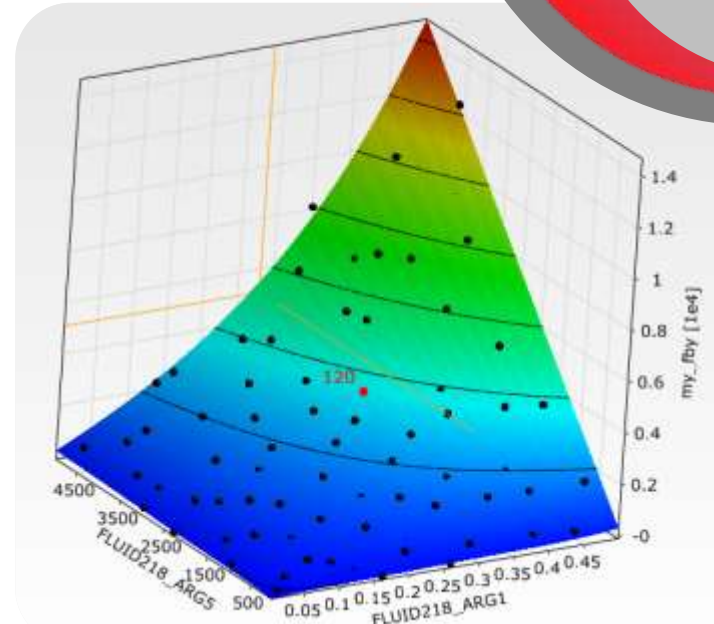
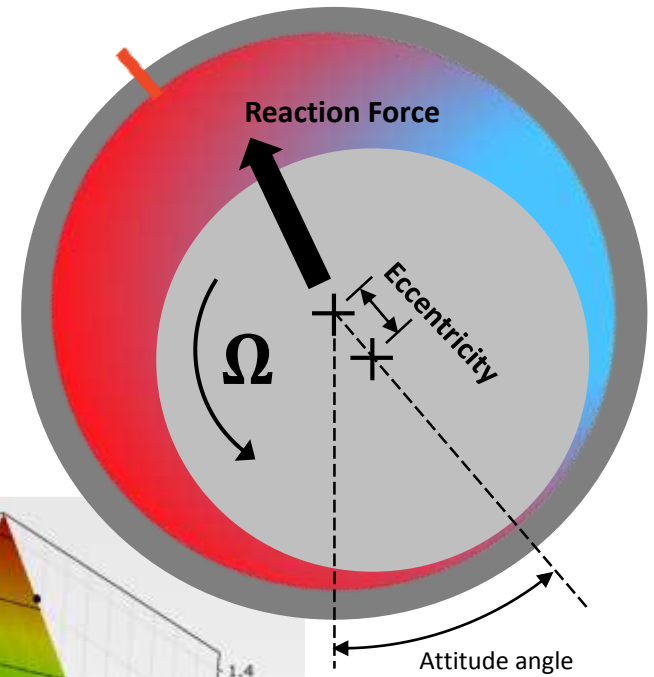
Repeat Simulation with varied Velocity $\rightarrow C = \frac{\Delta F}{\Delta \dot{x}}$



**2-Way-Coupled Fluid-Structure Interaction!
High Computational Effort!**

Reduced Order Model (ROM) Approach

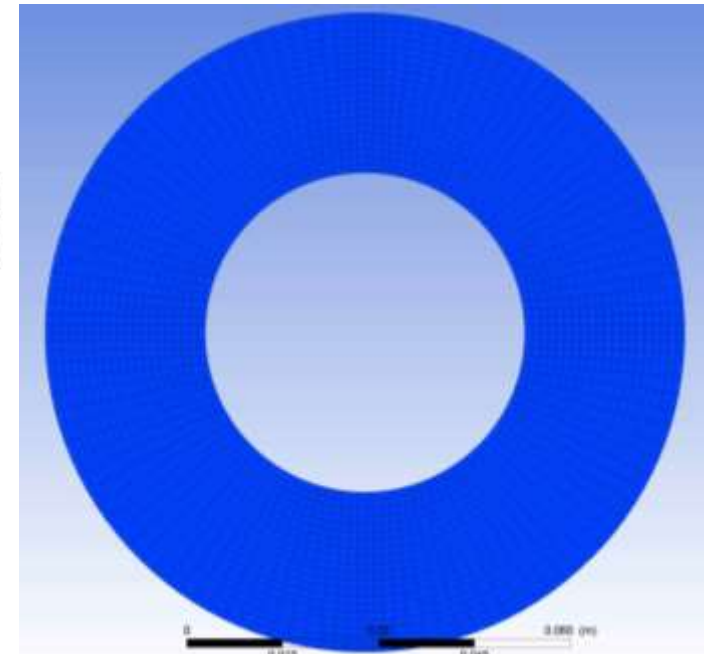
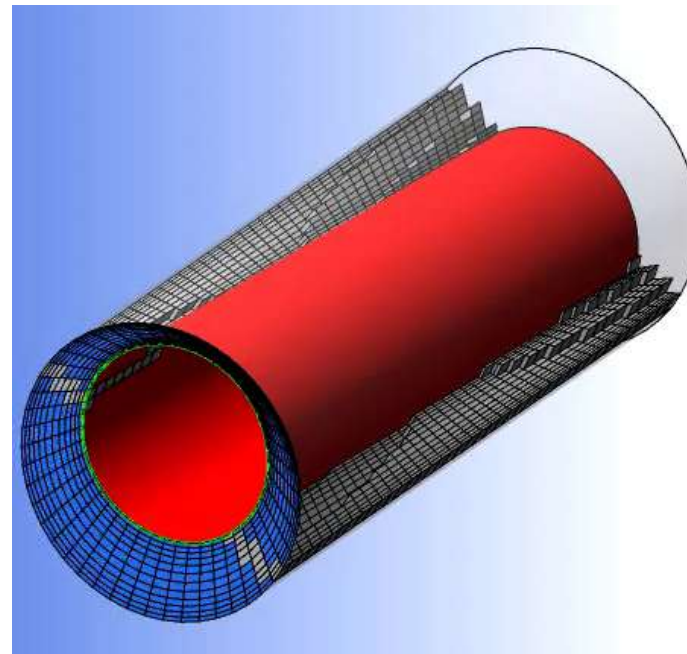
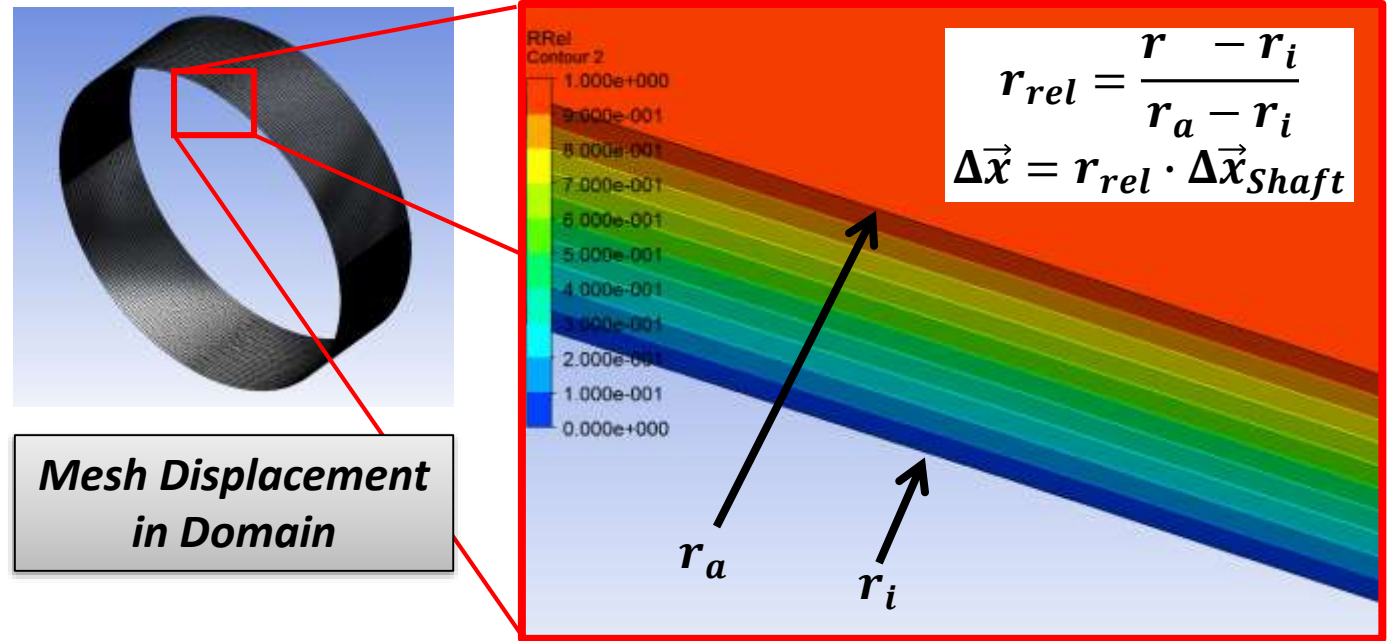
- Design of Experiments
- Variation of Eccentricity, Attitude Angle, ...
- Measure Reaction Force
- Response Surface is calculated (=ROM)
- Reaction Force = $f(\text{Eccentricity}, \text{Attitude Angle}, \dots)$
- Optimization to find
- Eccentricity, Attitude Angle, ...
- For given External Force
- Stiffness is Derivative of Response Surface
- Damping is calculated at Equilibrium



3D Navier-Stokes in CFX

- 3D Resolution & Kinematics
- Steady Simulation
- Re-Meshing for each Position
- Mesh Morphing
- Transient Simulation
- Mesh Morphing
- → Analytical Mesh Morphing

Outlook:
Analytical Mesh Morphing

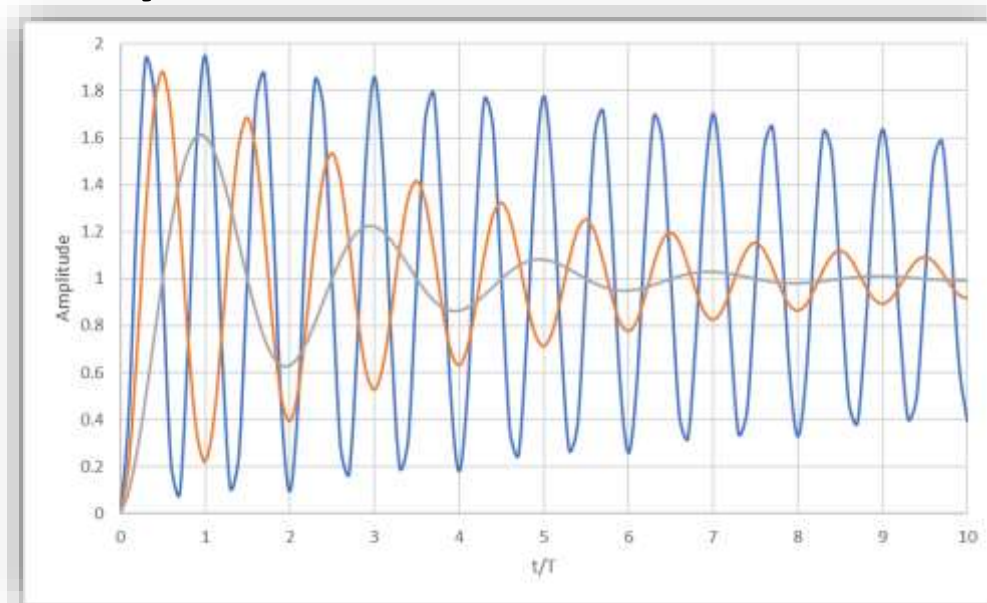
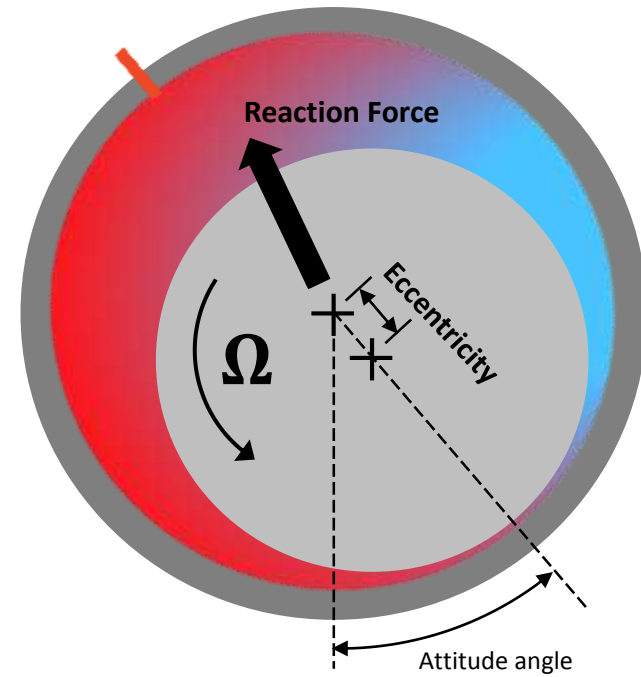


Equilibrium

- **Steady State: Design of Experiments**
- Variation of Eccentricity, Attitude Angle, ...
- Measure Reaction Force
- Get Equilibrium from Response Surface
- **2-Way-Coupled FSI with Rigid Body**
- Rigid Body Dynamics is solved in CFX!

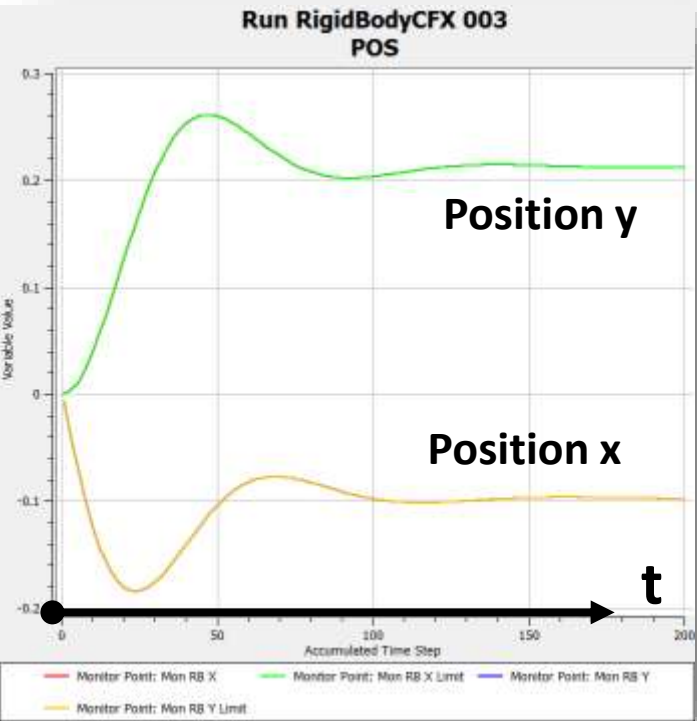
$$m \cdot \ddot{x} + \underbrace{d \cdot \dot{x}} = F_{Fluid} - m \cdot g$$

Artificial Damping to
avoid overshoots,
zero for Equilibrium!

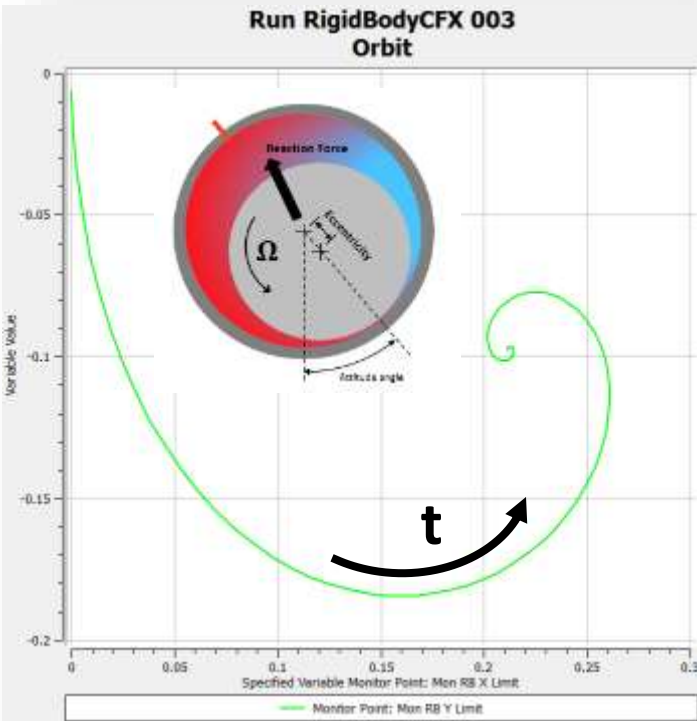


Steady State
Just Fluid Damping
+Artificial Damping

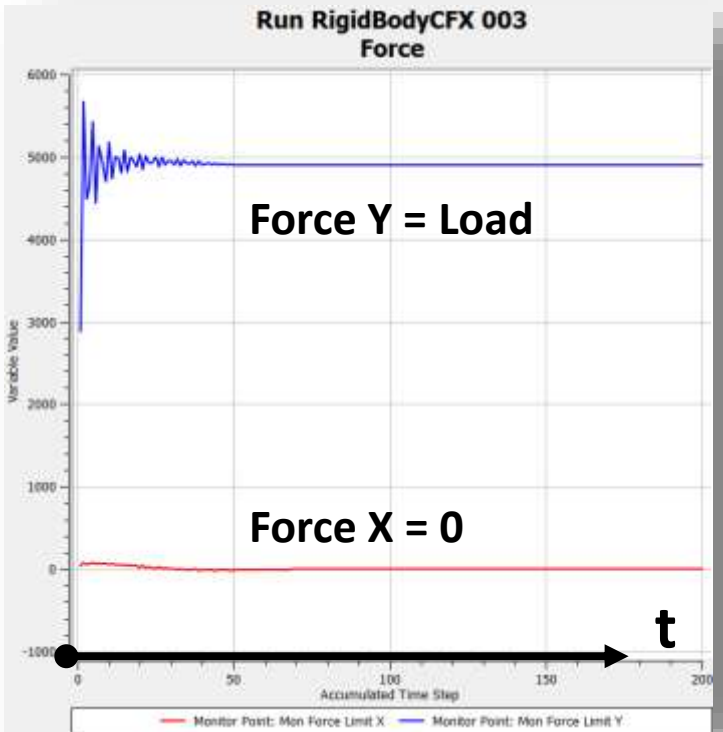
Result: 2-Way-Coupled FSI with Rigid Body



Position, constant for increasing Time
→ Steady equilibrium



Orbit Plot
Position in X-Y Plane



Force, constant for increasing Time
→ Steady equilibrium

Calculate Stiffness and Damping

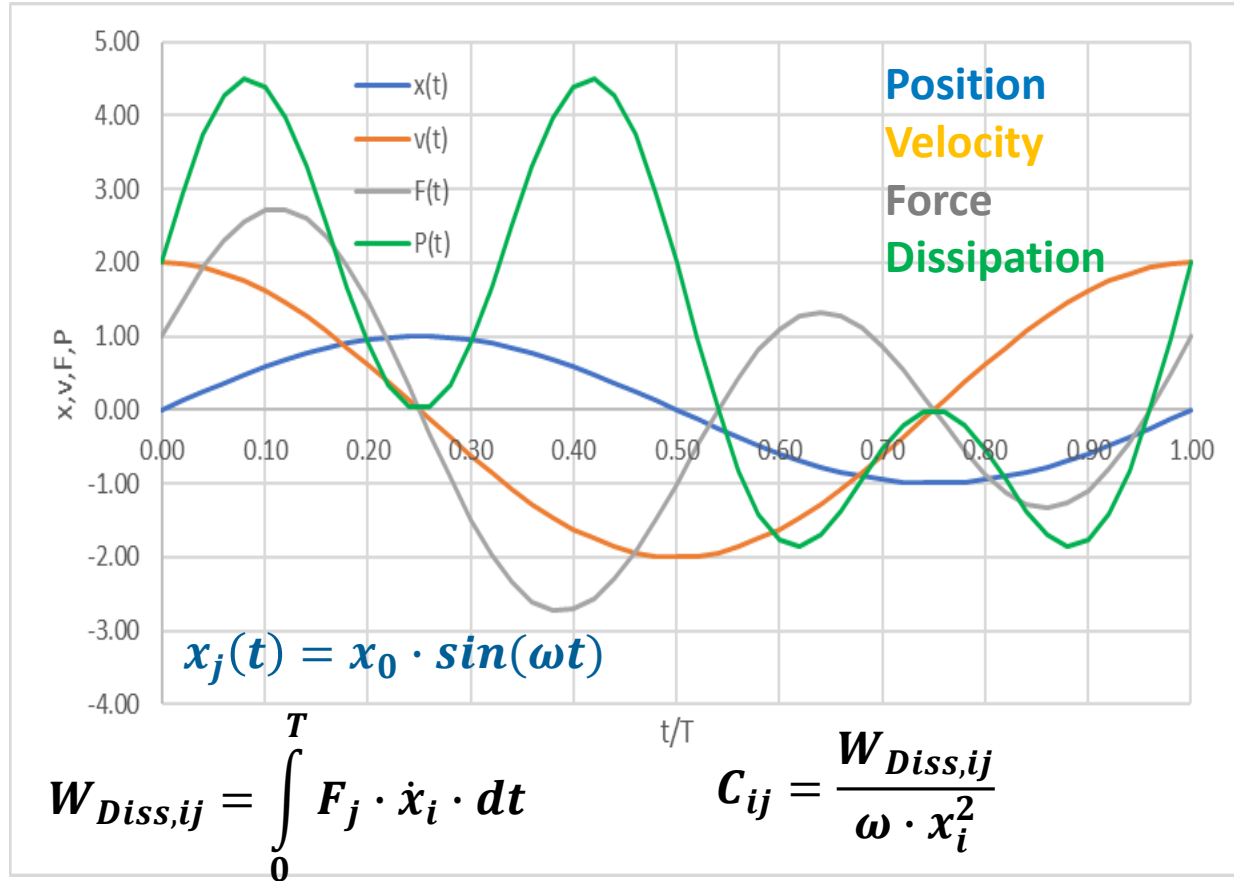
- Calculate Equilibrium Position

- Stiffness Coefficient:
$$\begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} \end{bmatrix}$$

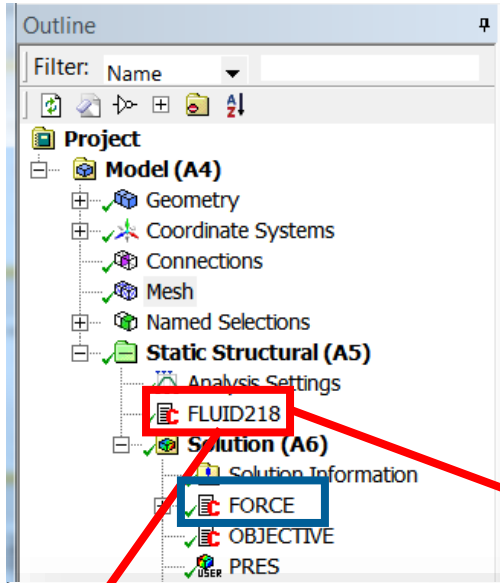
Repeat Steady Simulation with varied Position $\rightarrow K = \frac{\Delta F}{\Delta x}$

- Damping Coefficient:

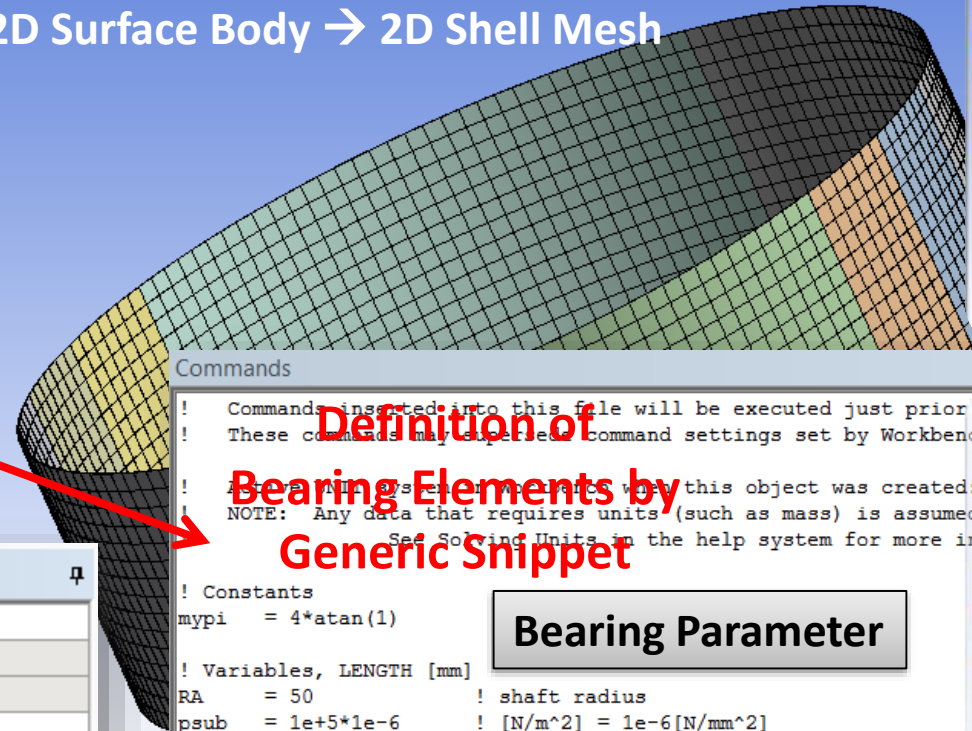
- Transient Simulation with oscillating Shaft (one for x and one for y) until periodic Result
- Dissipation Work: integrate Force x/y and Velocity x/y over one Period
- Normalization \rightarrow Damping



Bearing Model – Mechanical



2D Surface Body → 2D Shell Mesh



Definition of Bearing Elements by Generic Snippet

```

! Commands inserted into this file will be executed just prior
! These commands may supersede command settings set by Workbench
! If you change any of the parameters of this object was created:
! NOTE: Any data that requires units (such as mass) is assumed
! See Solving Units in the help system for more info

! Constants
mypi = 4*atan(1)

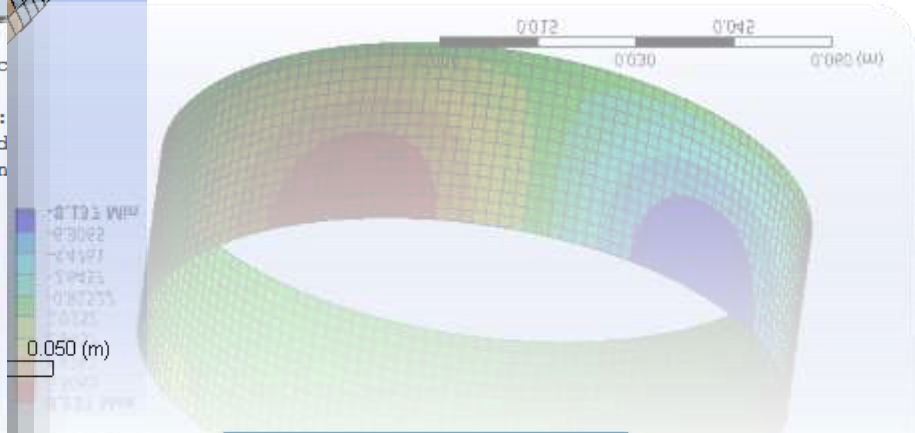
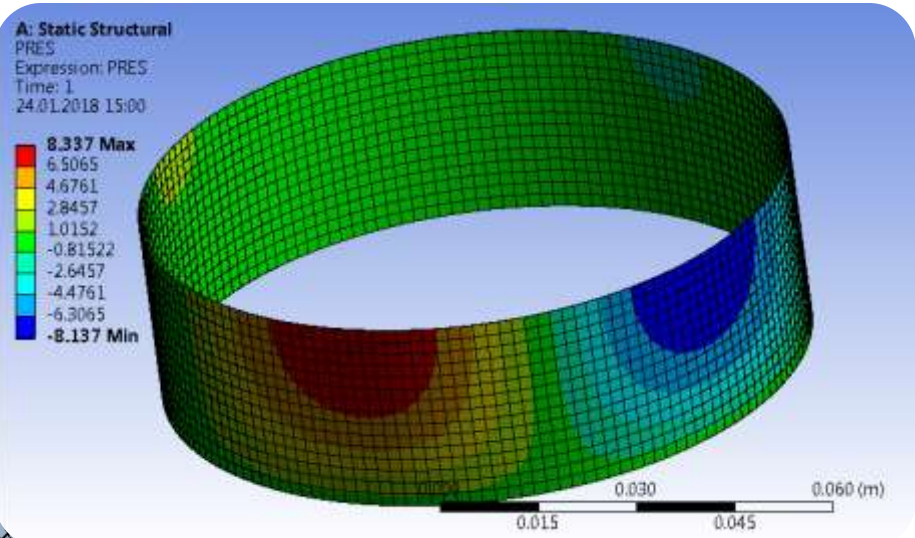
! Variables, LENGTH [mm]
RA = 50 ! shaft radius
psub = 1e+5*1e-6 ! [N/m^2] = 1e-6[N/mm^2]
mymu = 1e-3*1e-6 ! mu=1e-3[Pa s] = 1e-9[MPa s]
mydens = 900*1e-9 ! dens=900[kg/m^3] = 900*1e-9[kg/mm^3]
my_rpm = arg5 ! speed of revolution
wshaft = my_rpm*mypi/30
myext = 0.01

*afun, rad
Xpos = arg1*cos(mypi*arg2/180) ! XX=X/myext
Ypos = arg1*sin(mypi*arg2/180) ! YY=Y/myext
Xvel = arg3*RA*wshaft
Yvel = arg4*RA*wshaft
! *****
    
```

Bearing Parameter

Details of "FLUID218"

File	
File Name	
File Status	File not found
Definition	
Suppressed	No
Target	Mechanical APDL
Input Arguments <i>Input Parameter:</i>	
P ARG1	0.5 <i>Eccentricity</i>
P ARG2	-90. <i>Attitude Angle</i>
P ARG3	0. <i>Velocity X</i>
P ARG4	0. <i>Velocity Y</i>
P ARG5	4000. <i>Speed of Revolution</i>



Output Parameter

Results

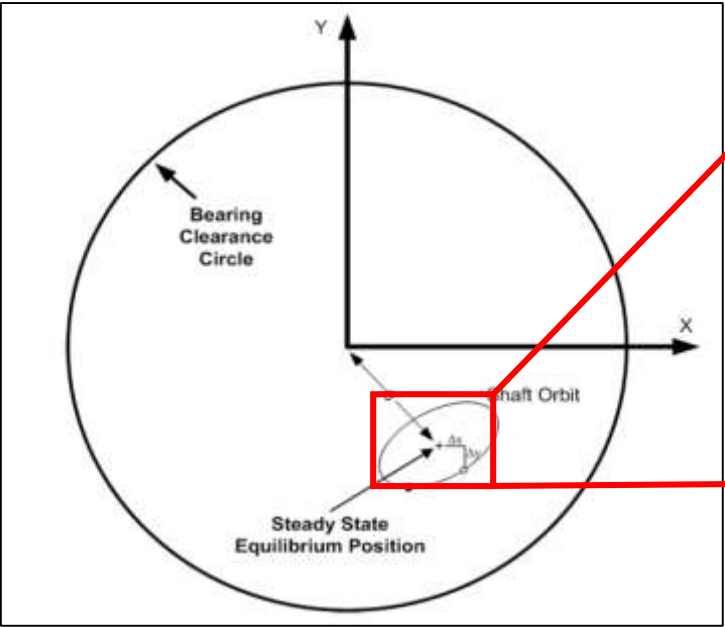
P my_fbx	4768.9
P my_fby	4935.5
P my_So	0.43692
P my_SoX	0.3036
P my_SoY	0.31421



Calculate Stiffness and Damping

Vary Equilibrium Position with Δx , get Reaction Force and calculate Stiffness:

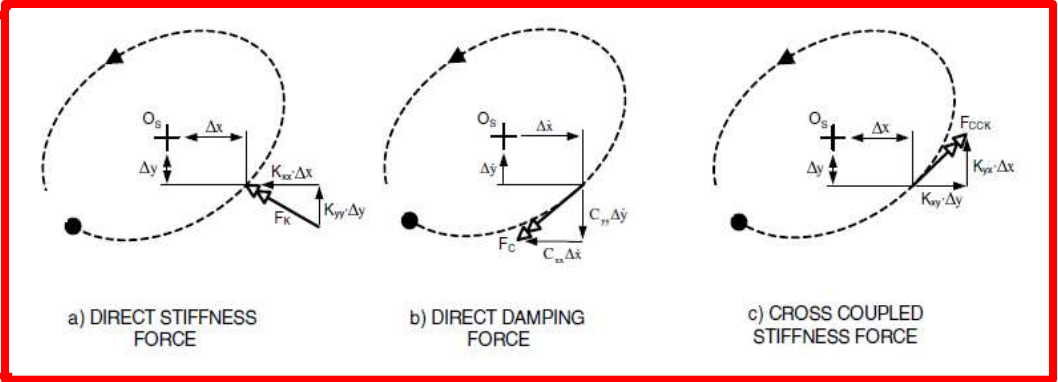
$$K_{ij} = \frac{F_j(x_{eq} \pm \Delta x_j) - F_{j,eq}}{\Delta x_i}$$



Equilibrium Position

Shaft Velocity can be applied in steady State Simulation!
Calculate Reaction Force and Damping

$$C_{ij} = \frac{F_j(x_{eq}, \Delta \dot{x}_j) - F_{j,eq}}{\Delta \dot{x}_i}$$

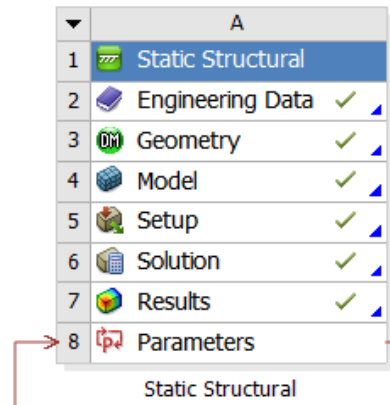


Perturbation and Induced Forces

$$\frac{\partial}{\partial x} \left(\frac{h^3}{12\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{h^3}{12\mu} \frac{\partial p}{\partial z} \right) = \frac{U}{2} \frac{\partial h}{\partial x} \frac{\partial h}{\partial t}$$

$$\frac{\partial h}{\partial t} \sim \Delta \dot{x}_i$$

Reduced Order Model / Response Surface



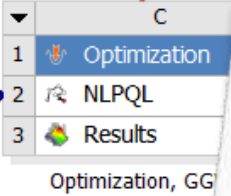
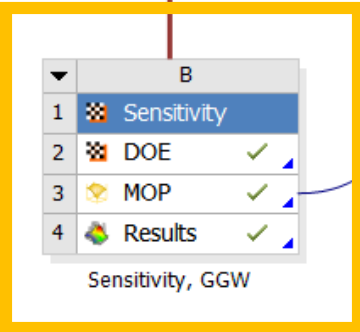
Parameter Set

Input:

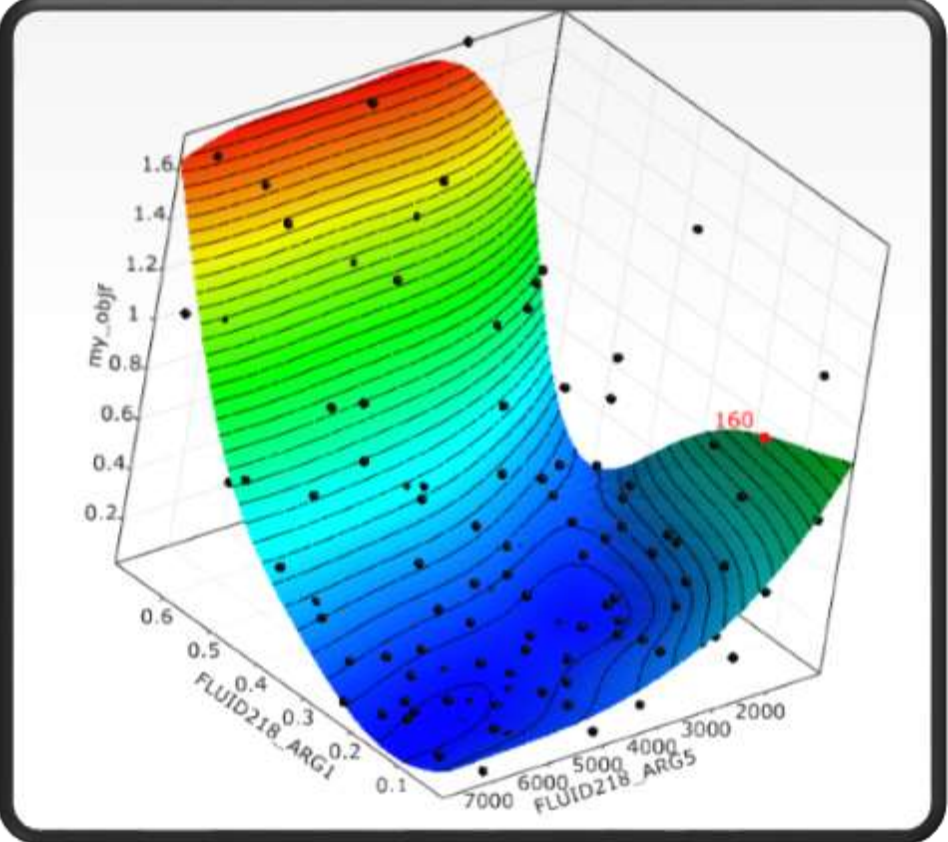
- Eccentricity
- Attitude Angle
- Rotational Speed
- Equilibrium Force (see later)

Output:

- Force X,Y
- Sommerfeld-Number
- Equilibrium Objective (see later)



Input Parameters		
Static Structural (A1)		
P1	Rshaft	50
P2	Hbearing	30
P3	FLUID218 ARG1	0.5
P4	FLUID218 ARG2	-90
P5	FLUID218 ARG3	0
P6	FLUID218 ARG4	0
P9	FLUID218 ARG5	4000
P27	OBJECTIVE ARG1	1000
New input parameter		
	New name	New expression
Output Parameters		
Static Structural (A1)		
P7	my_fbx	4768.9
P8	my_fby	4935.5
P10	my_So	0.43692
P18	my_SoX	0.3036
P19	mv_SoY	0.31421



$$\text{Reaction Force} = f(\text{Eccentricity, Attitude Angle, ...})$$

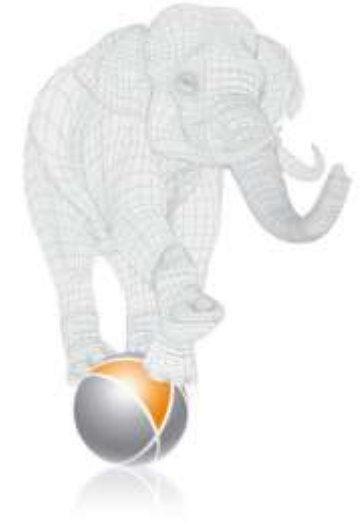
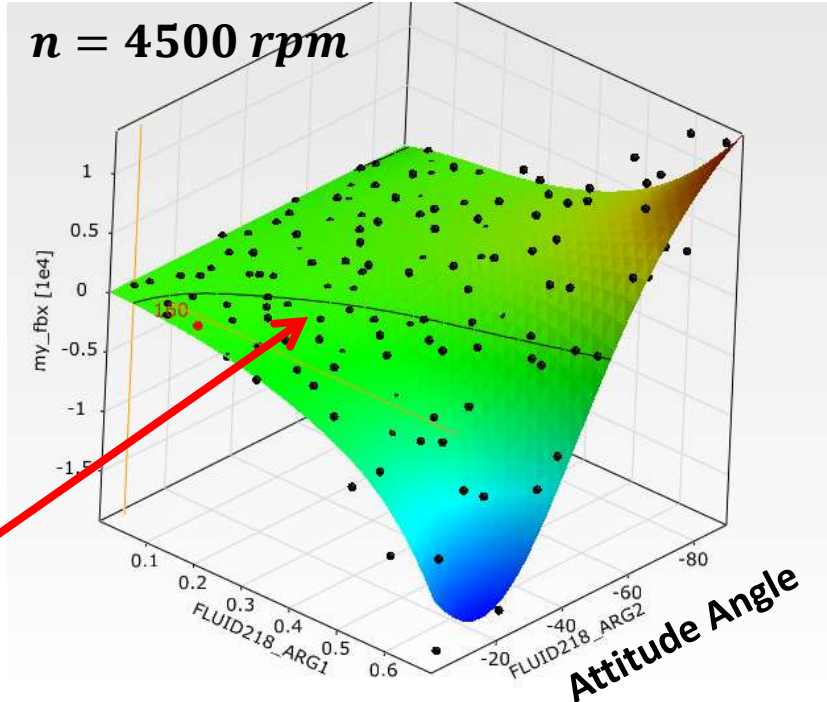
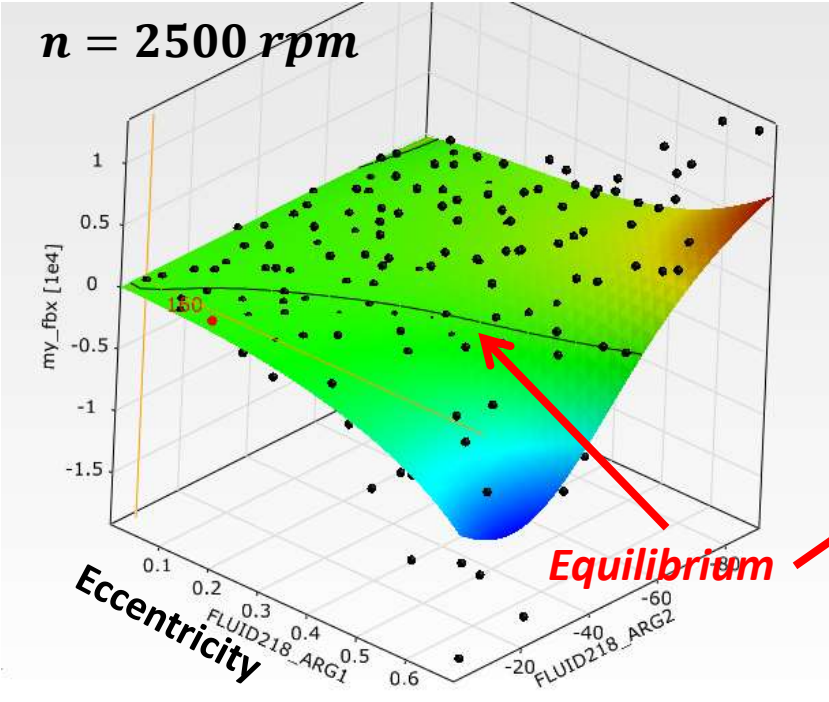
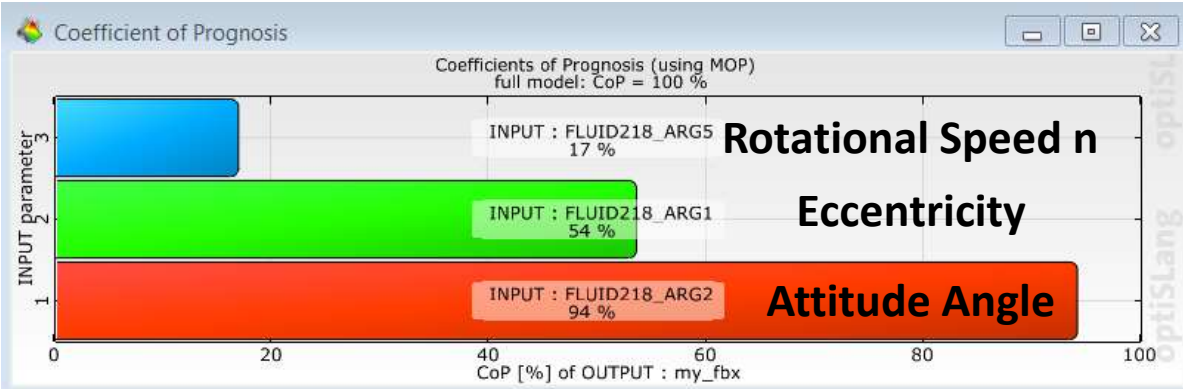
Response Surface = ROM
(Meta-Model of Optimal Prognosis)



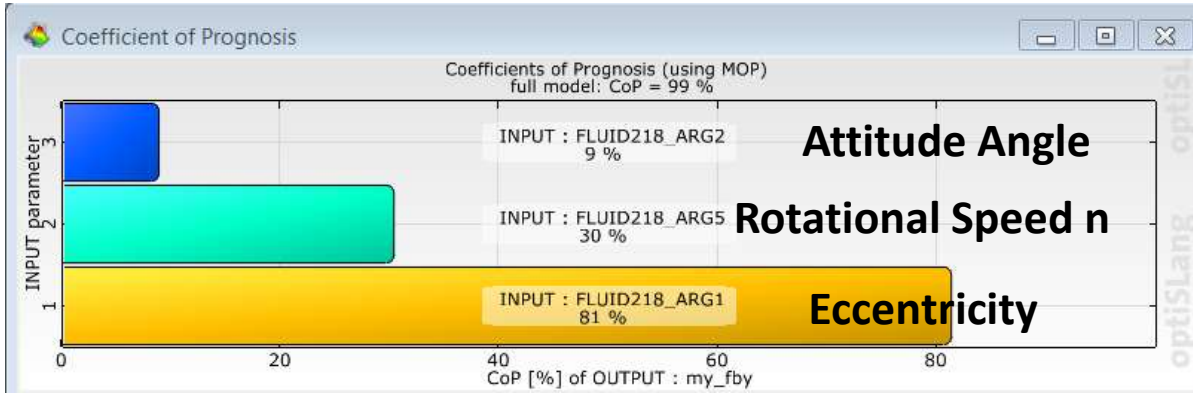
Reaction Forces X

Equilibrium: Reaction Force X=0

Reaction Force X depends on Eccentricity, Attitude Angle and Rotational Speed

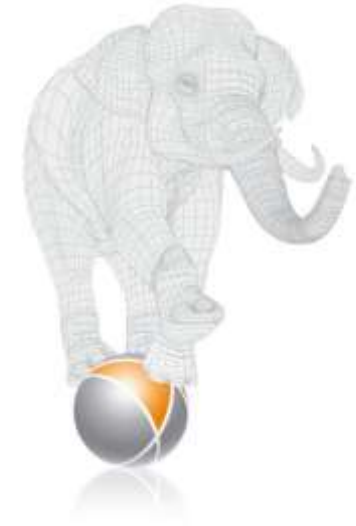
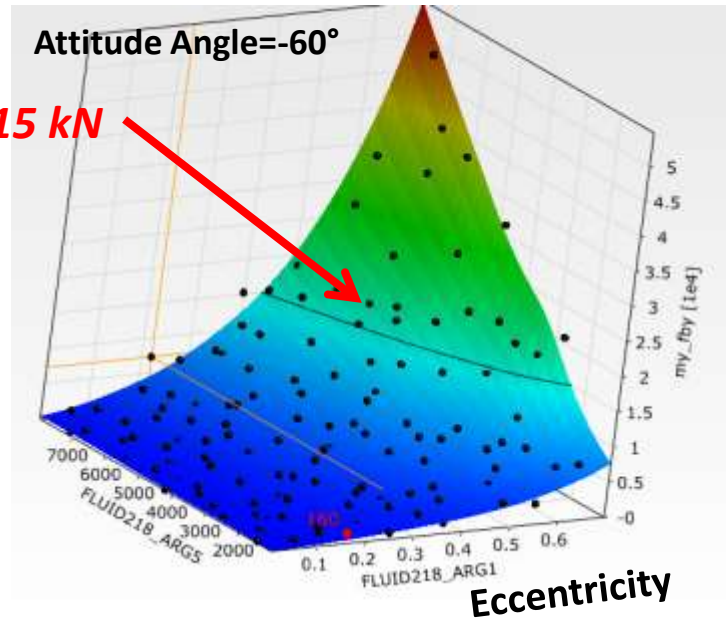
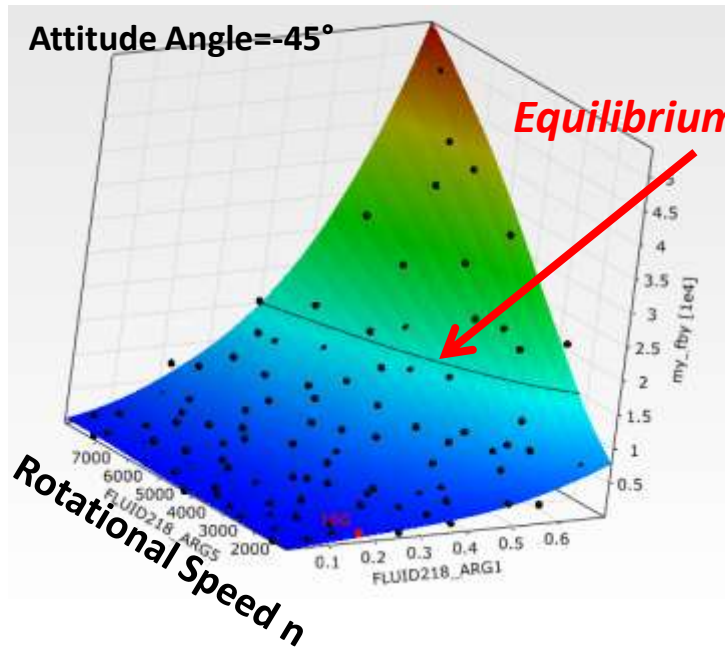


Reaction Force Y



Equilibrium Force = Reaction Force Y

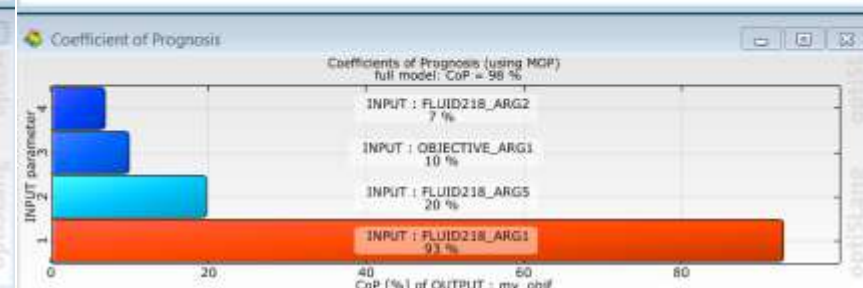
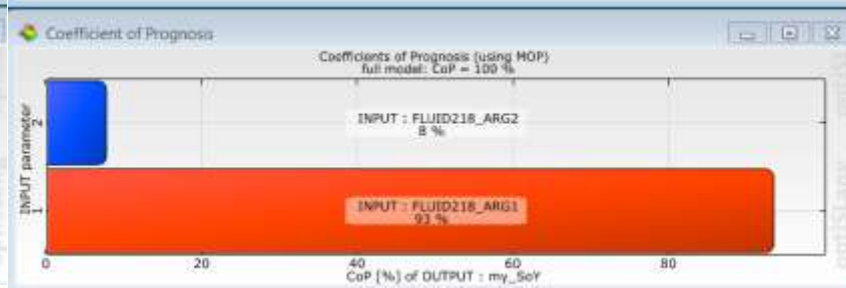
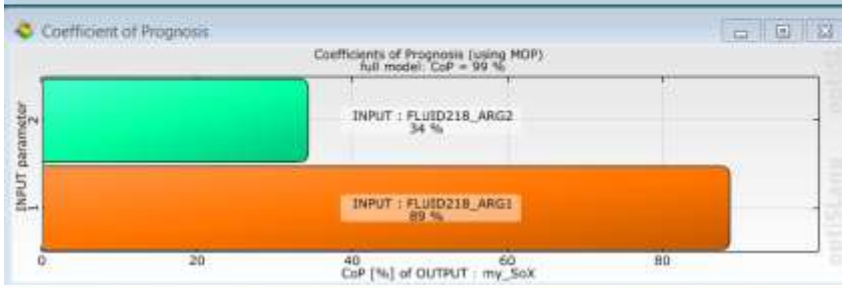
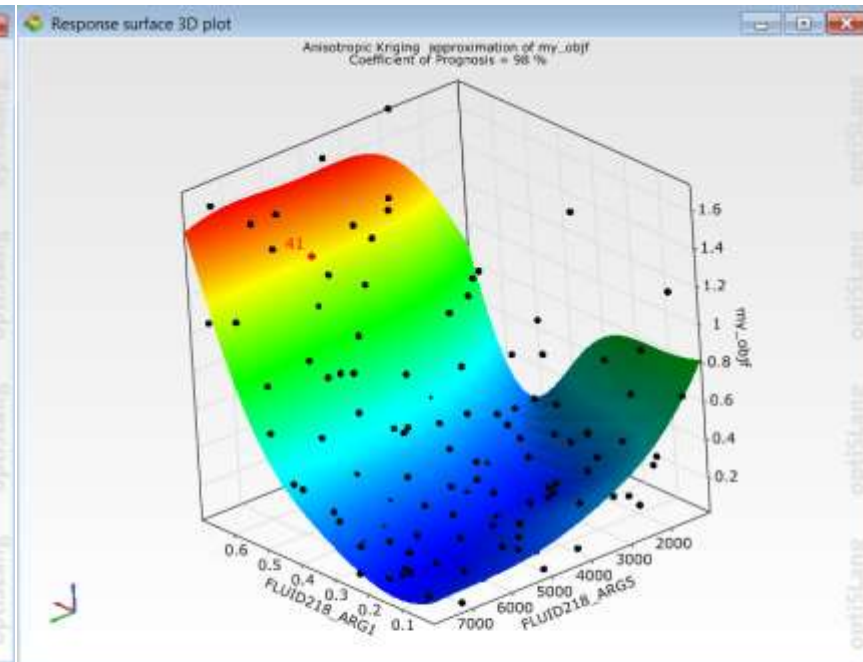
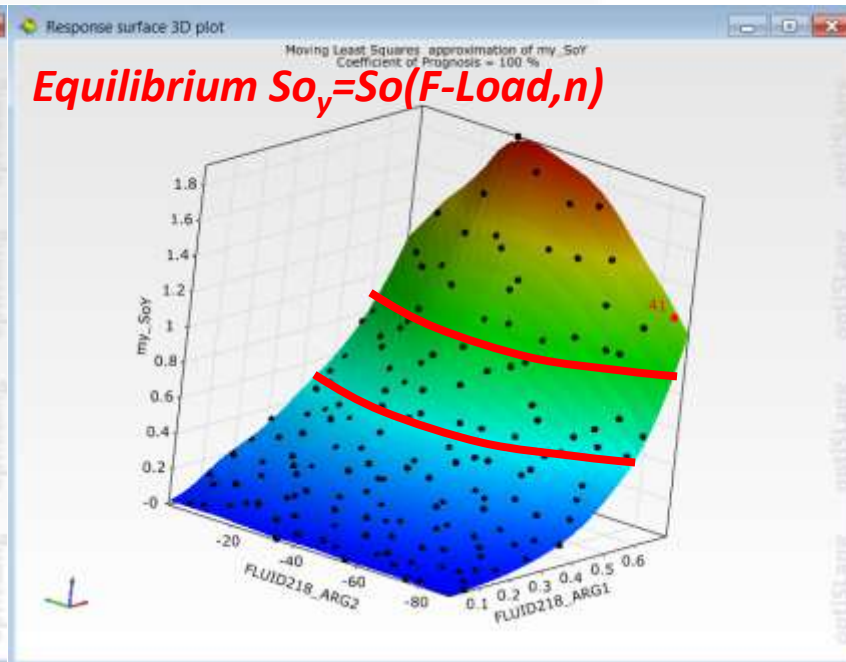
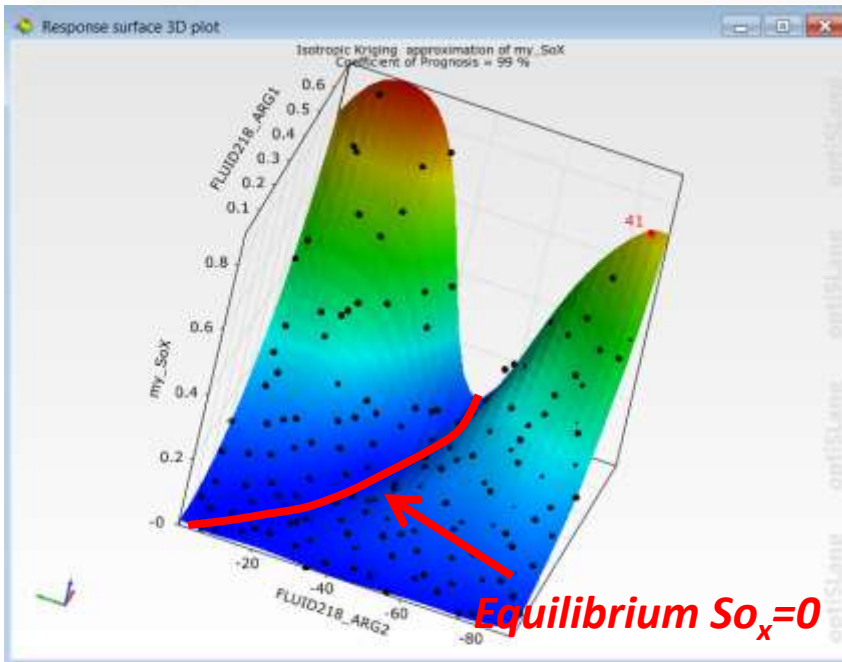
Reaction Force Y depends on Eccentricity, Attitude Angle and Rotational Speed



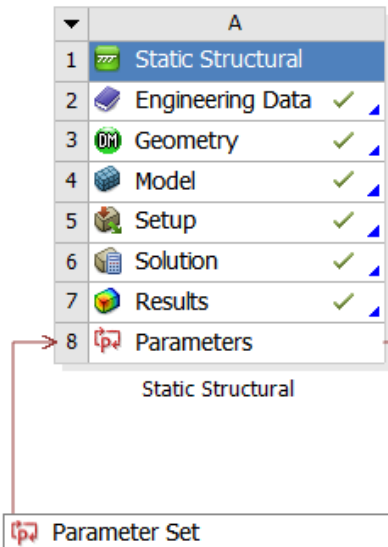
Sommerfeld Number $S_o = \frac{p_m \cdot \Psi^2}{\eta \cdot \omega} \sim \frac{F}{\Omega}$

Number of relevant Parameter reduced by non-dimensional Analysis
 S_{o_x} shows Line for all Equilibrium Positions
 S_{o_y} shows Equilibrium on Axis for non-dimensional Load

$$Objective \sim \frac{1}{\Omega} \sqrt{F_x^2 + (F_y - F_{Load})^2}$$



Find Equilibrium Position

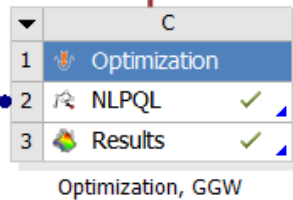
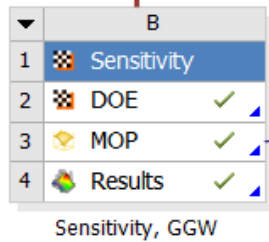


Input:

- Eccentricity = ?
- Attitude Angle = ?
- Rotational Speed = 5000 rpm
- Equilibrium Force = 7000 N

Optimization:

- Objective $\rightarrow 0$
- \rightarrow Equilibrium

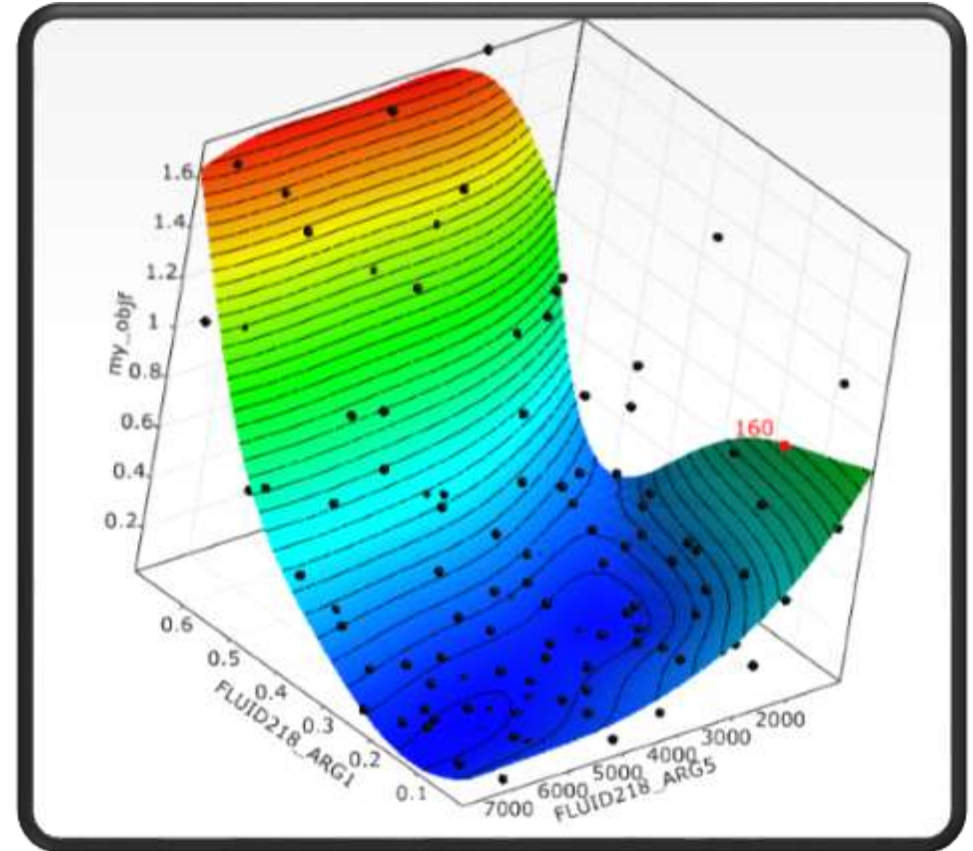


Optimization on Response Surface \rightarrow Equilibrium

Optimum/Equilibrium is validated by Simulation!!!

```
my_objf (calculated)
0.0528057
my_objf (MOP)
0.0626903
```

Relative Difference
0.5%
CoP = 98%



Reaction Force = $f(\text{Eccentricity, Attitude Angle, ...})$

optiSLang Usability

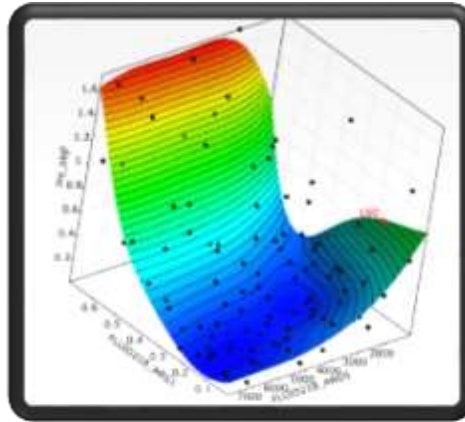
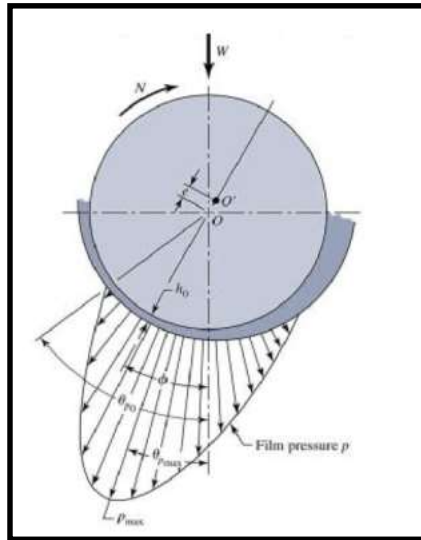
The screenshot displays the optiSLang 6.0 software interface. On the left, an Excel spreadsheet shows a table of results for various parameters and objectives. The table is color-coded, with red indicating high values and blue indicating low values. A yellow callout box with black text points to the 'Run MOP solver' button in the MOP solver panel on the right. The callout text reads: 'Push-Button Import of Meta-Model Additional Calculation in Excel with MOP-Solver'. The MOP solver panel includes fields for the metamodel file path, checkboxes for 'Write CoP Matrix' and 'Extrapolation', and a 'Run MOP solver' button. The Excel spreadsheet shows a formula bar with '=P25-P24' and a cell containing the value '11542.03'.

	FLUID218_ARG1	FLUID218_FLUID218	FLUID218	OBJECTIVE	Full model
my_objf	92.83%	6.72%	19.58%	9.77%	97.74%
my_obj7	74.80%	8.80%	55.30%		96.20%
my_obj6	84.77%	7.96%	42.33%		97.24%
my_obj5	94.79%	7.52%	28.18%		98.74%
my_obj4	95.17%	6.29%	15.53%		99.21%
my_obj3	97.72%	4.71%	7.28%		99.27%
my_obj2	98.81%	4.74%	2.45%		99.67%
my_obj1	97.88%	2.92%			98.82%
my_fby	81.31%	8.81%	30.31%		99.29%
my_fbx	53.53%	94.14%	16.86%		99.69%
my_SoY	93.40%	7.65%			99.88%
my_SoX	88.56%	34.20%			98.56%
my_So	97.40%	3.84%			99.88%

Parameters					Responses									
Lower Bound	0.0021875	-89.7188	1021.875	1018.75										
Upper Bound	0.6978125	-0.28125	7978.125	6981.25										
ID	FLUID218_ARG1	FLUID218	FLUID218	OBJECTIVE	my_So	my_SoX	my_SoY	my_fbx	my_fby	my_obj1	my_obj2	my_obj3	my_obj4	my_obj5
0	0.5	-45	4000	2000	0.772792	0.042314	0.765901	521.1379	11542.03	0.688097	0.637123	0.580445	0.517357	0.4339
dr	0.6	-45	4000	2000	1.200009	0.042897	1.190274	-610.375	18077.87	1.139645	1.068779	1.020984	0.951166	0.90030
dphi+	0.5	-40	4000	2000	0.797529	0.042123	0.791484	-415.378	11779.9	0.695755	0.662064	0.607944	0.541135	0.45761
dphi-	0.5	-50	4000	2000	0.745315	0.082218	0.733471	1396.035	11124.47	0.675668	0.609276	0.549736	0.491073	0.40955
FX-FX0	-1131.51258													
FY-FY0	=P25-P24													

Summary

Modelling



**Calculate Equilibrium:
Reduced Order Model is much
more efficient than 2-Way FSI !!!**

- Design of Experiments
- Variation of Eccentricity, Attitude Angle, ...
- Measure Reaction Force
- Response Surface is calculated (=ROM)
- Reaction Force = $f(\text{Eccentricity, Attitude Angle, ...})$
- Optimization to find
- Eccentricity, Attitude Angle, ...
- For given External Force
- Stiffness is Derivative of Response Surface
- Damping is calculated at Equilibrium

