Dynamic Simulation Modeling and Analysis of Under-sodium Fuel during In-vessel Transfer Motions

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Contents

Introduction

- What is the PGSFR in-vessel transfer system (IVTS)?
  - PGSFR is Prototype Gen-IV Sodium-cooled Fast Reactor, being developed by Korea Atomic Energy Research Institute.(KAERI)
  - IVTM carries a fuel assembly(FA) under sodium to perform refueling with the reactor lid closed, because the sodium reacts with air and water.

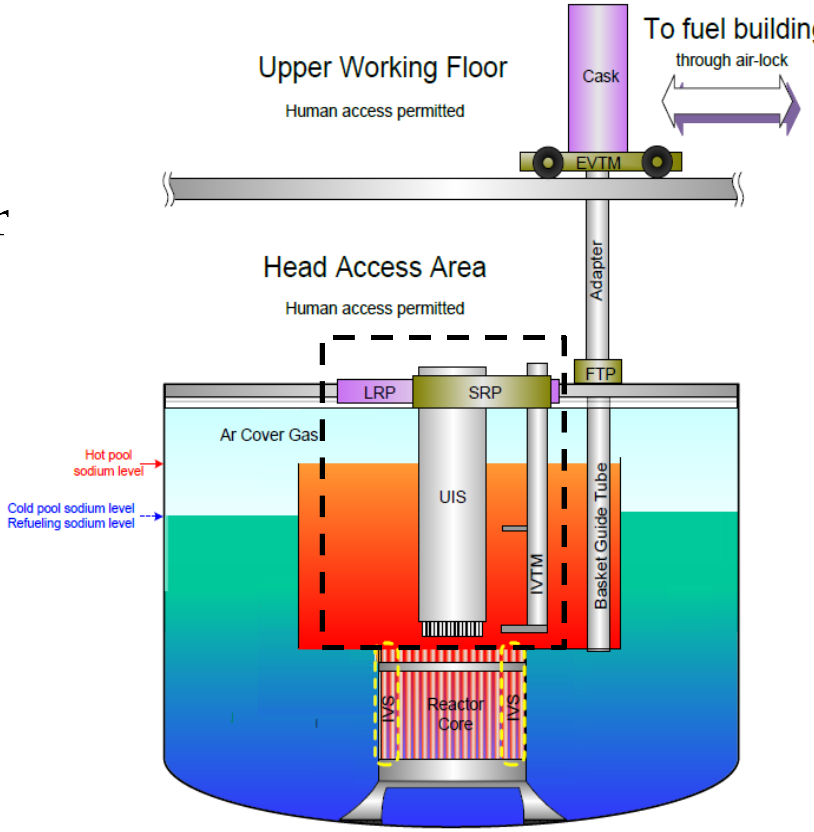


Fig.1 The overview of PGSFR fuel handling with only IVS

Introduction

- Why is the dynamic analysis needed?
  - The structural damage due to hydrodynamic forces needs to be quantified through the dynamic analysis.
  - FA deflection can be analyzed by performing the dynamic analysis.
- Contents of this paper.
  - A dynamic simulation model without applying the fluid domain.
  - A commercial dynamic simulator was used for demonstration.

Introduction

- Simulating a fuel handling process by a standard four-bar linkage system.
  - The refueling mechanism can be analyzed in position, velocity and acceleration, and possible solution can be synthesized.
  - CAD-based synthesis study of all the possible trajectories can be considered.

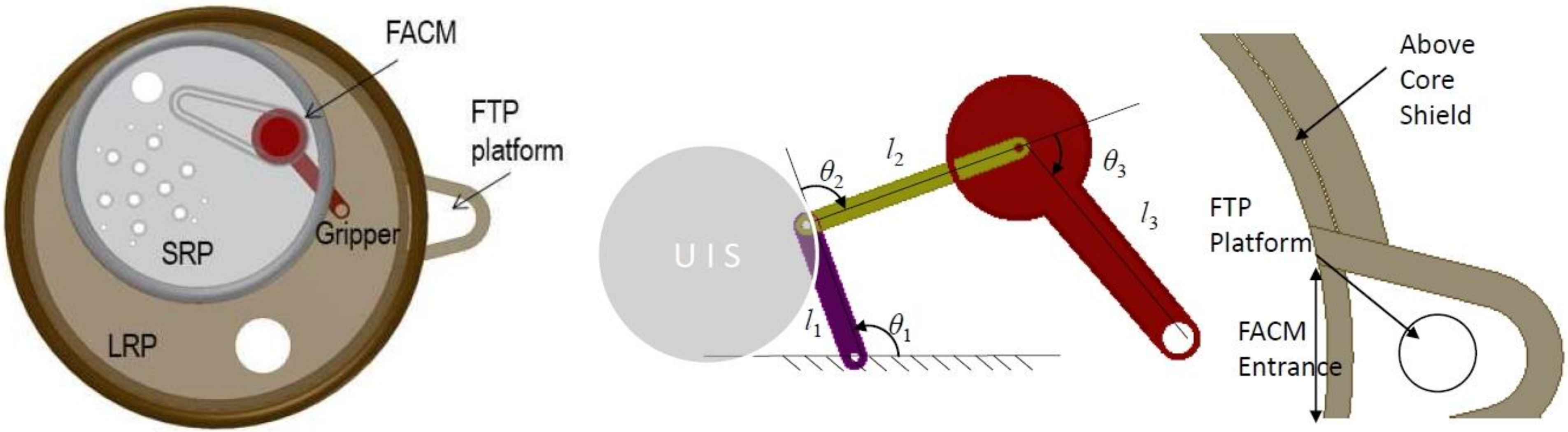


Fig.2 Top view of PGSFR IVTS

Problem formulation

- Scope of Analysis
  - Among many FA transfer moves, one of the most critical transition from/ to core to/ from the fuel transfer port.(CF move)

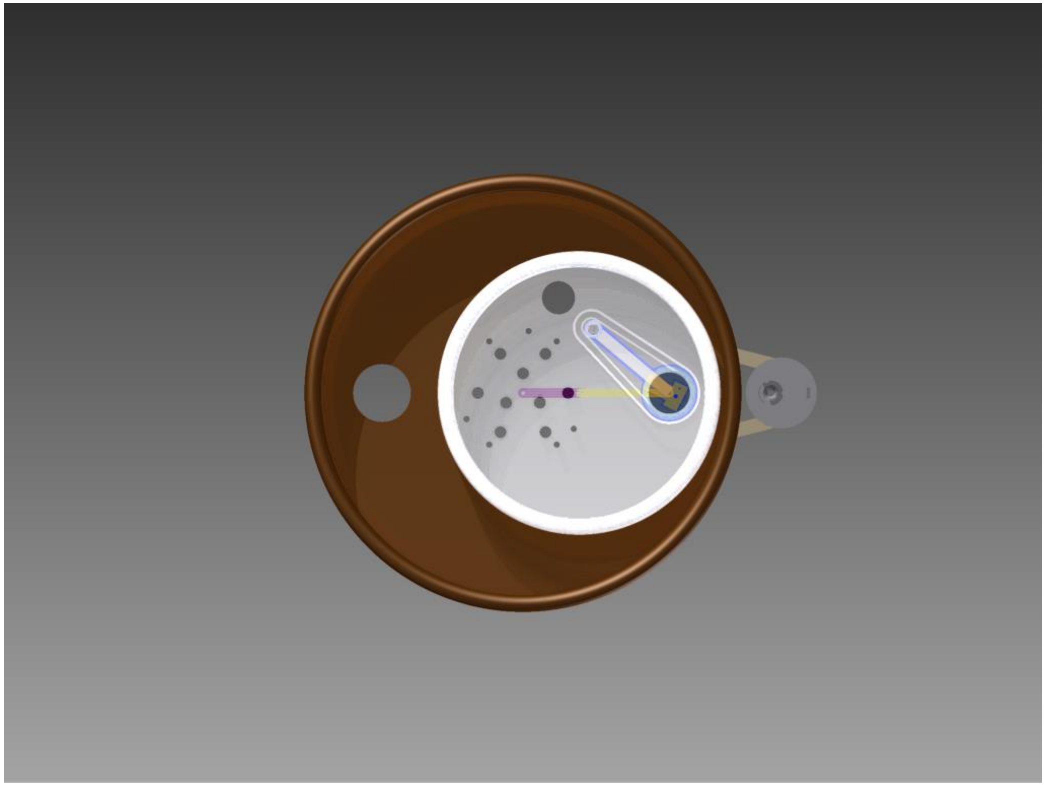


Fig.3 An example of refueling procedure

Problem formulation

- System description
  - The FA deflection due to its motions can be described as a cantilever beam supported at one end.

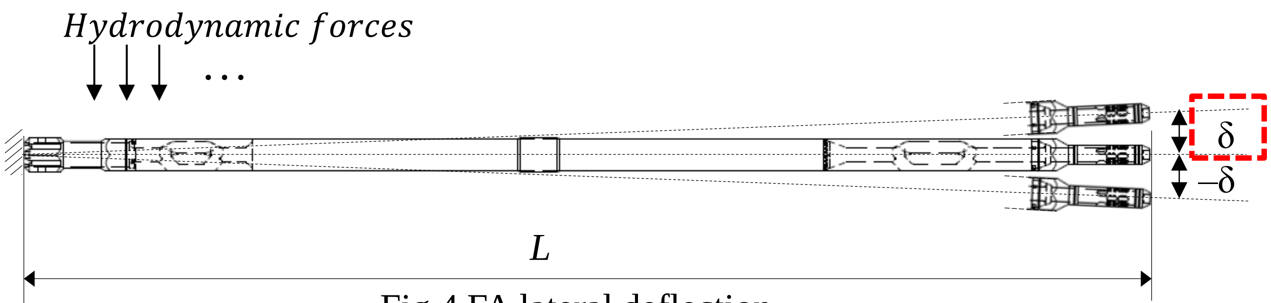


Fig.4 FA lateral deflection

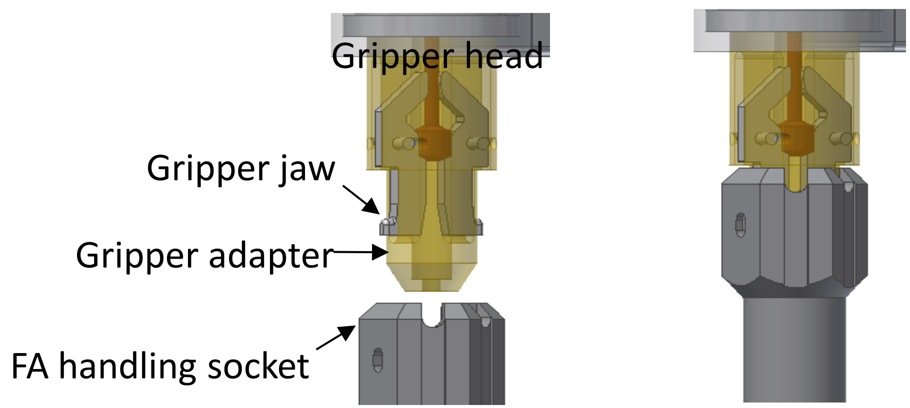


Fig.5 FA gripper in a disengaged view(left), and FA engaged in the gripper (right)

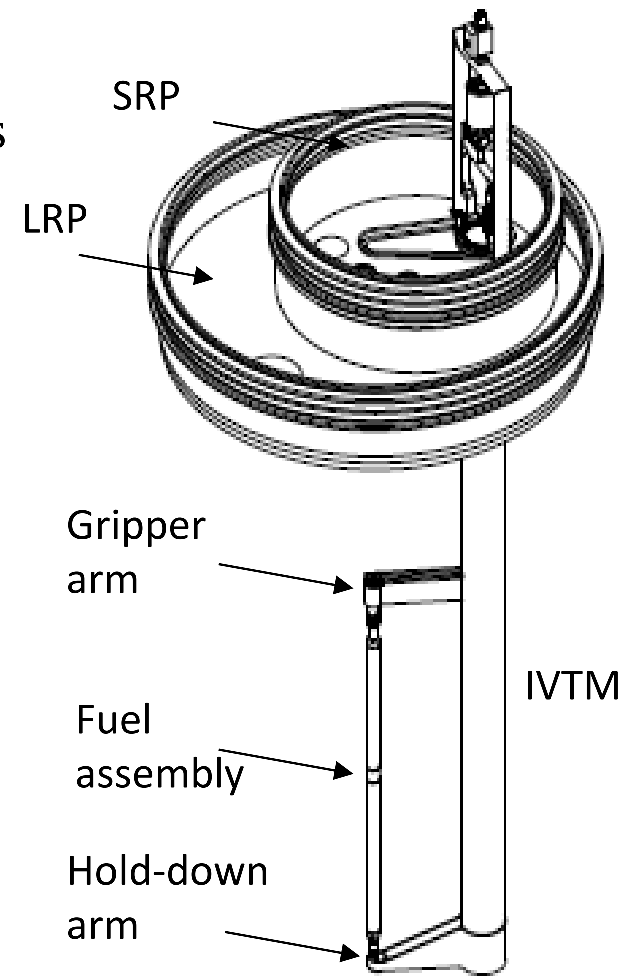


Fig.6 PGSFR IVTM design concept

Problem formulation

- δ : deflection of the cantilever beam
- w: uniform load
- L: length
- E: young's modulus
- I: moment of inertia of the cantilever beam
- F_e: the equivalent force
- K_e: the equivalent stiffness
- f_1: the natural frequency of the cantilever beam
- m_e: the equivalent mass
- δ_e: relative displacement of the FA tip to the gripper as a function of time
- C : the damping coefficient
- F_{hydro}: hydrodynamic force
- ρ_s: sodium density
- C_m: the inertial coefficient
- d : diameter of the FA
- C_d: the drag coefficient

▪ Equation of motion

➢ The FA body can be substituted as a point mass v
damping elements.

☞ Equation

$$\delta = -\frac{wL^4}{8EI} \quad (1)$$

$$WL = F_e \quad (2)$$

$$F = K\delta \quad (3)$$

$$K_e = \frac{8EI}{L^3} \quad (4)$$

$$f_1 = \sqrt{\frac{K_e}{m_e}} \quad \text{and} \quad m_e = \frac{k_e}{f_1^2} \quad (5)$$

$$m_e\ddot{\delta}_e + C\dot{\delta}_e + k_e\delta_e = F_{hydro} \quad (6)$$

$$F_{hydro}(t) = \frac{\pi}{4}\rho_s C_m d^2\ddot{\delta} + \frac{1}{2}\rho_s C_d d\dot{\delta}^2 \quad (7)$$

➡ Morrison's equation

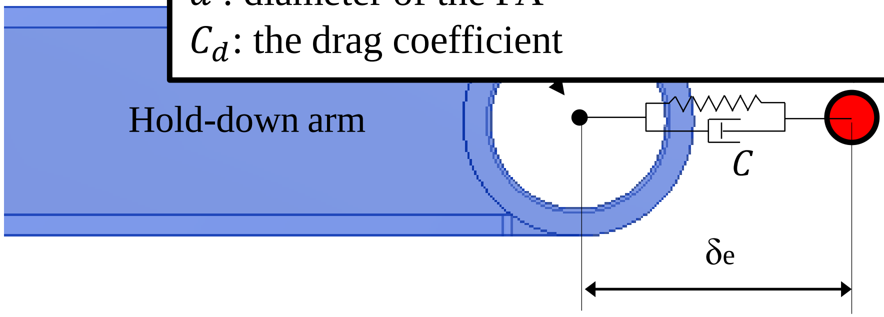


Fig.7 FA modeling as a point mass to render the tip deflection in simulation (top view)

Simulation test

- Simulation process
  - Two simulation round are performed in series.

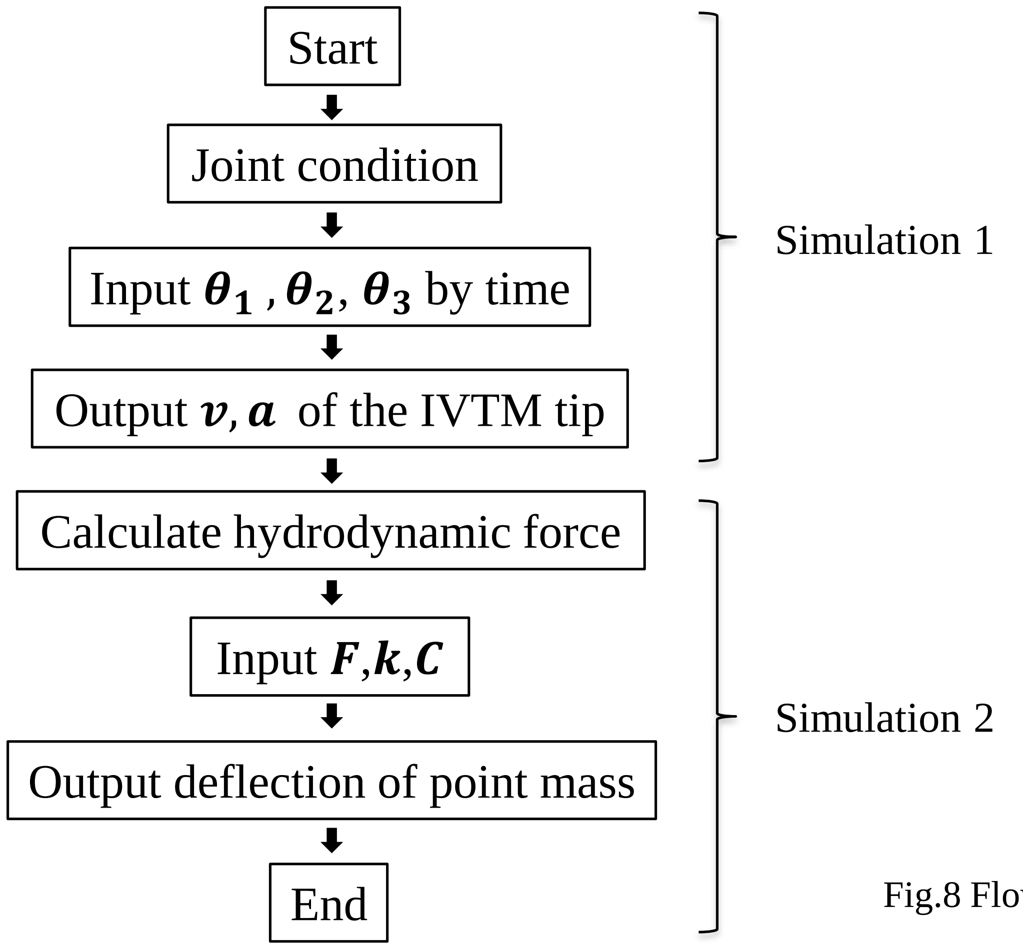


Fig.8 Flow chart of the dynamic simulation

Simulation test

- Simulation 1

  ➢ The first run is a procedure to obtain positions, velocities and accelerations of the hold-down arm for the whole discrete step for one transfer procedure.

☞ Input $\boldsymbol{\theta_1}$, $\boldsymbol{\theta_2}$, $\boldsymbol{\theta_3}$ by time

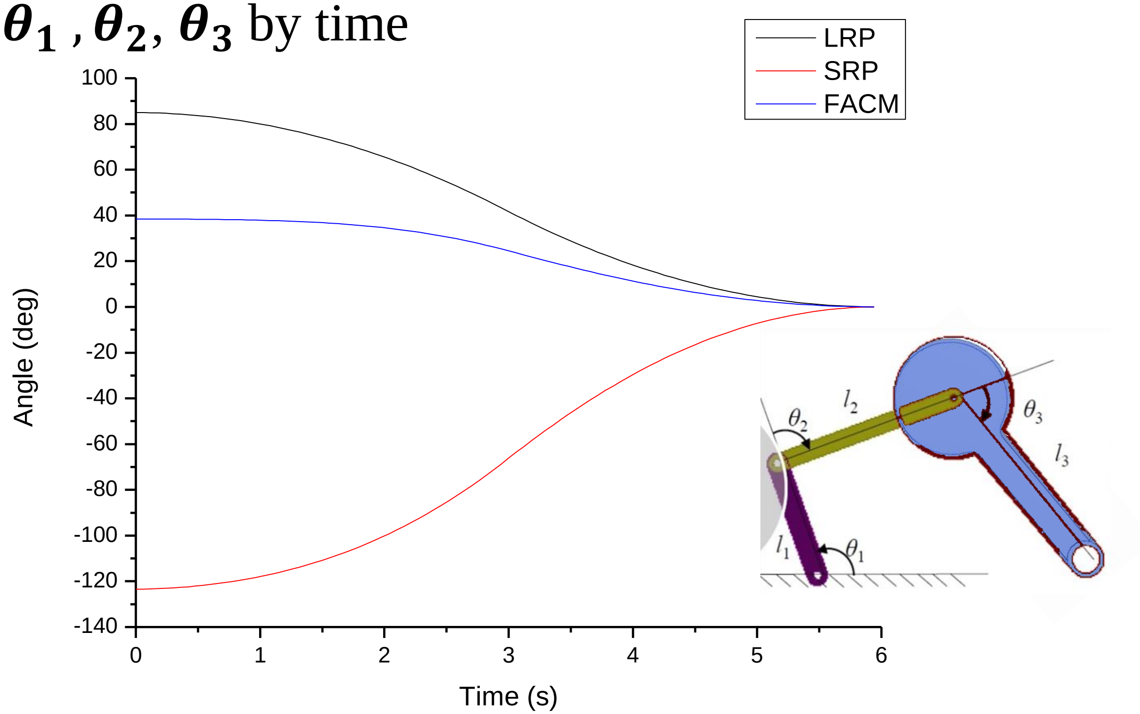
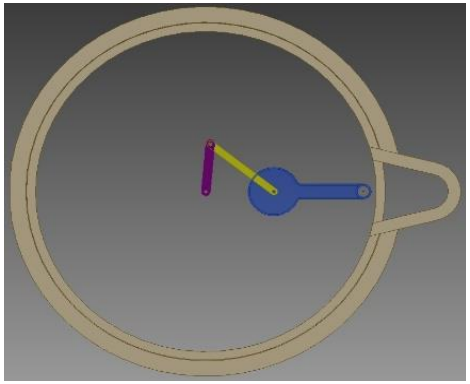
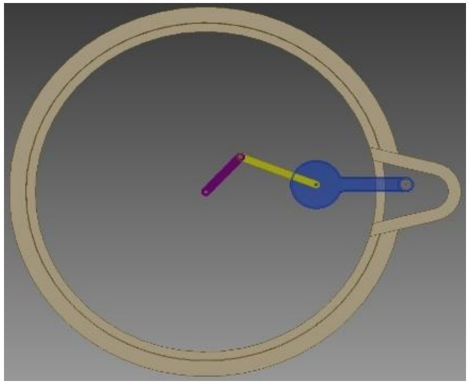
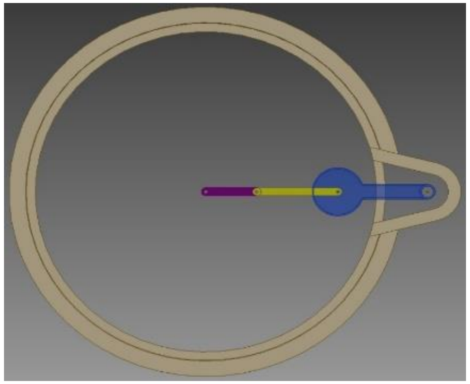


Fig.9 FA Insertion FTP platform ($V_{avg,LRP} = 2.32\ rpm$)







Simulation test

- Simulation 1

  - The first run is a procedure to obtain positions, velocities and accelerations of the hold-down arm for the whole discrete step for one transfer procedure.

☞ Input $\boldsymbol{\theta_1}$, $\boldsymbol{\theta_2}$, $\boldsymbol{\theta_3}$ by time

Modeling and constraint

↓

Set $\boldsymbol{\theta_1}$, $\boldsymbol{\theta_2}$, $\boldsymbol{\theta_3}$ by time

↓

Start simulation

↓

Obtain velocities and accelerations

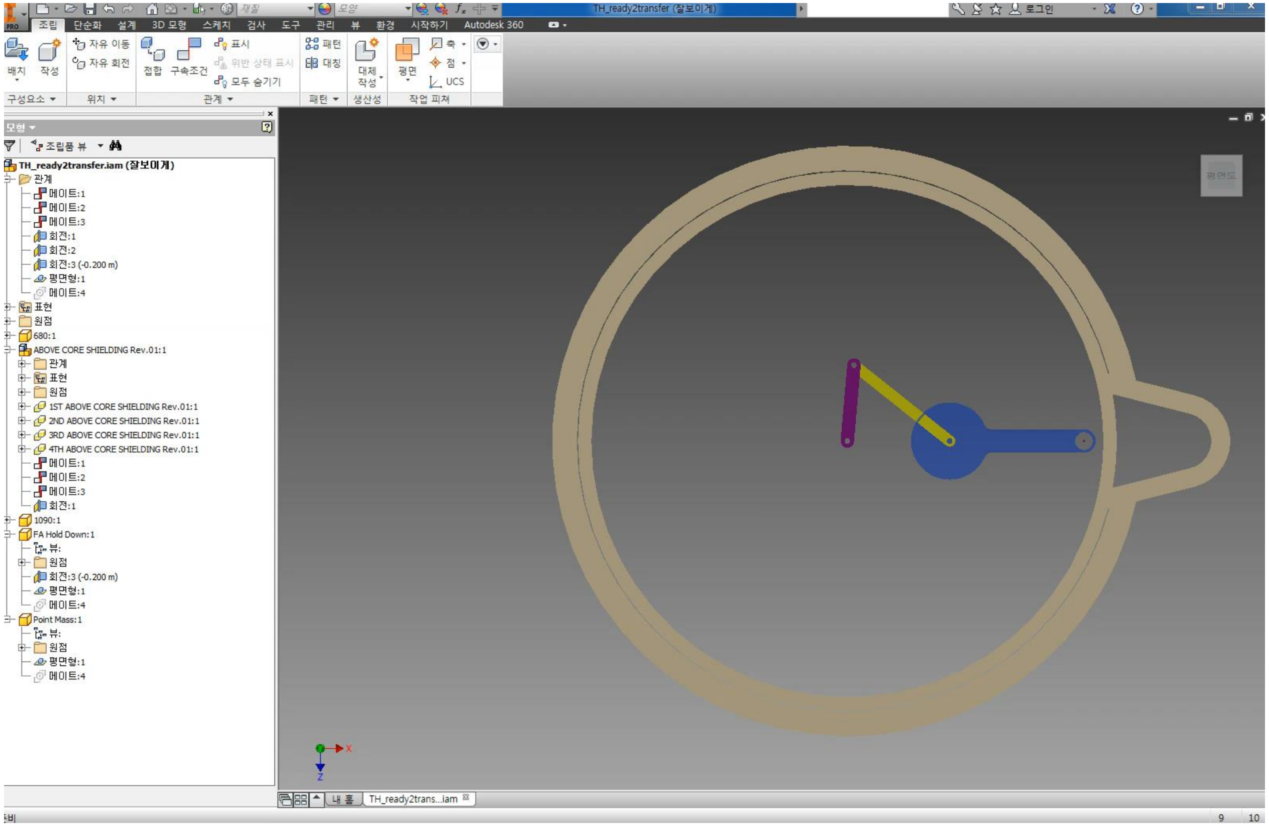


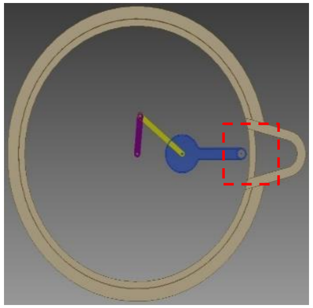
Fig.10 Setting procedure of 1st simulation

Simulation test

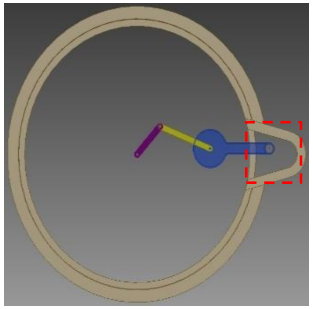
- Simulation 1

  ➢ The first run is a procedure to obtain positions, velocities and accelerations of the hold-down arm for the whole discrete step for one transfer procedure.

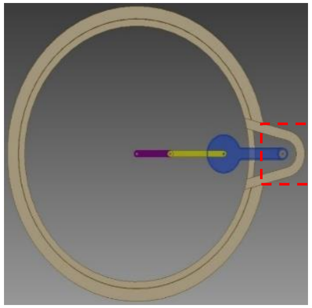
☞ Output $\boldsymbol{v}, \boldsymbol{a}$ of the IVTM tip



1st



2nd



3rd

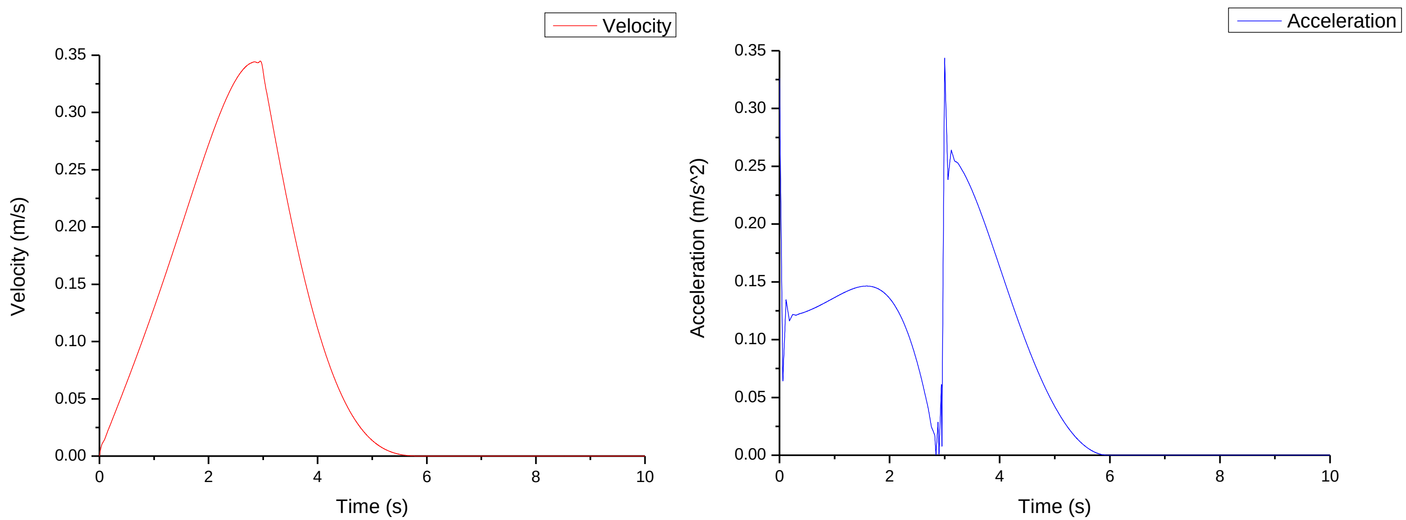


Fig.11 Velocity and acceleration induced by transfer motions

Simulation test

▪ Simulation 2

- ➢ Hydrodynamic forces are calculated by the IVTM arm tip velocity, and acceleration.

☞ Calculate hydrodynamic force

$$F_{hydro} = f(v^2, a)$$

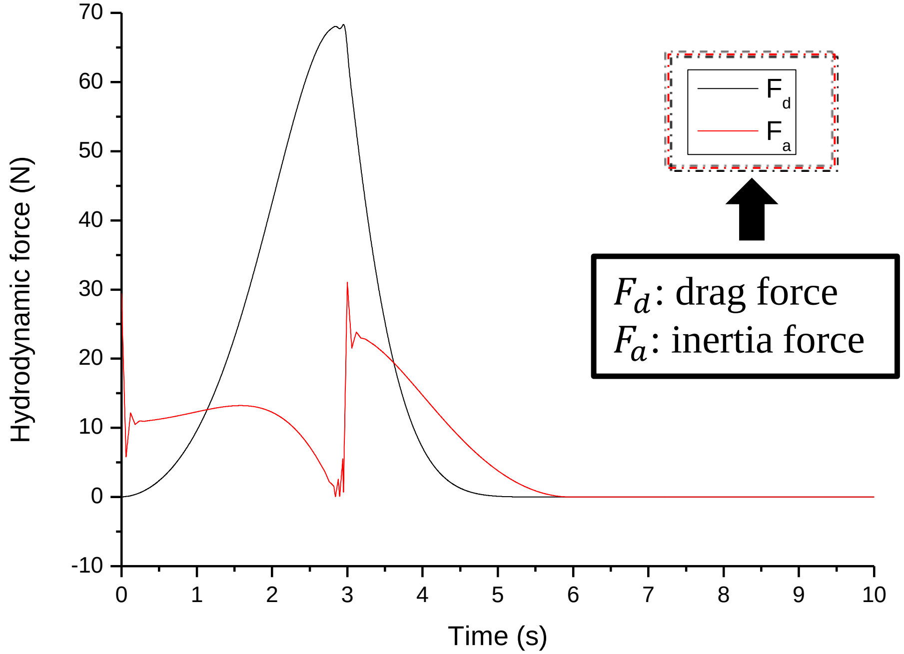
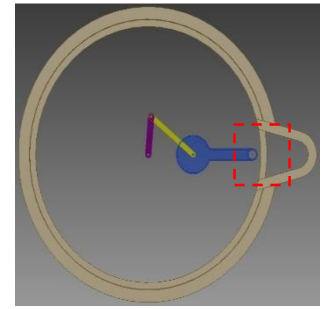
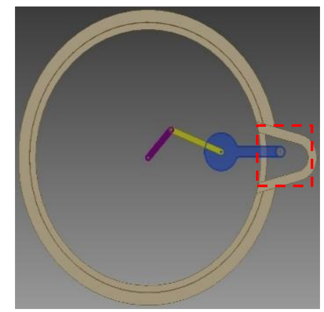


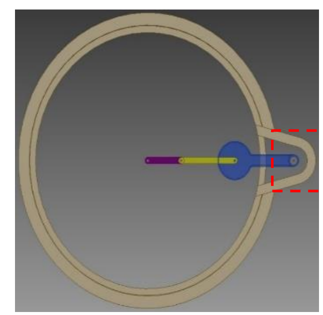
Fig.12 Hydrodynamic forces calculated by the velocity and acceleration



1st



2nd



3rd

Simulation test

- Simulation 2
  - ➢ By running the second round of simulation for the same CF move, the deflections of the FA are calculated.

☞ Input ***F*,*k*,*C***

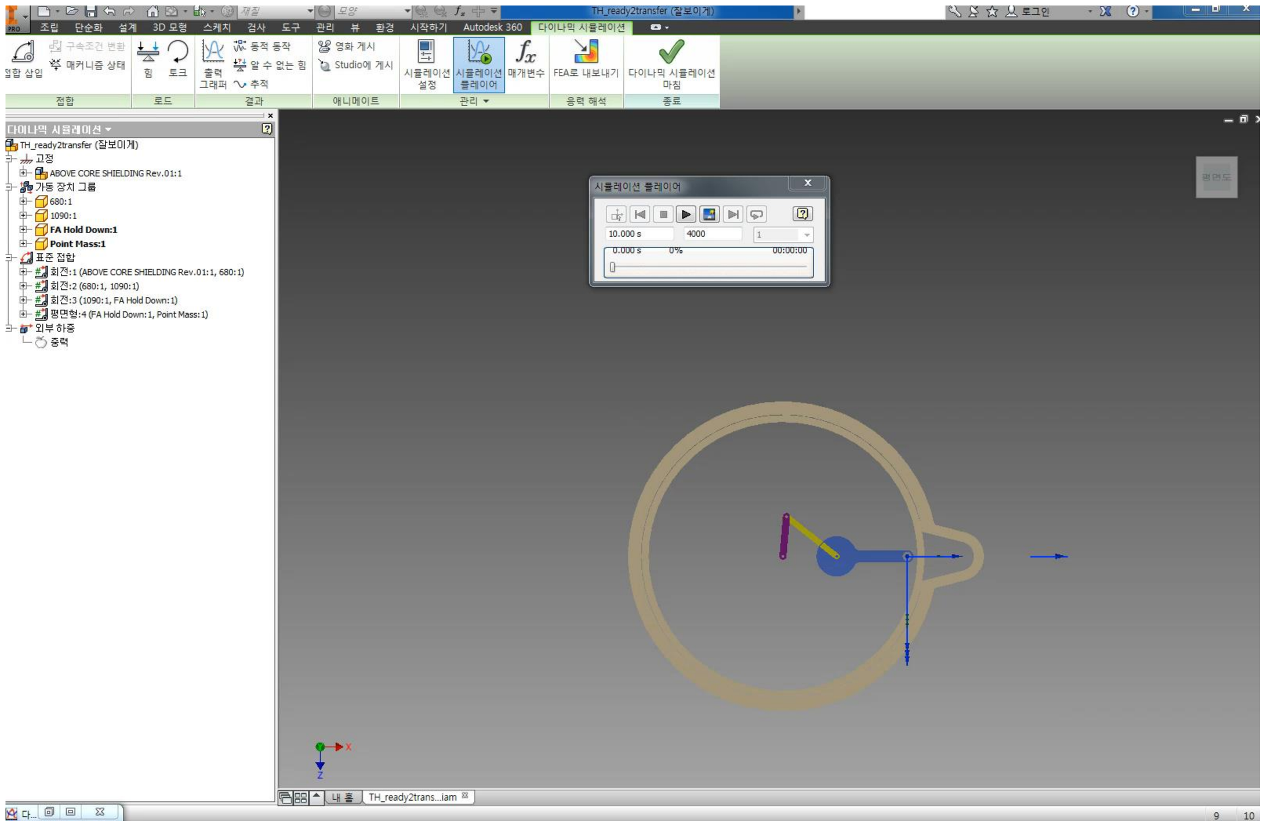


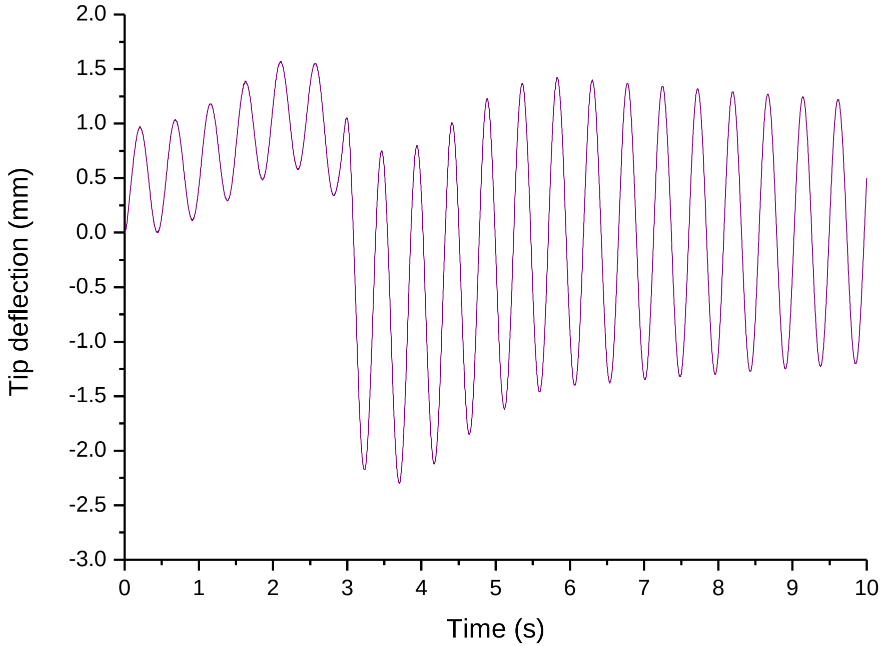
Fig.13 Setting procedure of 2nd simulation

Simulation test

- Simulation 2

  ➢ By running the second round of simulation for the same CF move, the deflections of the FA are calculated.

☞ Output deflection of point mass



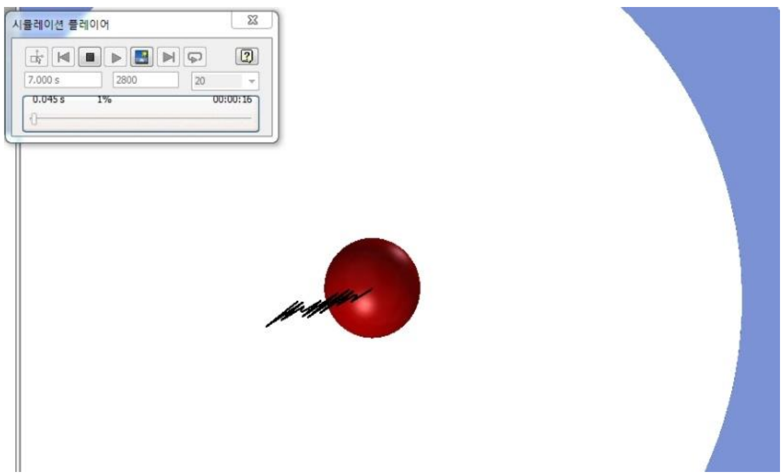


Fig.14 Tip deflections of the transferred FA

Test results

- Results

  - Case studies that the LRP rotation speed of 2 ~ 7 rpm are performed to obtain maximum deflection & total vibration/time of each cases.

☞ Output deflection of point mass

Table.1 Design parameters for the study

End time [sec]	SRP [deg/s]	LRP [deg/s]	FACM [deg/s]	LRP avg. rpm
3	-28.3	41.1	-12.8	6.85
5	-17	24.7	-7.7	4.12
7	-12.3	17.8	-5.5	2.97
9	-9.5	13.9	-4.3	2.32

Table.2 Case study results

End time (s)	Total variation [mm-sec]	Freq. [Hz]	Max. deflection [mm]
3	1.01	3.41	4.64
5	0.70	3.37	1.8
7	0.33	3.35	0.89
9	0.20	3.40	0.57

Conclusions

- For PGSFR, **the in-vessel transfer system**, which employs DRP and IVTM, and its refueling procedure **were briefly reviewed**.

- For the application of FA deformations in PGSFR refueling, an efficient dynamic simulation model of an FA attached to the gripper for in-vessel transfer motions considering hydrodynamic forces was proposed as **a simple spring-mass-damper system**.

- The simulation effectively reflected fluid forces **without the fluid volume** in the setting, and so it runs effortlessly (at **a low computational cost**).

- A case study that the gripper enters the fuel transfer port with the LRP rotation speed of **4.12 rpm** was given for a demonstration. The hydrodynamic forces were able to be considered by the intermediate inputs, and a range of **1.8 mm tip deflections** was obtained. This oscillation range was determined as **an acceptable level**.

Thank you for your attention