Dynamic Analysis of an In-Vessel Transfer System in Prototype Gen-IV Sodium-cooled Fast Reactor

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Abstract: A Sodium-cooled Fast Reactor (SFR) as a generation IV (Gen-IV) reactor design employs one of the most advanced refueling methods. These refueling systems are mostly controlled automatically using state-of-the-art sensors and actuators. The in-vessel fuel transfer system (IVTS) refers to a fuel handling machine and driving mechanism in the reactor vessel, and IVTS is the most critical in that accurate positioning and stable driving make the reactor operation reliable for a few decades. Sub-components that IVTS comprises are only the moving parts in the vessel, and dynamic analysis of the IVTS components is of great importance for the successful SFR design and operation. This paper considers IVTS dynamic simulations of a Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR). For PGSFR IVTS, double rotating plugs (DRP) and a fixed-arm charge machine (FACM) are deployed for the refueling system. This paper proposes an efficient modeling approach to reflect the full 3D dynamic behavior of PGSFR IVTS. The modeling task engages in formulating a standard robot manipulator problem set for PGSFR IVTS. Based on the modeling with a coordinate system, its kinematics analysis yielded strategic path planning. A simplified dynamic simulation model was used as a spring-mass-damper system. The simulation method proposed reflected hydrodynamic forces without employing the fluid domain. The parametric study on an angular velocity of up to 7 rpm of each actuator was carried out through a dynamic simulation. The motion induced vibration was also analyzed to set up a safe refueling procedure. The study concluded that a rotational speed of up to approximately 2 rpm of all rotational components can be allowed based on the tip displacement analysis.

Keyword: In-vessel fuel Transfer System (IVTS), Dynamic Analysis, Dynamic Simulation, Sodium-cooled Fast Reactor (SFR), Velocity Parametric Study, SFR Refueling

1 Introduction

The refueling is a procedure to replace a spent or damaged nuclear fuel with a fresh fuel for the power generation of nuclear fissile reactor plants. Dedicated fuel handling equipment and a refueling process is required. Particularly, Sodium-cooled Fast Reactors (SFRs) have challenges in refueling, because the sodium as a coolant is liquid at high temperature (> 98 °C), opaque, and rapidly reacts with air and water producing heat and fire. Therefore, SFRs maintain the pressure boundary between air and inert regions all the time even during the refueling period. In this reason, refueling in modern SFRs is performed with the reactor vessel head (or cover) closed. For this task, most SFRs employ an in-vessel transfer machine (IVTM)[1]. IVTM is a refueling system to grip, release, and transport a fuel assembly (FA) in a reactor vessel. In SFRs, because IVTM is operated in a vessel without removing the coolant, IVTM carries an FA under sodium, and motions in sodium can cause adverse effects on the FA and/or IVTM structures due to viscous hydrodynamic forces. An excessive viscous force caused by a fast motion is not desirable in considerations of structural damage. Moreover, the induced lateral deflection of an FA needs to be analyzed for the position accuracy of the refueling process.

A spent fuel transported under sodium is a fluid-immersed object, which vibration induced by hydrodynamic forces has been studied. Blevins[4] described a general governing equation that considers fluid drag forces to an under-fluid cylinder as a damping element. The equation can be used for a low Reynolds number flow with high viscosity.

Recently, a method to run a simulation on fluid-structure interaction (FSI) has been studied [5]. In the paper, a series of numerical simulations were performed for a vibrating fuel rod in a nuclear reactor using the fluid induced vibration (FIV) method. This method makes it possible to calculate all the forces loaded on the fuel rod and fluid-field effects by the fuel rod motions. However, it requires high computational power, and it takes a long time to get results. Shah et al.[6] addressed a vibration control problem of the refueling machine by dynamic simulation. In the paper, authors considered hydraulic forces by using the Morison equation[7]. The finite difference method (FDM) was implemented for numerical analysis to solve the rod deflection. And the simulation was verified by experimental tests. In [6], the hydrodynamic force was simply treated by empirical equations to implement vibrations of the fuel rod in the simulation.

In this paper, the dynamic behavior of an SFR FA transferred by an IVTM under sodium fluid is considered. To the end, adopting equations in [6], an efficient dynamic simulation method of an FA attached to the IVTM gripper in a hydrodynamic environment is proposed. This method reflects fluid drag forces without applying the fluid volume (or fluid domain) in the simulation. Also, the equation of motion for an FA is developed as a simple spring-mass-damper system. The properties of the sodium coolant and FA structure for a Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) are applied to the simulation. The simulation can predict the dynamic behavior of an FA transferred under sodium, and thus mechanical effects on an FA can be evaluated with an efficient calculation method. First, the PGSFR refueling system is briefly introduced in section 2. The simulation method for a transferred FA is explained in section 3. Simulation results and discussion are in section 4. This paper wraps up with conclusions in section 5.

2 PGSFR Refueling System

SFR research in Korea has set out to demonstrate advancements of PGSFR, which construction by 2028 had been planned, and its approval by 2020[2]. For PGSFR, being developed by Korea Atomic Energy Research Institute (KAERI), the concept of the refueling system design is illustrated in Fig. 1. A fixed arm charge machine (FACM) is designed as an IVTM shown in Fig. 2. The FACM gripper (shown in Fig. 3) can access to whole core FAs in combination of rotating small and large rotatable plugs (SRP and LRP, respectively), and it picks up an FA one by one. FACM is basically two (upper and lower) cantilever beams attached to a vertical main support column (see Fig. 2). FACM has 5 degrees of freedom: gripper jaw open/close, gripper yaw rotation, FACM yaw 360° rotation, gripper up/down, and hold-down movement to spread neighboring FAs from the target FA.

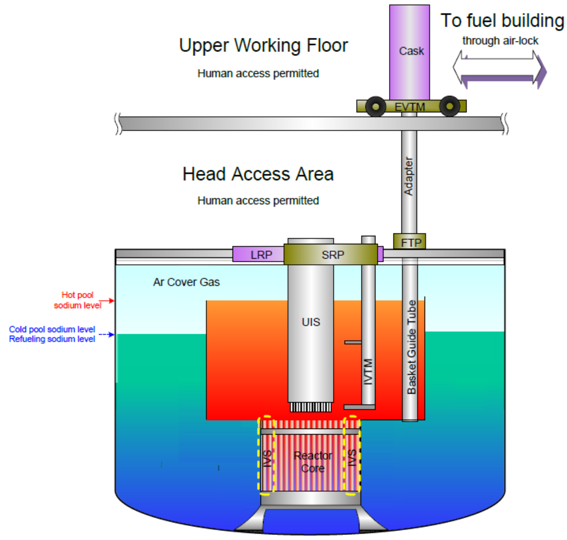

Fig. 1 The overview of PGSFR fuel handling with IVS

DRP is composed of SRP and LRP where SRP is offset by 680 mm from the center of LRP. The offset rotation of SRP makes FACM accessible to the whole core area by combination of LRP and FACM rotations. DRP structurally supports IVTM and other primary components such as control rod drive machine and upper internal structure.

A spent FA gripped by FACM is moved to the cask located in the upper working floor through the gate valve of the fuel transfer port (FTP) in the reactor head guided by the basket guide tube. Self-

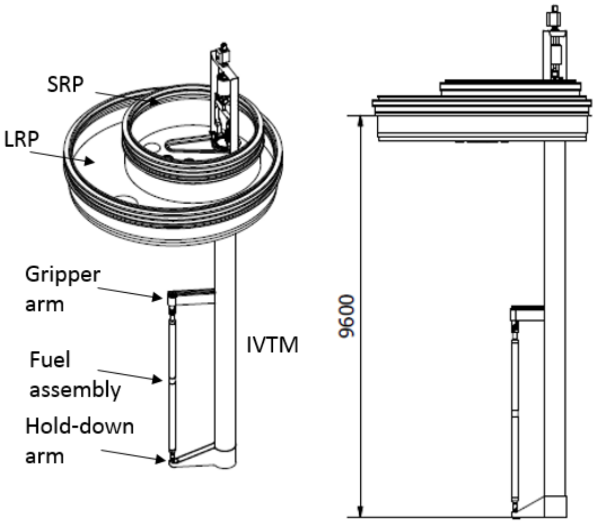

Fig. 2 PGSFR IVTM design concept

motorized ex-vessel fuel transfer machine–the cask carriage–provides an inert environment of the FA pathway, and goes back and forth between the reactor and fuel buildings, passing an air-lock gate.

For the dynamic simulation of an transferred FA by the In-Vessel fuel Transfer System (IVTS), which consists of IVTM and DRP, a simple four bar manipulator model as PGSFR IVTS has been proposed[9]. It suggested that the motion of SRP, LRP, and IVTM can be simplified by a four-bar linkage system. Using this model, the speed of the IVTM can be obtained by setting the angular velocities of two plugs and the FACM arm.

3 FA Modeling in a Hydrodynamic Environment

In order to transport an FA, IVTM uses a gripper equipped at the end of the gripper arm, and the top of an FA—the FA handling socket—is held by two gripper jaws. The gripper mechanism is illustrated in Fig. 3. As shown, the gripper adapter is inserted into the FA handling socket at its head, and the gripper jaws are fitted into the key holes of the socket. The whole body of FA is held by its head. Zhao and Wu [8] described the coupling equations for motions of a rotating cantilever beam. Similarly, the FA deflection due to its motions can be described as a cantilever beam which is supported at one end as shown in Fig. 4. Its lateral deflection is mainly due to the inertia and viscous forces, and the gravity is not considered.

Lee[3] verified the property of the FA which is being developed for the initial core of PGSFR. Bending stiffness, vibration characteristics, and impact properties of the FA are measured using a dynamic simulator to test a response of the FA under seismic conditions. This study takes the structural properties of FA from [3].

The relative location of the tip to the hold-down arm (or the ring, which the FA tip at rest is located in the center of) is of great concern. Considering its slow motion, the maximum deflection is at the tip, and its tip deflection δ is considered for this study as a metric of its accuracy measurement. Moreover, the extent of external forces exerted on the body can be estimated by the tip deflection.

Therefore, the FA body can be substituted as a point mass with its structural stiffness and damping elements in Fig. 5, and this spring-mass-damper system connected to the center of the hold-down ring can be modeled to demonstrate the tip deflection of an FA attached to the gripper. In other words, when the FA body is not deflected as aligned to the center line of the gripper, the red dot for the FA tip is at the center of the ring, and δ_e becomes zero. To simplify the complicated

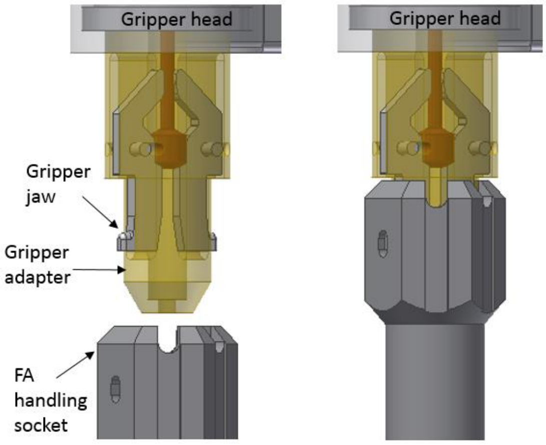

Fig. 3 FA gripper in a disengaged view (left), and FA engaged in the gripper (right)

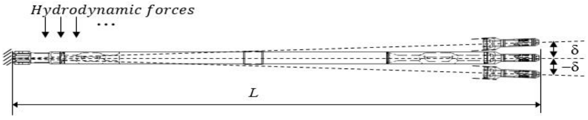

Fig. 4 FA lateral deflection

cantilever beam system as a simple mass-spring-damper system, equivalent values such as equivalent mass, and equivalent frequency were calculated. The following equations are the process to calculate the equivalent values. The maximum deflection δ of the cantilever beam under distributed load is

$$\delta = -\frac{wL^4}{8EI} \tag{1}$$

where w, L, E, and I are the uniform load, length, young's modulus, and moment of inertia of the cantilever beam. And the total distributed load is

$$wL = F_e \tag{2}$$

where F_e is the equivalent force of the mass-spring-damper system. In the simple mass-spring system, the relation between the deflection and force is

$$F = k\delta \tag{3}$$

Using equation (1), (2), and (3) the equivalent stiffness of the system is calculated.

$$k_e = \frac{8EI}{L^3} \tag{4}$$

In the spring-mass system, the natural frequency is calculated by the following equation.

$$f_1 = \sqrt{\frac{k_e}{m_e}} \text{ and } m_e = \frac{k_e}{f_1^2} \tag{5}$$

f_1 is the natural frequency of the cantilever beam which was measured experimentally[3]. m_e is the equivalent mass of the system calculated by the above equation.

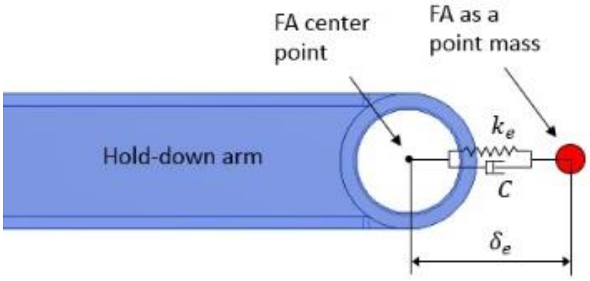

Fig. 5 FA modeling as a point mass to render the tip deflection in simulation (top view)

With the system parameters described in the above, assuming no external forces exerted on the FA, the equation of motion for the tip deflection considering hydrodynamic forces by its lateral motions becomes

$$m_e\ddot{\delta} + C\dot{\delta} + k_e\delta = F_{hydro} \tag{6}$$

In the equation, δ is the relative displacement of the FA tip to the gripper as a function of time. $\dot{\delta}$ is the relative speed of the FA tip to the gripper, and $\ddot{\delta}$ is the acceleration. C is the damping coefficient. In Eq. (6), F_{hydro} is the hydrodynamic force due to the fluid reaction which can be deduced by Morison's equation[6].

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

where ρ_s, C_m, d, and C_d are the sodium density, the inertial coefficient, diameter of the FA and the drag coefficient[6].

4 Simulation Results and Discussion

4.1 Simulation Method

One of the most critical transitions among a numerous combinations of FA transfer moves is from/to the core to/from the fuel transfer port, called CF move. Thus, this study only considers the CF only. As explained earlier, rotations of LRP, SRP, and FACM are substituted by links for an easy illustration in a plane view. In Fig. 6, a sequence of the CF move is shown as a series of slides. By three rotations of LRP, SRP and IVTM synchronously, the IVTM gripper (or the hold-down) arm can be inserted in a straight line into the port to take a new FA or to send out a spent FA.

To evaluate effects on the structure by motion induced hydrodynamic forces, two simulation rounds in a row, summarized in Fig. 7, are performed. The first run is a procedure to obtain positions, velocities, and accelerations of the hold-down arm for the whole discrete steps for one transfer procedure with the fixed joint to the FA. In this first simulation set, the point mass as an FA is locked, and it follows exactly the motions of the hold-down arm. Fig. 8 is the first input that makes the CF move. In the figure, the CF move ends in 6 seconds. The obtained speed and the fluid property, the Reynolds number, the hydrodynamic forces of the flow field through which the fuel travels are calculated by Eq. (7).

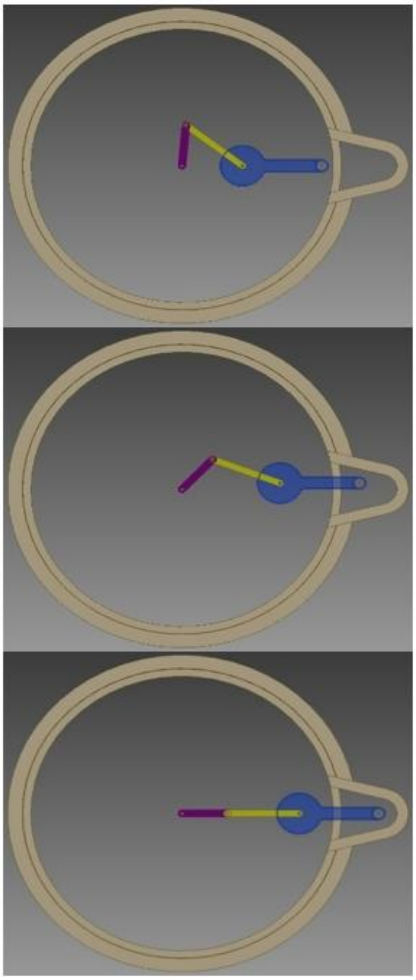

Fig. 7 Fuel transportation of the CF move

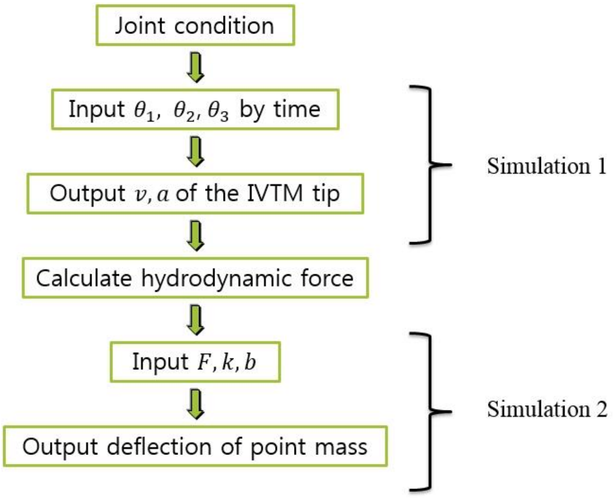

Fig. 6 Flow chart of the dynamic simulation

Table 1 Basic properties

Properties	Unit	Value
Inertia moment (I)	m^4	3.07E-06
Young's modulus (E)	GPa	200
Length (L)	m	4.55[3]
Equivalent stiffness (k_e)	N/m	55243
Damping ratio (ζ)	-	0.3[3]
Damping coefficient (C)	Ns/m	15.4
Natural frequency (ω_1)	rad/s	21.1[3]
Equivalent mass (m_e)	kg	117

The calculated forces are submitted for an additional input as settings at each simulation step. By running the second round of simulation for the same CF move, the deflections of the FA can be simulated, while the hold-down arm has the exactly same move with the first simulation round. Then, the vibration characteristics of the object can be predicted through the inherent frequency, stiffness, and damping of the object.

The basic properties listed in Table 1 [3] were used for this simulation study. The moment of inertia for the FA structure was calculated by the FA cross-sectional shape. Young's modulus was taken from its design material, stainless steel 316SS. Equivalent stiffness and mass values, 55 kN/m and 117 kg respectively, were calculated by Eqs. (4-5). The damping coefficient C was calculated from values of m_e, k_e, and ζ.

4.2 Results

Fig. 9 shows the first simulation results of the CF move in velocity and acceleration. In this simulation, LRP rotates from 85° to 0° at the average speed of 2.4 rpm. For the straight translation of the hold-down arm (from the top to bottom posture shown in Fig. 6) to the port, SRP and IVTM rotate synchronously based on the position profile given in Fig. 8.

Following the first simulation, hydrodynamic forces are plotted in Fig. 10 (top). The black and red curves represent a viscous drag and added mass force due to the acceleration of the fluid, respectively. As shown in the figure, the drag force gradually increases until the middle of its travel. But, as the gripper approaches to the port, its drag force shortly falls, and becomes zero when the gripper stops at about 6 seconds. The added mass force slightly fluctuates as the gripper velocity changes. As the gripper stopped, the added mass force also becomes zero. However, the FA vibration is sustained for a few more seconds due to its inertia, as shown in the bottom of Fig. 10, even after the CF move has been terminated. This approach had been verified by the parameters taken from [6], and the end-point displacements were well recovered by the method proposed here (see Fig. 11).

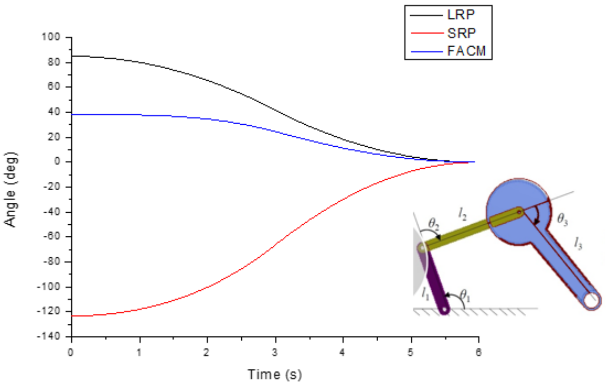

Fig. 8 Insertion to FTP platform

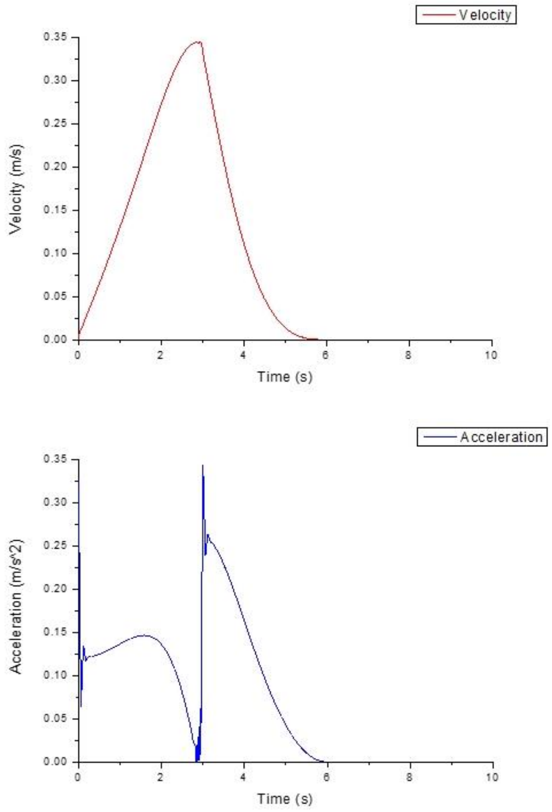

Fig. 9 Hold-down arm velocity (top) and acceleration (bottom) by CF move

4.3 Parametric Study

A parametric study on the effects by various velocities of LRP, SRP, and FACM rotation joints was conducted by investigating the FA tip deflection δ. The termination time of the CF move was chosen for the parameter variable in Table 2. In other words, varying the time duration for the same CF move could result in various velocities.

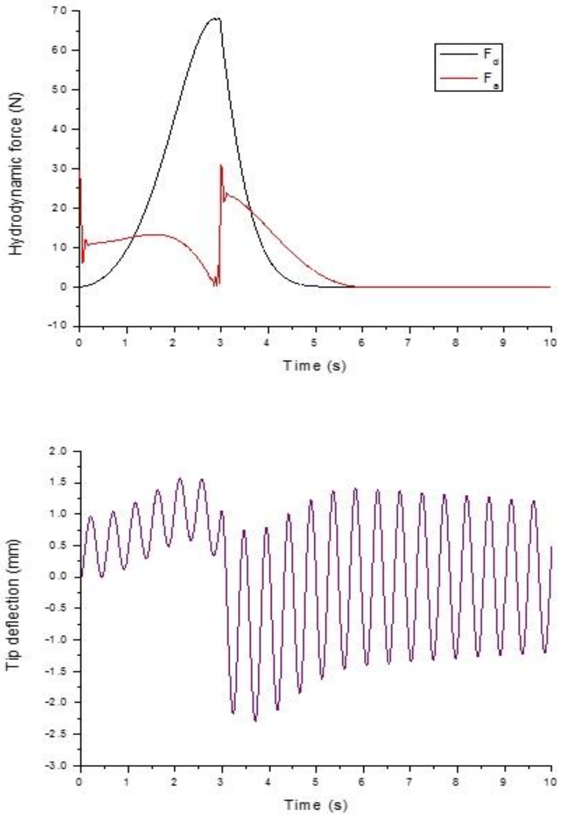

Fig. 10 Hydraulic forces induced by transfer motions (top) and corresponding tip deflections of the transferred FA (bottom)

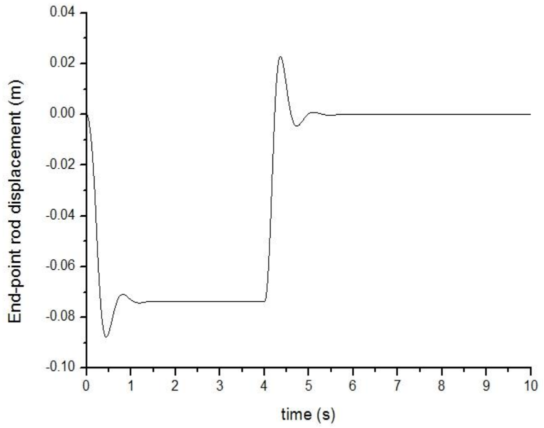

Fig. 11 Verification of the method proposed: Displacements of the rod endpoint recovered from the work [6]

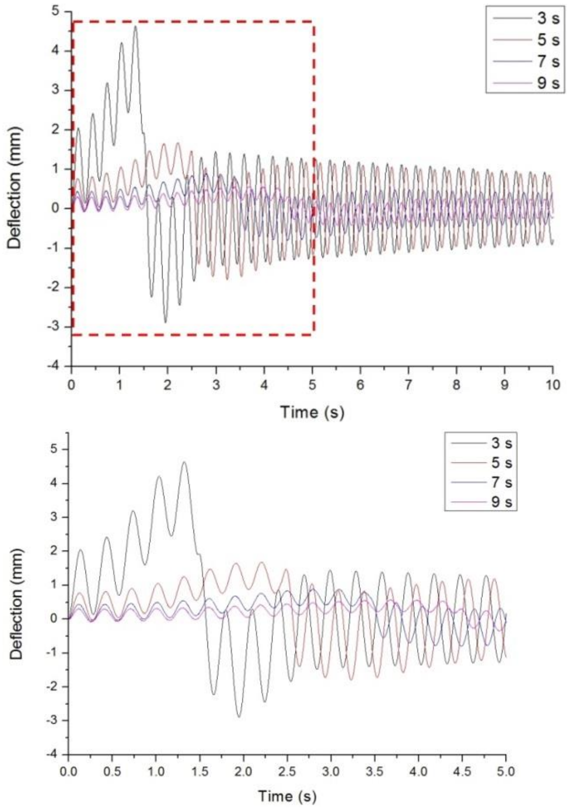

Fig. 12 FA tip displacements δ of cases for various rotational velocities dictated by travel periods for the total simulation time of 10 seconds (top) and magnified plots for 5 seconds (bottom)

Figure 12 shows the displacements of the FA tip for various input velocities made by four travel periods: 3, 5, 7, and 9 seconds. It is obvious that the shortest travel time made the greatest fluctuation compared with other cases, having the largest total variation. Also, the peak point is the highest as well for the shortest travel time, which is a big contrast even with the next parametric case, 5 seconds. The oscillation for the longest travel time (9 seconds), however, was reduced a little not so much as the 5 second case compared with the shortest one. Also, it is noted that the dominant frequencies of all cases are about same. This is mainly due to the system's structural characteristics, which do not change over time for different inputs.

Table 3 summarizes the parametric study with total variation, dominant frequency of oscillation, and maximum deflection. In the table, total variation has a large value when the simulation end time is short. It is observed that the maximum deflection has also the same trend. The dominant frequency does not vary much for different velocity settings.

Table 2 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 3 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

5 Conclusions

The PGSFR in-vessel fuel transfer system, which employs DRP and IVTM, was considered for the motion analysis of an FA being transferred. Motions in sodium caused by viscous hydrodynamic forces on an FA being transferred were analyzed. For the application of FA deformations in PGSFR refueling, an efficient dynamic simulation model of an FA attached to the FACM gripper was proposed as a simple spring-mass-damper system for in-vessel transfer motions. This system is in the effects of fluid drag and added forces due to FA motions. The simulation effectively reflected fluid viscous forces without the fluid volume (or fluid domain) in the setting, and so it runs fast with low computational cost.

A simulation set of two continuous runs was introduced in this paper. The first simulation run gave required dynamic information of the gripper (or hold-down arm) for calculations of hydrodynamic forces, which were set on the FA for the second simulation round. Then, the tip displacements of the transferred FA could be obtained. By the first and second simulation rounds, the tip displacement results could be used for the evaluation of the maneuvering accuracy and structural damage.

The simulation method was verified with reference work[6], and a parametric study of various velocities was conducted. From the results, as higher the rotational speed was, greater oscillation of the tip was observed. Furthermore, the oscillation was much reduced by having the travel period of 5 seconds or less (~4 rpm of LRP rotation). When it comes to ~3 rpm of LRP rotation, the effects on the tip vibration became small.

In terms of the accuracy, the tip displacement of 1.8 mm is acceptable, considering the IVTM accuracy requirement of +/- 2.5 mm. At the LRP average velocity of 4.12 rpm (the travel time of 5 seconds); the tip swayed up to 1.8 mm. With a sufficient margin of safety, a rotational speed of up to approximately 2 rpm of all components can be allowed based on the tip displacement analysis

The structural evaluation due to the hydrodynamic effects is left for future work. With a relation between the tip displacement and overall deformation of the FA body in consideration of the FACM gripper, an FSI (fluid structure interaction) problem of an efficient dynamic analysis can be tackled. Also, a better velocity profile or moving trajectory will be studied to lower the displacements and to make the motion smoother.

Acknowledgement

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References

[1] Y. Chikazawa, M. Farmer, and C.Grandy, “Technology gap analysis on sodium-cooled reactor fuel-handling system supporting advanced burner reactor development,” Nuclear Technology, Vol. 165, pp. 270-292, 2009.

[2] J. Yoo, J. Chang, J. Lim, J. Cheon, T. Lee, et al., “Overall system description and safety characteristics of prototype Gen IV sodium cooled fast reactor in Korea,” Nuclear Engineering and Technology, Vol. 48, pp. 1059-1070, 2016.

[3] C. B. Lee, et al., “Metal Fuel Development and Verification for Prototype Generation IV Sodium-Cooled Fast Reactor,” Nuclear Engineering and Technology 48.5, pp. 1096-1108, 2016.

[4] R. D. Blevins, Flow-Induced Vibration, Van Nostrand Reinhold, New York, 1990.

[5] E. ter Hofstede, S. Kottapalli, and A. Shams, “Numerical prediction of flow induced vibrations in nuclear reactor applications,” Nuclear Engineering and Design, vol. 319, pp.81-90, 2017.

[6] U. H. Shah, K. S. Hong, and S. H. Choi, “Open-Loop Vibration Control of an Underwater System: Application to Refueling Machine”, IEEE/ASME Transactions on Mechatronics, vol.22, no.4, pp.1633-1632, 2017.

[7] A. W. Troesch and S. K. Kim, “Hydrodynamic forces acing on cylinders oscillating at small amplitudes,” J. Fluids Struct., Vol. 5, No. 1, pp. 113-126, 1991.

[8] G. Zhao and Z. Wu, “Coupling vibration analysis of rotating three-dimensional cantilever beam,” Computers & Structures, Vol.179, pp.64-74, 2017.

[9] Y. -H. Kwon, D. -W. Lim, and S. -K. Kim, “Dynamic Simulation Modeling and Analysis of Under-sodium Fuel during In-vessel Transfer Motions,” Proceedings of the KNS2017, Gyengju, Korea, Oct. 26-27, 2017.