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Conceptual Design on Primary Control Rod Drive Mechanism of a Prototype Gen-IV SFR

Lee, Jae-Han [a*] and Koo, Gyeong-Hoi [a]
[a] *Korea Atomic Energy Research Institute, Yuseong-gu, Daejeon, The Republic of Korea*
[*] *jhlee@kaeri.re.kr*

1. Introduction

The prototype Gen-IV SFR (sodium-cooled Fast Reactor) is of 150MWe capacity. The reactor has six primary control rod assemblies(CRAs)[1]. The primary control rod is used for power control, burn-up compensation and reactor shutdown in response to demands from the plant control or protection systems.

The control rod drive mechanism (CRDM) consists of the drive motor assembly, the driveline, and its housing as shown in Fig.1. The driveline consists of three concentric members of a drive shaft, a tension tube, and a position indicator rod, and it connects the drive motor assembly to the CRA. Main issue is that these many driving parts shall be enclosed within a limited housing diameter because the available pitch of CRDMs is limited by 300mm.

This paper describes the key concept of the drive mechanism, and suggests a required motor power and reducer gears to meet the functional design requirements listed in Table 1, and a seismic response analysis of CRDM housing is performed to check its structural integrity.

2. Design concept of primary CRDM

Each CRDM has two means of rod insertion. The first is by un-gripping the CRA from the driveline, allowing it to drop into the core by gravity. The second is inserted by the control shim motor or the fast drive-in motor activated by the plant control or protection system.

Axial motion of a CRA within a hexagonal duct in reactor core is produced by a motor-driven ball nut acting on a lead screw of a drive shaft. Rotation of the ball nut raises and lowers the lead screw.

An electromagnet is attached to the upper part of the drive shaft, which is supported on the lead screw through a motor-driven nut mounted on CRDM housing. The electromagnet holds an armature to which is attached a tension tube, which extends down through the hollow drive shaft to the uppermost end of the CRA.

The multiply bellow seals between housing, drive shaft and tension tube are adopted to protect the moving parts such as motors and gears from primary sodium vapor. The bellows is located below the reactor head as shown in Fig.2. There is a bushing element in the drive shaft at bottom part of bellows to protect a sodium jet by core exit flow.

The driveline passes down through a shroud tube in the upper internal structure, which provides driveline alignment, support, and coolant flow guide from the reactor outlet. Its length is 12 m~14 m long.

The tension tube has a multi-fingered collet-type gripper at its lower extremity as shown in Fig.3 and holds the CRA. Re-gripping is accomplished by driving the gripper down to the bottom end of its stroke, and gripping is done by raising the gripper to its trigger position.

The innermost of the driveline is a position indicator rod. Its lower extremity rests on top of the CRA and its upper extremity extends to a point at upper part of the control rod drive mechanism where its elevation can be measured during power operation.

Scram is accomplished by de-energizing an electromagnet, attached at upper part of a drive shaft, so that the tension tube (assisted by a compressed spring) drops down about 10 ~ 15mm, and releases its gripping force on the CRA, then it drops into the core by gravity.

In order to limit the amount of reactivity insertion due to an uncontrolled rod withdrawal event, a rod stop system (RSS) is installed on the CRDM housing.

3. Calculation of drive motor power

An AC servo motor is selected as a CRA driving power because it uses permanent magnets and is brushless type while DC motor needs a brush and a coil rotates. The control shim motor size is constrained by a housing diameter of 250mm. The driving system has several design requirements as listed in Table 1.

To calculate the motor power, the drive shaft torque is needed. One part of the drive shaft has a lead screw, driving by a ball-nut. The ball screw driver torque (Tr) is calculated by some equations as follow [2];

$$T_r = \frac{1}{2\pi}\left(\frac{F_l}{\eta} + F_{ao} \times \mu\right) \times l \quad \left(\because Typically,\ F_{ao} = \frac{1}{3} \times F_l\right)$$

$$= \frac{1}{2\pi}\left(\frac{F_l}{\eta} + \frac{1}{3}F_l \times \mu\right) \times p \quad \left(\because F_l = 8{,}000\,(N),\ l = 10mm,\ \eta = 0.9\right)$$

$$= \frac{1}{2\pi}\left(\frac{8{,}000(N)}{0.9} + \frac{8{,}000(N)}{3} \times 0.21\right) \times 0.01(m)$$

$$\left(\because \mu = 0.05\frac{1}{\sqrt{\tan\beta}},\ \tan\beta = \frac{p}{\pi \times d},\ d = Screw\ Nt\ Diameter\right.$$

$$\left. = 0.05\left(\sqrt{\frac{\pi \times d}{l}}\right) = 0.05\left(\sqrt{\frac{3.14159 \times 0.055}{0.010}}\right) = 0.2078\right)$$

$$= 14.147 + 0.882\,(N \cdot m)$$

$$= 15.03\,(N \cdot m)$$

A plenary linear coupling reducer of 2 stages (25 : 1) with a motor axis is selected, its efficiency is assumed about 80%. Another reducer between screw nut and motor shaft is a spur gear with a reduction ratio of 1/4. The PCD are 30mm and 120mm, respectively.

Motor torque(T_m) required is calculated as follow;

- T_m = screw driver torque(Tr) / reducer ratio / reducer efficiency
  = 15.03/ 100 / 0.8 (N-m)
  = 0.1879 (N-m).

A servo motor with a nominal power of 100W, a nominal torque of 0.32 N-m (max. 0.48N-m) is selected considering a safety margin. Its diameter is about 50mm. The calculation sheet is suggested in Table 2.

The fast drive-in motor needs a strong power to insert enforcedly the stuck CRA into core within a required time. The motor sizes are calculated by the same procedure. The diameters are in the range of 80mm to 110mm by the insertion time (10 ~ 24 seconds).

4. Seismic response analysis of CRDM housing

The mode shapes and natural frequencies are calculated to check the displacements and the housing integrity as represented in Fig.4 and Table 3. The first frequency is about 9Hz. The maximum displacement of 5mm and the maximum stress intensity of 28MPa for 0.3g earthquake loads are low levels compared to their material allow values.

ACKNOWLEDGEMENT

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REFERENCES

[1] Lee, Jae-Han, Conceptual study of reactor control and shutdown rod drive mechanism of an SFR, KAERI/TR-4712/ 2012.
[2] "Selection of ball nut," A15-14~37, THK.

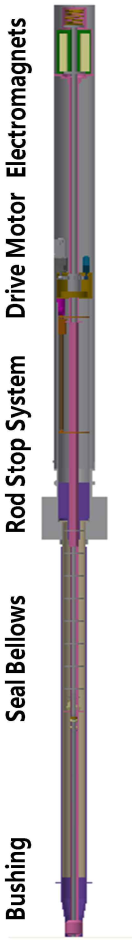


Fig.1 Conceptual design of CRDM

Table 1 Tentative design requirements of CRDM

Parameters	**Prototype**
Hosing diameter limit	250mm
Maximum motor force	8,000 N
Maximum motor stroke	1,100 mm
Fast drive-in rod insertion time	10~24 seconds (TBD)
Gripping on-off stroke	10 ~15mm
CRA weight	~ 40 kg
Gripper	Collet type
Coil type (number)	Solenoids (dual)
Sealing from sodium	Stroke and gripping bellows

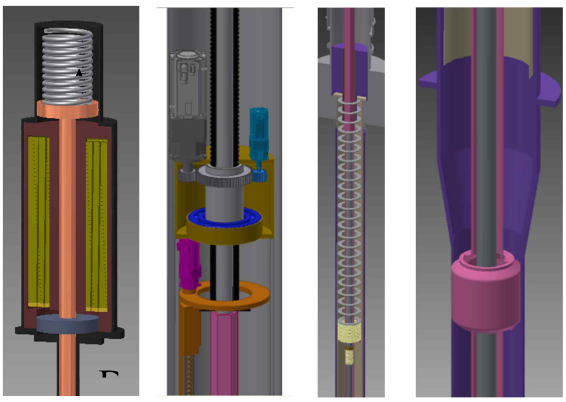


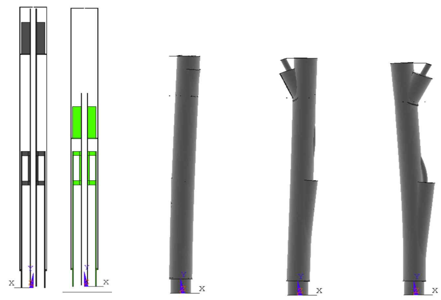
Fig. 2 Magnet, screw &motor, seal bellows and bushing

Table 2 Driving motor sizing for design requirements

	Normal drive	Fast drive-in
Screw axial moving speed	< 5 mm/sec	~100 mm/sec

Load (moving force of stuck CRA, Fm (N)	8,000
Ball bearing efficiency	0.9
Mean diameter of lead screw, dm	0.06 m
Lead, l	0.01 m
Preload of ball nut, Fao (N) ~ 1/3 Fm	2667
Coefficient of friction, u or k	0.22
Lead angle(ramda), degree	3.04
Tan (ramda)= l/pi*dm	0.05 m
Torque reflected to ball screw (N-m),Tr	**15.07**
Horse power(hp)	0.06
Stroke maximum length, m	1.1
Screw driver speed, m/s	0.005
Ball nut revolution speed, rpm	**30**
Full-in insertion time (seconds)	**200**
Reducer ratio (total = plenary + spur gears)	100.0
Reducer efficiency of plenary gear (2 stages)	0.80
Safety margin	1.70
Motor revolution speed (rpm)	**3,000**
Motor torque(N-m),Tmotor	**0.32**

Fig.3 Gripper concept of control rod assembly



	Diameter	Length	Thickness	Mass
Motor support	22.0(cm)	120(cm)	0.6(cm)	38.7(kg)
Housing	25.0(cm)	300(cm)	0.3(cm)	55.8(kg)

Fig.4 Mode shapes and size of CRDM upper part

Table 3 Dynamic responses of CRDM upper part

Seismic responses	Full-out position	Full-in position
Frequencies (Hz)	8.97 (1st), 41.71(2nd) 169.7 (vertical)	18.1(1st), 49.1(2nd) 279.8 (vertical)
Displacements	4.98 (mm)	0.916 (mm)
Stress intensity	28.1 (MPa)	25.5 (MPa)
Reaction forces on head (KN)	18.9 (x & z) 56.6 (y)	10.5 (x & z) 31.7 (y)