Kinematic Analysis of Link System Used in Collapsible Type In-Vessel Handling Machine

Sanjeev kumar, Jose Varghese, R. Vijayashree, S. Raghupathy, P. Chellapandi, S.C.Chetal

Abstract

In fast breeder reactors, spent fuel subassemblies are replaced with fresh subassemblies during fuel handling. Three types of machines namely, straight pull, offset arm and collapsible type or pantograph are used for in-vessel handling operations. The pantograph type uses a collapsible link system identical to a Scott-Russel mechanism. Though design is very complex with many links working inside sodium, use of pantograph type machine is being considered in the recent advanced reactor designs due to overall economic benefits. Kinematic analysis of the link system is very important in order to meet the accuracy of positioning of gripper and to arrive at the basic dimensions of the machine including its drive system. Displacement, velocity and acceleration diagrams were generated for the gripper assembly connected to output end of the link system in relation to the movement of the input link (lower carriage) using Multibody Dynamics analysis software and the same was verified analytically. The displacement, velocity and acceleration at the output link (gripper) vary non-linearly. Analysis showed that the maximum velocity of the link system is very small within the operating range of the machine and hence does not influence the positional accuracy of the gripper for a velocity of 50mm/s at the lower carriage. The inertia force developed on the gripper assembly is negligibly small.

Keywords: Fast breeder reactors, Prototype fast breeder reactor, Fuel handling, In-vessel handling machine, Kinematic analysis of mechanisms.

1 Introduction

India's second stage nuclear program was started with the construction of Fast Breeder Test Reactor (FBTR) at Kalpakkam, which is in operation since 1985. A 500 MWe Prototype Fast Breeder Reactor (PFBR) is currently under construction.

Energy is produced by the nuclear fission of mixed oxides of uranium and plutonium fuel provided in the form of fuel subassemblies (SAs). Additionally, blanket, control and shielding SAs are provided which together form the reactor core. The process of replenishment of spent SAs with the new ones is called fuel handling for which a combination of two rotatble plugs (large and small) and in-vessel handling machine is used. The outer shielding SAs in PFBR are designed for 40 years of life and are not normally handled. For handling these SAs during

Sanjeev Kumar (Corresponding author)
CHMD/NSEG, Indira Gandhi Centre for Atomic Research, Kalpakkam, E-mail:sky@igcar.gov.in.

Jose Varghese, R. Vijayashree, S. Raghupathy, P. Chellapandi, S.C.Chetal
CHMD/NSEG, Indira Gandhi Centre for Atomic Research, Kalpakkam,
E-mail:{varghese, rviji, rags, pcp, chetal}@igcar.gov.in.

decommissioning, use of a collapsible type machine is envisaged and this machine is supported on the large rotatable plug (LRP).

In FBRs, the diameter of main vessel is taken as an index of economy and design efforts are made towards achieving minimum vessel diameter. The straight pull type is the simplest type of in-vessel handling machine (IVHM) but results in a large vessel diameter, while the collapsible type machine gives the least value indicating maximum economy. However, it involves a system of hinged links immersed and moving inside sodium. The machine construction is such that the links are collapsed during insertion into the reactor through a small circular opening and are expanded to achieve a variable reach during fuel handling.

The salient design requirements of the link system are:

- Maximum reach : 700 mm
- Minimum reach : 420 mm
- Height available inside vessel for link movement : 5800 mm
- Maximum diameter of the machine : < ϕ600 mm

The collapsible type of machine is used in PFR (UK) [1] and was/is proposed to be used in reactors like PEC (Italy) [2] and DFBR (Japan) [3].

2 Description of the Machine

Fig. (1) shows the schematic of collapsible type in-vessel handling machine. The machine consists of two parts namely upper part and lower part. The upper part consists of drives required for operation of the lower part of the machine.

The lower part consists of main body, gripper support tube (GST), gripper, link system, gripper hoisting arrangement and gripper finger actuation mechanism. Both the upper and lower parts are joined together at the top level of the LRP.

The various movements provided in the machine are:

- Radial movement of the GST with respect to the machine centreline
- Vertical movement of the GST with respect to the top of the core
- Gripper hoisting
- Finger actuation and
- Rotation of machine about its own axis

The main body is cylindrical in shape and encloses the mechanisms working in sodium and argon cover gas. GST, which houses the gripper and the gripper hoisting arrangement, is supported from the lower carriage using the link mechanism. The lower carriage is housed within the main body and moves axially upward & downward. Movement of the lower carriage downward/upward causes the link mechanism to move radially inward/outward causing the GST to be positioned radially with respect to the axis of main body (or machine). These movements give the required radius or reach for the collapsible type machine. The main body has a slot in the lower portion, which permits movement of the GST and the links connected to the GST. In the fully collapsed condition, the GST is retracted completely within the main body thus permitting removal of the machine in the fully collapsed condition. The radial movement of the GST together with LRP rotation and machine’s rotation about its own axis enables positioning of the gripper over the required SA to be handled.

The gripper hoisting arrangement consists of a ball screw & nut arrangement driven by an electrical motor through a splined shaft and universal joints. The ball screw is supported within the GST and the gripper is connected to the ball nut.

Rotation of the ball screw causes the nut to move axially thereby hoisting the gripper. The ball screw length is equal to the subassembly height to enable complete hoisting of the subassembly out of the core.

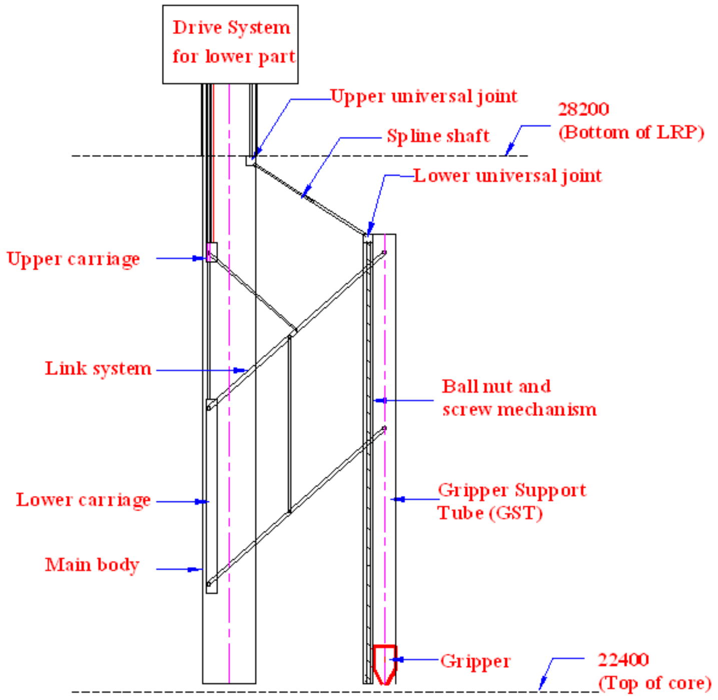

Figure 1: Schematic diagram of collapsible type of in-vessel handling machine

3 Evolution of the Link System

The link system is kinematically identical to the Scott-Russel mechanism (Fig. (2)) and translates linear motion in vertical direction to horizontal direction with amplification of the movement at output end. To achieve this, the acting length of the short link DA needs to be half of that of link BC, pivot B shall be in line with the pivot D.

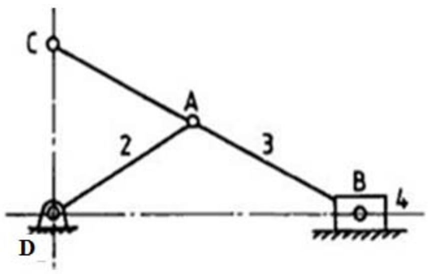

Figure 2: Schematic diagram of Scott-Russel mechanism.

3.1 Link system of collapsible type machine

Fig. (3) shows the link system for the collapsible type in-vessel handling machine. Link ‘a’, link ‘b’ and lower carriage (e) make a Scott-Russel mechanism. Link ‘c’ and link ‘d’ are provided additionally to provide rigidity and to keep the link ‘f’ vertical. Only link ‘a’, link ‘b’ and lower carriage (e) will govern the kinematic analysis of the total link system.

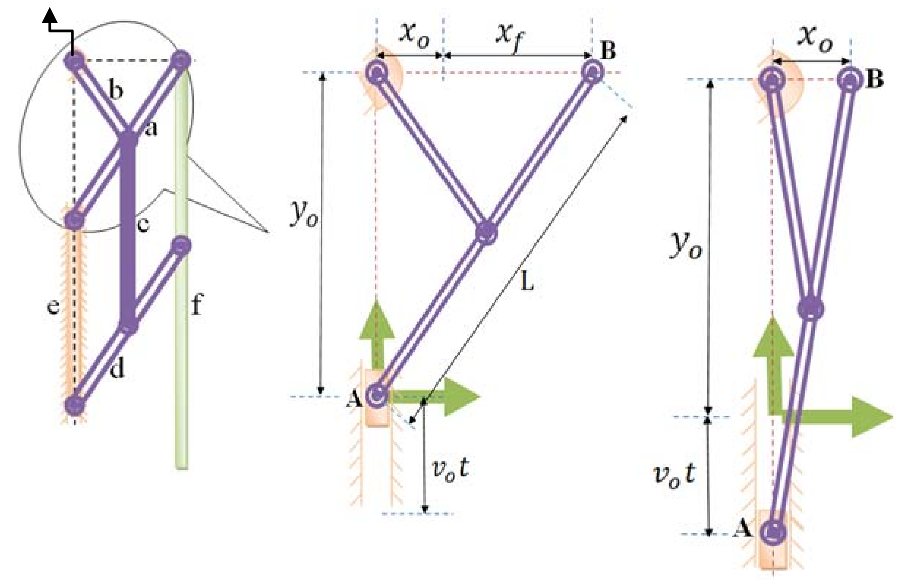

Figure 3: Schematic diagram of Link system. A call out is used to show the link system required for the derivation of equations. The link system is also shown in its two extreme positions.

3.1.1 Equation for kinematic analysis

From Fig. (3) using Pythagoras theorem it can be written

$$(x_o + x_f)^2 + (y_o + v_o t)^2 = L^2$$

Where,

x_o is the horizontal distance of pivot ‘B’ from the axis of the lower carriage when the link system is in fully collapsed condition,

x_f is the horizontal displacement of pivot ‘B’,

L is the length of link ‘a’,

v_o is the input velocity of the lower carriage at point ‘A’ and

t is the time

$$Displacement \qquad x_o + x_f = \sqrt{L^2 - (y_o + v_o t)^2} \qquad (1)$$

Differentiating Eq. (1) with respect to time will give the velocity

$$Velocity \qquad \dot{x_f} = v_x = -\frac{v_o(y_o+v_o t)}{\sqrt{L^2-(y_o+v_o t)^2}} \qquad (2)$$

Differentiating Eq. (2) with respect to time will give the acceleration

$$Acceleration \qquad \ddot{x_f} = a_x = -\frac{L^2 v_o^2}{[L^2-(y_o+v_o t)^2]^{3/2}} \qquad (3)$$

The equation (1), (2) & (3) are the equations for the kinematics of the link system.

4 Kinematic Analysis

4.1 Methodology

The proportioning of the link system is done meeting the design requirements defined in section 1. The link system is then modeled in MultiBody Dynamics software called SIMPACK. Displacement, velocity and acceleration diagrams are generated at the output link (gripper) and the same is verified analytically using the methodology indicated in 3.1.1.

4.2 Proportioning of link system

Total height available to accommodate the lower part of the machine is 5800mm as per section 1. Out of this, 800 mm is required to accommodate the two universal joints and one spline shaft. 100 mm should be the clearance between the core top and the machine bottom. Accordingly, the following equations are arrived at from Fig. (4).

$$Lsin\alpha_1 = 925 \qquad (4)$$

$$Lsin\alpha_2 = 420 \qquad (5)$$

$$Z + E + y = 4600 \qquad (6)$$

Where,

L is the length of the link 'a',

α_1 & α_2 are the angles of the link 'a' with the machine centre line in fully extended and fully retracted condition respectively,

Z is the length as shown in Fig. (4). It varies from Z_1 when the link system is in fully extended condition to Z_2 when the link system is in fully retracted condition,

E is the active length of the lower carriage (e),

y is the input displacement required and it varies from 0 when the link system is in fully extended condition to Y when the link system is in fully retracted condition.

Based on parametric studies, the value of α_1 is taken as 45^o. From Eq. (4)

$$L = \frac{925}{\sin 45} \qquad \Rightarrow \qquad \boxed{L = 1308\, mm}$$

From Eq. (5)

$$\alpha_2 = \sin^{-1}(420/1308) \qquad \Rightarrow \qquad \boxed{\alpha_2 = 18.7^o}$$

Case-1: Links in fully extended condition

$$Z_1 = L\cos\alpha_1 \qquad \Rightarrow \qquad Z_1 = 925\, mm$$

Substituting this value in Eq. (6)

$$E + Y = 4600 - 925$$

$$E + Y = 3675 \quad (7)$$

Case-2: Links in fully retracted condition

$$y = 0 \; and$$

$$Z_2 = L\cos\alpha_2 \quad \Rightarrow \quad Z_2 = 1239\; mm$$

Substituting these values in Eq. (6)

$$1239 + E + 0 = 4600$$

$$\boxed{E = 3361\; mm}$$

From Eq. (7)

$$3361 + Y = 3675 \quad \Rightarrow \quad \boxed{Y = 314\; mm}$$

The final dimensions arrived at are

$\alpha_1 = 45^o, L = 1308\; mm, \alpha_2 = 18.73^o, Z_1 = 925\; mm, Z_2 = 1239\; mm, E = 3361\; mm$ and $Y = 314\; mm$.

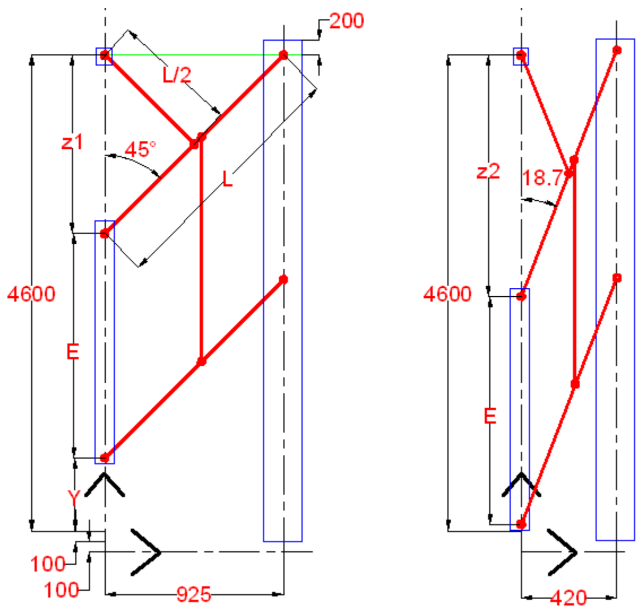

Figure 4: Optimised size of the link system. Here the link system is shown in two extreme conditions. For clarity point of view the figure is not made to the scale.

4.3 Modelling and analysis of link system

Kinematic model was generated using MultiBody Dynamics software and is shown in Fig. (5). The mechanism is considered as planar in nature. All the joints are modeled as revolute joints except the one between the lower carriage and the main body. Constant downward velocity of 50mm/s is applied at the lower carriage. As the objective is to calculate the displacement and velocity at gripper location which lies in the GST, all the output request is given at the GST. Based on kinematic analysis the time dependent displacement, velocity and acceleration values are obtained and are shown in Fig. (6).

It is clear from the results obtained that for a constant velocity at lower carriage (input link) the GST (output link) experiences a nonlinear displacement, velocity and acceleration. The velocity and acceleration are minimum when the link system is in fully extended condition and it increases as the links are retracted and attains maximum value at the fully retraced condition.

The displacement, velocity and acceleration for the link system are also calculated at point ‘B’ shown in Fig. (4) based upon the equations derived in section 3.1.1. The results obtained from the kinematic analysis compares well with the analytical estimation. The analytical results are also shown in Fig. (5).

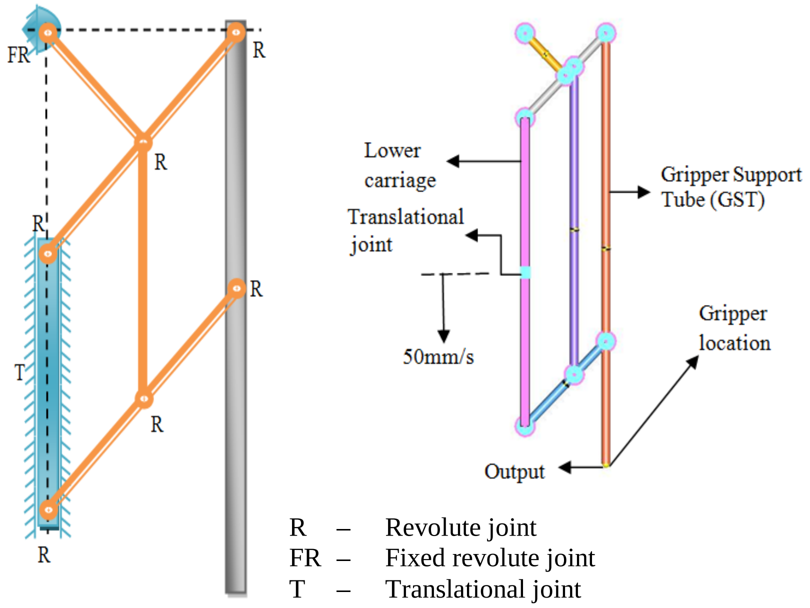

Figure 5: Kinematic model of the link system. Input and output locations are shown clearly. Type of joint are also marked.

5 Results and Discussion

It is seen from the Fig. (6) that the results from kinematic model and analytical method are matching. The horizontal displacement at the gripper location is nonlinear for a linear movement of input link (lower carriage). The maximum velocity of gripper location is ~ 150mm/s (0.15m/s) which is important for the positioning of the gripper. The obtained results provide input for design of control system for positioning of gripper.

The maximum acceleration is 58mm/s^2 (0.058m/s^2) and hence inertial effects are negligible.

6 Conclusions

A kinematic model was generated and kinematic analysis was carried out for a constant input velocity of 50mm/s at the lower carriage. The displacement, velocity and acceleration values at the gripper location for different positions of the link system were obtained from the kinematic model. The displacement, velocity and acceleration were found to be varying nonlinearly for the different link positions. It is seen that displacement, velocity and acceleration are increasing as the link system moves from fully extended condition to fully retracted condition. The maximum velocity is seen as 150 mm/s. From positioning point of view, the input link speed has to be ramped gradually down to zero for last 100mm. The maximum acceleration is seen as 58mm/s^2 and hence inertial effects are negligible.

The results from the kinematic model were compared with analytically estimated results and are found to be well matched which validates the kinematic model.

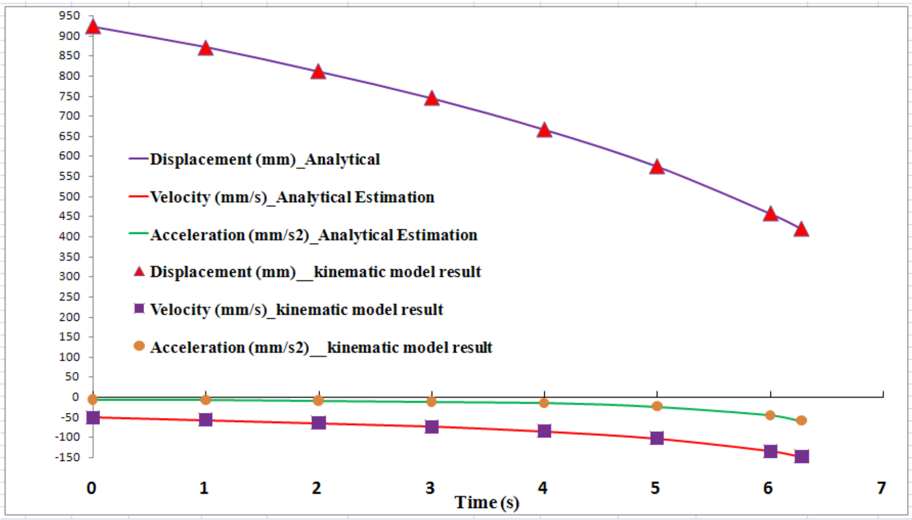

Figure 6: Displacement, velocity and acceleration diagram extracted from the kinematic analysis and analytical estimation.

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