Use of Six Bar Mechanism for Reduction in Force and Stroke Requirement as Against Four Bar Mechanism

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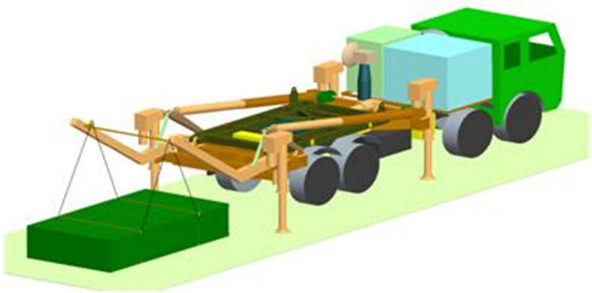
***Abstract*- The advantage of six bar mechanism as against the existing four bar mechanism used in articulation of the missile launcher system and how self-replenishment of missile container from ground was made possible is brought out in this paper. The application has been designed, and development in this paper has a requirement of having a dual role of not only articulation from the 0^0 to 90^0 but also to act as self replenishment system for the missile container thus avoiding usage of external crane. Replenishment system means to place the missile container in horizontal condition from the ground on to the vehicle platform at a height of around 1500 mm (from ground). Articulation means to articulate the same missile container on the vehicle platform from 0^0 to 90^0 (Horizontal to Vertical). In this paper the comparison of the four bar mechanism and the six-bar mechanism has been evolved for such type of application. Here the main requirement is to quickly reload and articulate the missile container on the vehicle platform avoiding the usage of external crane. As there is no real reference material on this subject the first step has been the description of the kinematics of the articulation cum reloading mechanism of the mobile missile launcher system. The six bar mechanism has been manufactured and realized and also the functionality tests have been carried out.**

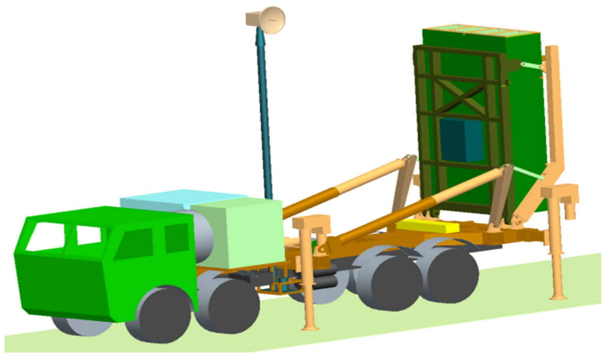
Keywords- electromechanical actuators: six bar mechanism: four bar mechanism: actuator axial force: articulation: replenishment

I. INTRODUCTION

The main aim is to articulate as well replenish the missile container**.** Articulate means to elevate the missile container from horizontal (0^0) to Vertical (90^0) and replenish means unloading container from the vehicle platform on to the ground in horizontal (0^0) condition and vise versa. The angles of measurement are with respect to the ground. Initially, an inversion of four bar linkage mechanism was designed to carry out the dual purpose of articulation as well as the replenishment. The electromechanical linear ball screw actuator forms the sliding pair of four bar mechanism. Due to larger stroke requirement and higher actuator force, the four bar mechanism was ruled out. Alternatively, an inversion of six bar Watt's mechanism [1],[2] was thought of to carry out the dual purpose of articulation and replenishment of the missile container. The payload of four ton in the form of missile container is to be picked up from the ground for replenishment and to be kept on the platform at the height of around 1500mm from the ground. This is one mode of operation that is replenishment mode shown in figure 1 (a). The other mode of operation is articulation mode. In articulation mode the missile container is kept and locked on the vehicle launch platform and articulated from 0^0 to 90^0 shown in figure 1(b). The replenishment and articulation using six bar linkage mechanism of the missile container is shown in figure 1 below. This paper brings out the comparison of 4 bar and 6 bar mechanism used for both the articulation and replenishment operation.



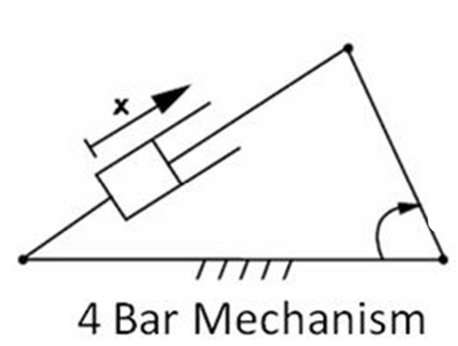
(a)



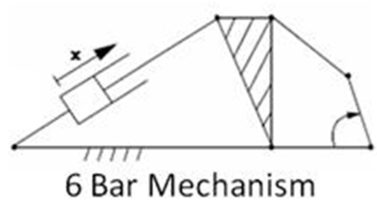
(b)

Fig. 1. (a) Replenishment of Missile Container; and (b) Articulation of Missile Container

The six bar mechanism has been used in this scheme for both (Articulation and Replenishment) modes of operation which is driven by a set of linear ball screw actuator. The set objective was to achieve reduction in stroke and actuator force so that the manufacturability of the ball screw actuator is feasible and economical. The advantage of using the six bar mechanism is that the overall stroke and the force requirement is reduced as against the four bar mechanism. The schematic of four bar and six bar linkage mechanism in shown in figure 2a and 2b.



(a)



(b)

Fig. 2. (a) Four Bar Mechanism; and (b) Six Bar Mechanism [1]

II. COMPARISON OF FOUR BAR AND SIX BAR MECHANISM FOR ARTICULATION AND REPLENISHMENT OF MISSILE CONTAINER

The main function of the launcher is to replenish and articulate the missile container. The missile container has to be reloaded from ground and placed on to the vehicle platform (which is at a height of 1500 mm from ground) and then the missile container is articulated from 0^0 to 90^0. Earlier a separate hydraulic crane was being used for replenishing the missile container from the ground to the vehicle platform and inversion of four bar mechanism is used for articulation. In this launcher the function of replenishing and articulation are being done using an integrated linkage mechanism to avoid the use of separate hydraulic crane for replenishment. This integrated linkage mechanism was designed in two schemes. Scheme I is by using inversion of 4 bar mechanism and Scheme II is by using inversion of 6 bar mechanism. The comparison of these two schemes is presented in this paper.

Synthesis and kinematic analysis of the four bar mechanism has been done to carry the dual Articulation and Replenishment modes of the launcher. For replenishment the boom has to rotate from 0° to 187° with respect to ground while for articulation the boom rotates from 0° to 90° with respect to ground. The boom initial angle with respect to ground is 0^0 shown in figure 3(a). It was found that by using four bar mechanism, the transmission angle of 4 bar mechanism during replenishing the missile container from ground is very low and hence actuator force and stroke requirement are very high and practically not possible to achieve. So there was a need to have some alternative mechanism which can handle both the dual modes of the launcher operation. So a six-bar linkage mechanism was evolved. Synthesis and kinematic analysis of the six bar mechanism is done, which is explained in the later part of the paper. The comparison table of the four and six bar mechanism is given in the table 1 & 2. The table 1 gives the comparison both the linkage mechanism during replenishment while table 2 gives the comparison during articulation of the missile container. Both the mechanisms are driven by ball screw actuators which are driven by a BLDC Servo Motor through a reduction gearbox.

TABLE 1: RESULTS FOR FOUR BAR AND SIX BAR MECHANISM DURING REPLENISHMENT

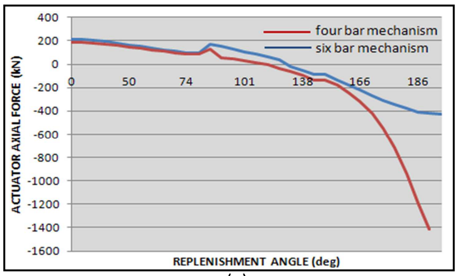
Replenishment of Missile Container (0° to 187°)		
Parameters	**Four Bar Mechanism**	**Six Bar Mechanism**
Actuator Stroke Length	2601 mm	2273 mm
Max. Actuator Axial Force	1420 kN	428 kN
Min. Actuator Angle	1.1 °	10°
Max. Actuator Screw Torque	3371 Nm	850 Nm
Max. Motor Torque	570 Nm	143 Nm

TABLE 2: RESULTS FOR FOUR BAR AND SIX BAR MECHANISM DURING ARTICULATION

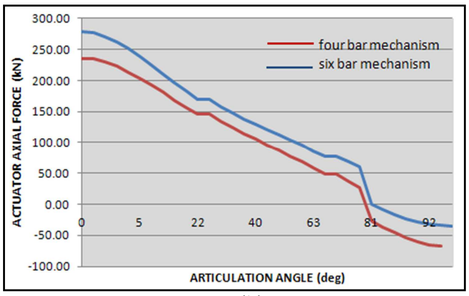
Articulation of Missile Container (0° to 93°)		
Parameters	**Four Bar Mechanism**	**Six Bar Mechanism**
Actuator Stroke Length	2005 mm	1600 mm
Max. Actuator Axial Force	236 kN	278 kN
Min. Actuator Angle	12 °	16°
Max. Actuator Screw Torque	469 Nm	554 Nm
Max. Motor Torque	51.4 Nm	96 Nm

The actuator stroke and force are chosen for parameters for comparison between four-bar and six-bar mechanism. The electromechanical type ball screw actuators are used for this mechanism, which are driven by a BLDC motor through a reduction gear box. The actuator axial force variation for four bar and six bar mechanism during articulation and replenishment are shown in the figure 3 (a) and 3 (b). This actuator force is shared by two actuators. The actuator stroke variation for four bar and six bar mechanism is shown in figure 4 (a) and (b).

As seen from the figure 4, as compared to four bar mechanism, there is reduction in actuator stroke for both replenishment and articulation mode using six bar mechanism. In replenishment mode, the stroke requirement of six bar is 2273 mm and for four bar is 2601 mm while in articulation mode the stroke requirement for six bar is 1600 mm while for four bar is 2005 mm.

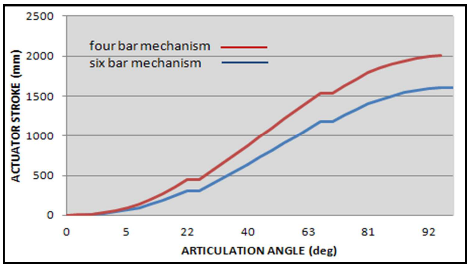


(a)

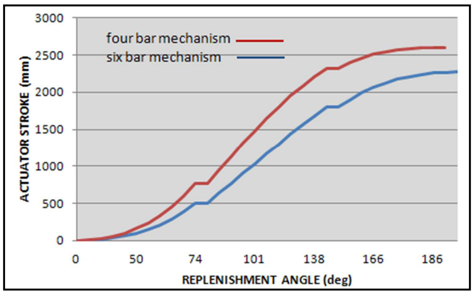


(b)

Fig. 3. Comparison of Actuator Force Variation (a) During Articulation; and (b) During Replenishment



(a)



(b)

Fig. 4. Comparison of Actuator Stroke (a) During Articulation; and (b) During Replenishment

The four bar mechanism for replenishment mode is practically not possible due to large actuator force (1420 kN) as shown in figure 3(b). The actuator force for replenishment mode using six-bar is optimized. Using six bar mechanism, the actuator manufacturability is economically possible and this also meets all the required functionality as compared to four bar mechanism. Hence six bar mechanism is selected for realization of actual hardware. The actuator axial force for six bar mechanism during articulation is found to be more than four bar mechanism; this is due to the configuration of the mechanisms within the overall system height from ground (3100 mm).

III. SYNTHESIS AND KINEMATIC ANALYSIS OF SIX BAR MECHANISM

Let a, b, c, d be the lengths of the links and L be the actuator length which is variable. Let r1 the distance between ternary link pivot and actuator bottom pivot. And r_2 be the distance between ternary link pivot and actuator top pivot.

The various angles and distances are as shown in the figure 5 below.

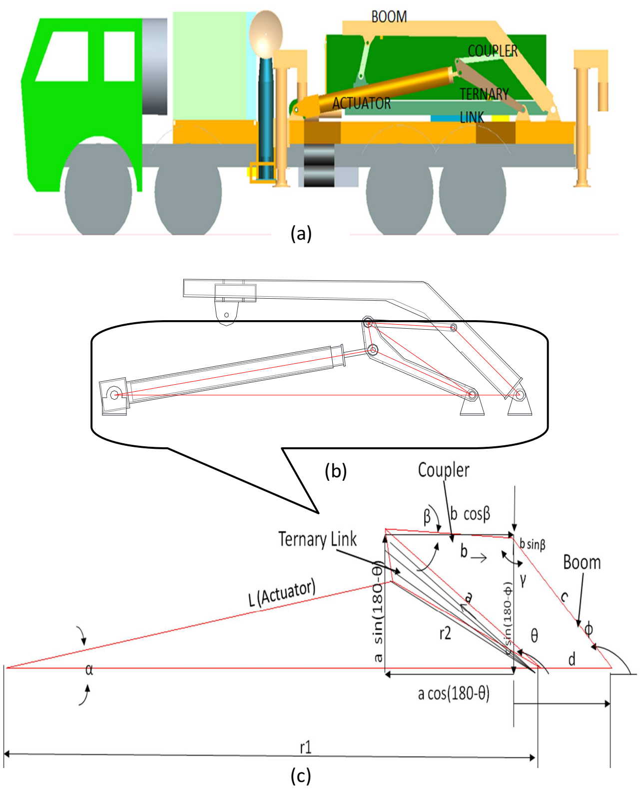


Fig. 5. (a) Missile Launcher; (b) Six bar mechanism combining articulation and replenishment; and (c) Schematic of linkage showing linkage parameters

The six bar mechanism is considered as a combination of a four bar mechanism and a slider crank mechanism. The synthesis of the four bar mechanism is done using Freudenstein's equation [4],[5] while the synthesis of the slider crank is done using cosine rule. The motion profile of the ternary link during articulation and replenishment is given figure 6. From above dimension values, the formulae are derived for finding out the instanteneous stroke, speed of screw, Angles, Forces, Torque, Motor Speed, Reduction Ratio and Motor Power etc. [6]. The term K in equation (1) relates the link dimensions a,b,c and d.

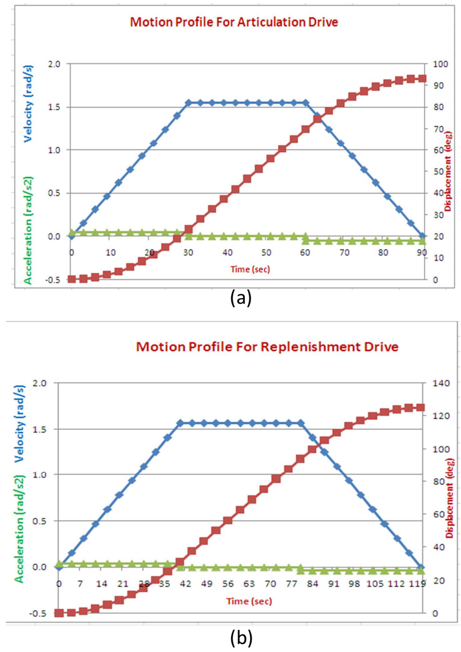


Fig. 6. Motion profile (a) For Replenishment; and (b) For Articulation

$$\left.\begin{aligned} K &= \frac{a^2 - b^2 + c^2 + d^2}{2}; \\ A &= k - a(d-c)\cos\theta - cd; \\ B &= -2ac.\sin\theta; \\ C &= k - a(d+c)\cos\theta + cd \end{aligned}\right\} \quad (1)$$

ϕ is the angle of the boom (link 'c') with the horizontal as shown in figure 5 (c)

$$\left.\begin{aligned} \phi &= 2Tan^{-1}\left[\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right]; \\ \phi' &= 180 - \phi \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} K' &= \frac{a^2 + b^2 - c^2 + d^2}{2}; \\ D &= k' - a(d+b)\cos\theta + bd; \\ E &= -2ab.\sin\theta; \\ F &= k' - a(d-b)\cos\theta - bd \end{aligned}\right\} \quad (3)$$

β is the angle of the coupler (link ‘b’) with the horizontal as shown in figure 5 (c)

$$\beta = 2Tan^{-1}\left[\frac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right] \qquad (4)$$

γ is the angle between boom and couple link, β’ is the angle between ternary link (link ‘a’) and coupler link , θ is the angle of link ‘a’ with the horizontal and α is the actuator angle with the horizontal as shown in figure 5 (c). The ternary link is formed by length r_2 and ‘a’ as shown in figure 5 (c). The included angle between r2 and link ‘a’ is fixed.

$$\gamma = \phi - \beta; \; \beta' = (180 - \theta) + \beta \qquad (5)$$

$$\left.\begin{aligned} \alpha &= \cos^{-1}\left[\frac{r_2^2 - r_1^2 - L^2}{2r_1 L}\right]; \\ \gamma_1 &= 180 - (\theta_1 + \alpha); \\ L &= \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos\theta_1} \end{aligned}\right\} \qquad (6)$$

The actuator length ‘L’ in equation (6) is found out using cosine rule. ‘θ_1’ is the angle of r_2 with horizontal in counter clock wise direction from r_2.

Linear Speed of the ball screw actuator is given by:

$$\frac{dL}{dt} = \frac{r_1 \times r_2 \times \left(\frac{d\theta_1}{dt}\right) \times \sin\theta_1}{L} \text{ mm/sec;} \qquad (7)$$

$$\text{Ball Screw Speed} = \frac{\frac{dL}{dt}}{Lead} \times 60 \text{ rpm} \qquad (8)$$

The angular velocities of the links ‘a’, ‘b’, ‘c’ and ‘L’ are ω_1, ω_2 , ω_3 and ω_4 respctively. The angular velocity of link ‘a’ that is ω_1 is assumed and follows the trapezoidal profile as shown in figure 6. The angular velocities in equations (10), (11) and (12) ie ω_2, ω_3 and ω_4 have been derived.

$$\frac{d\theta}{dt} = \omega_1; \frac{d\beta}{dt} = \omega_2; \frac{d\emptyset}{dt} = \omega_3 \qquad (9)$$

$$\omega_2 = a\frac{\omega_1 \sin(\emptyset - \theta)}{b \sin(\varphi - \beta)} \qquad (10)$$

$$\omega_3 = a\frac{\omega_1 \sin(\beta - \theta)}{c \sin(\varphi - \beta)} \qquad (11)$$

$$\omega_4 = (r_2\omega_1 - v_4 \sin(\alpha + \theta))/l \cos(\alpha + \theta) \qquad (12)$$

Using , $v = r\omega$, the tangential velocities of the different links is obtained.

Similarly the angular accelerations of the links ‘a’, ‘b’, ‘c’ and ‘L’ are derived and given in equations(13), (14), (15) and (16) repectively.

$$\frac{d\omega_1}{dt} = \alpha_1; \quad \frac{d\omega_2}{dt} = \alpha_2; \quad \frac{d\omega_3}{dt} = \alpha_3 \frac{d\omega_4}{dt} = \alpha_4$$

$$\alpha_2 = \frac{-a\alpha_1 \sin(\emptyset - \theta) + a\,\omega_1^2 \cos(\varphi - \theta) + b\omega_2^2 \cos(\varphi - \theta) - c\omega_3^2}{b} \qquad (13)$$

$$\alpha_3 = (-a\alpha_1 \sin(\beta - \theta) + a\,\omega_1^2 \cos(\beta - \theta) + b\omega_2^2 - c\omega_3^2 \cos(\varphi - \beta))/ c \sin(\varphi - \beta) \qquad (14)$$

$$\alpha_4 = (r_2\ \alpha_1 + r_2\omega^2 \sin 2\theta - 2v_4\omega_4 \cos(\alpha + \theta) + l\omega_4^2 \sin(\theta + \alpha) + 2a_1 \sin\alpha \cos\alpha)/l \cos(\alpha + \theta)) \qquad (15)$$

Using $a = r\alpha$; radial acceleration of all the links

Using $\alpha = r\omega^2$; tangential acceleration of all the links

The forces acting on different links during replenishment and articulation modes were found out. The missile container payload of 4000 kg acts on the linkage system during both articulation and replenishment. Wind load is also being considered to be acting on the system.

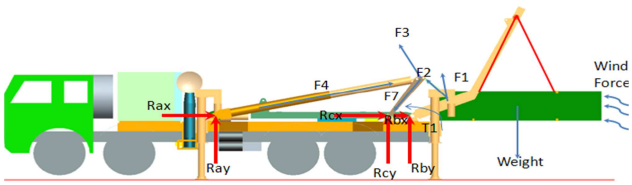


Fig. 7. Forces acting on the Six Bar Mechanism

$$F_1 = \frac{w \times x_3 + windforce \times y_3}{C} \text{ Force perpendicular to Link ‘c’} \qquad (16)$$

$$F_2 = \frac{F_1}{\cos(\gamma - 90)} \text{ .... Force along Link ‘b’} \qquad (17)$$

$$F_3 = F_2 \times \cos(180 - (90 + \beta')) \text{Force perpendicular to Link ‘a’} \qquad (18)$$

Torque at Link `a' Pivot = F_3 x a

Axial Force on Actuator, F_4 is derived and given in equation

$$F_4 = \frac{Torque\_at\_Link\_`a'\_Pivot}{r_2 \sin(\lambda_1)} \tag{19}$$

$$\text{Ball Screw Torque} = \frac{F_4 \times Lead}{2\pi \times \eta.gearbox} \tag{20}$$

$$\text{Motor Torque} = \frac{Screw\_Torque}{gearbox\_ratio \times \eta.gearbox} \tag{21}$$

Motor Speed = Ball screw Speed x Gear Ratio (23)

$$\text{Motor Power} = \frac{2.\pi.N.T}{60000}\ \text{kW} \tag{24}$$

The ternary link angle θ was varied and the other angles of the linkage and the link and actuator forces were found out for obtaining the variation in actuator forces, forces within the links of six bar mechanism and the motor parameters. The linkage dimensions and also the pivot points were changed. And actuator force and link forces were found for various combinations of link dimensions. The link dimensions and pivot distances were finalized when the actuator and link forces are minimal. The actuator axial force (shared by two actuators) variation is given in the figure 8.

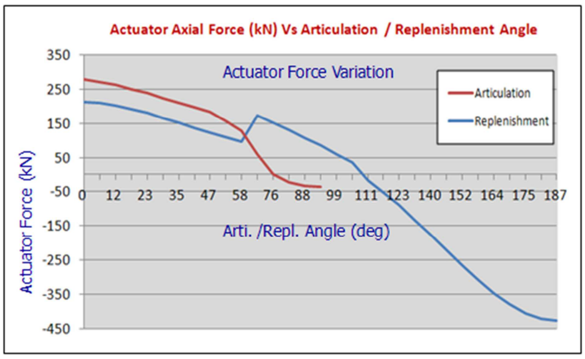


Fig. 8. Variation in Actuator Axial Force during Articulation and Replenishment mode

IV. REALIZATION AND TESTING

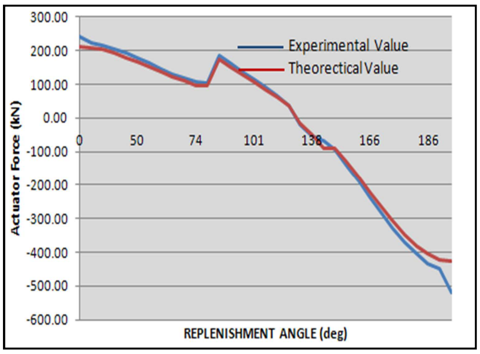
The system is being realized as shown in figure 9 and various functionality tests have been carried out on the system.

(a)

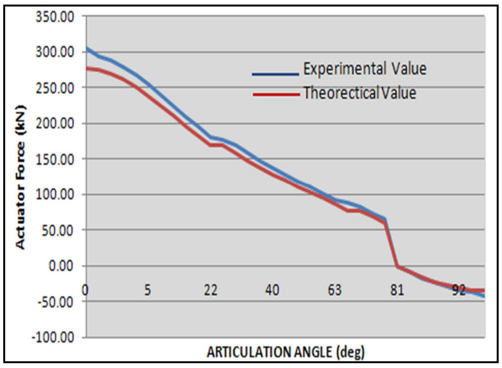
(b)

Fig. 9. (a) Replenishment of the missile container; and (b) Articulation of the missile container

The motor current values and actuator rotational speeds were measured during both replenishment and articulation modes. The experimental actuator force was found out using the measured motor current values. The comparison of actuator force experimentally and theoretically is shown in figure 10. The experimental actuator force values are more than expected values than the theoretical values due to unaccounted friction and system efficiencies.



(a)



(b)

Fig. 10. Comparison of Actuator Force (a) During Articulation and (b) During Replenishment

V. CONCLUSION

We have compared the four-bar and six bar mechanism for use in missile launcher which has unique capability of self replenishment and articulation of the missile container. The launcher quickly replaces the used missile container. The six bar mechanism is better option than four bar mechanism for such kind of missile launcher which has unique mechanism with the help of which the missile container is replenished quickly and articulated for firing. By using this six bar mechanism, the use of external crane is being avoided. The actuator strokes and forces are minimum in six bar mechanism as compared to four bar mechanism; hence manufacturing of the actuator is economical. The parameters such as actuator open length, close length, stroke, transmission angle, actuator axial force, etc were suitably derived to achieve the requisite functionality of the launcher. This system enables quick replenishment as well as the articulation of the missile container using same mechanism which was not possible using four bar mechanism. The system is being manufactured, integrated and all the functionality tests were being carried out and proved to be successful. The system was also proved for proper replenishment and positioning and articulation of the missile container.

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