ME6221 Theory of Mechanisms

Design & Analysis of a Swimming Pool Lift

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Problem Definition

Swimming as an activity is advantageous to everyone and provides multiple physical & mental benefits. However, most swimming pools incorporate stairs for entry & exit which are not accessible to disabled persons. This inhibits them from being able to perform one of the few therapeutic exercises that they can do. The aim of this project is to design a swimming pool lift for the disabled so that they can enter and exit the pool with ease.

The design constraints for the mechanism are stated by the American with Disability Act(ADA 2010) as follows:

1. Height of the seat from the ground = 405-485 mm
2. Clearance of the centre of the seat from the pool = 405 mm
3. Depth into the pool up to which the lift must enter = 455 mm
4. Minimum weight the lift must carry = 136 kg
5. Backrest is nearly vertical at all times

Selection of location for swimming pool lift at IIT Madras swimming pool

The location for the swimming pool was selected as per the space available for mounting & accessibility for wheelchair users. It was decided that the lift must be located at a point where the depth of the pool was as low as possible. The selected position is located in the images below. The depth of the pool at this location is only 1.5 metres & it is easily accessible via a wide ramp through the back gate of the pool.

Fig 1: Selected swimming pool location

Four Bar Synthesis

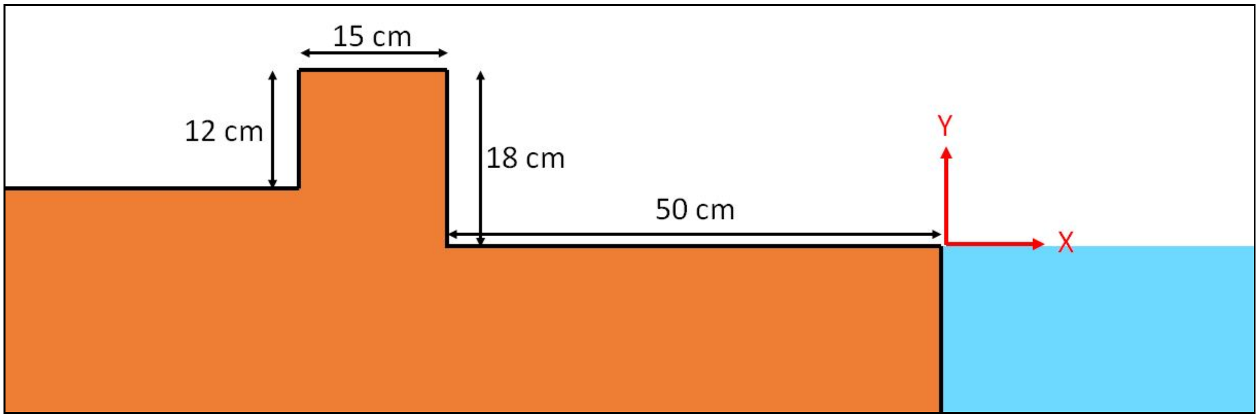

Fig 2: Cross-sectional dimensions of pool edge

Based on the given design parameters, we started with the design for a four bar non-parallelogram mechanism using 4 position analytical synthesis method. We located the global coordinate axes at the edge of the pool. For the four positions, we fixed on the initial and the final position coordinates as: (Xo,Yo): **(-405 mm,485 mm)** and the final position coordinates: (Xf,Yf): **(700mm,-455mm)** based on the prescribed ADA standards. The intermediate 2 positions were chosen such that the path approximately follows an arc or a straight line. The tolerance in the orientation of the seat was given to be around 5-10°. We could not find feasible pivot positions for this method and therefore proceeded towards 3 position synthesis.

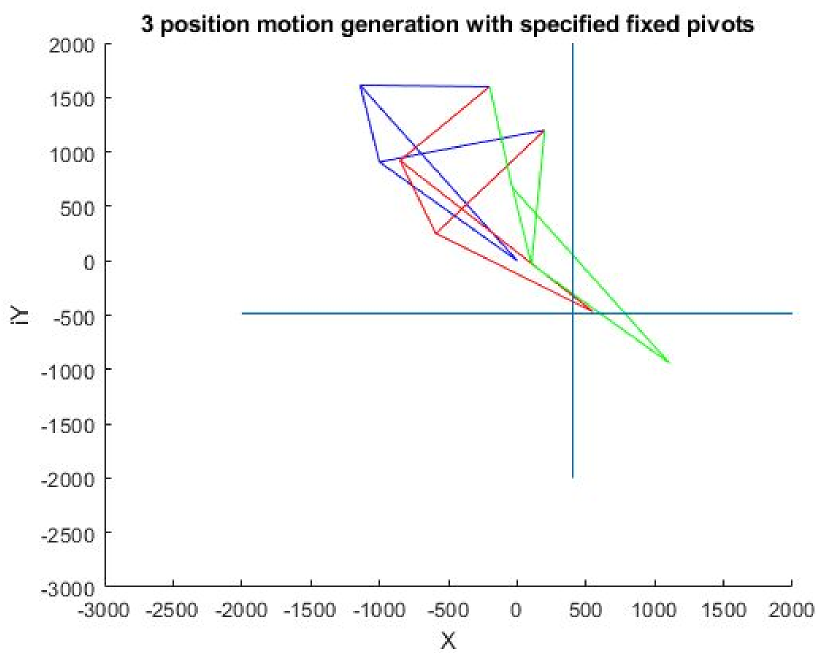

Fig 3: 3 position motion generation with fixed pivots

In 3 position synthesis, we chose the free choices to be the locations of the fixed pivots based on intuition. After several iterations, we found that the choice of fixed pivots placed at a height above the ground near the edge of the swimming pool produced a mechanism which could perform the desired motion. We then chose a generic point in the generated path and re-performed 4 position synthesis to optimize the locations of the fixed pivots.

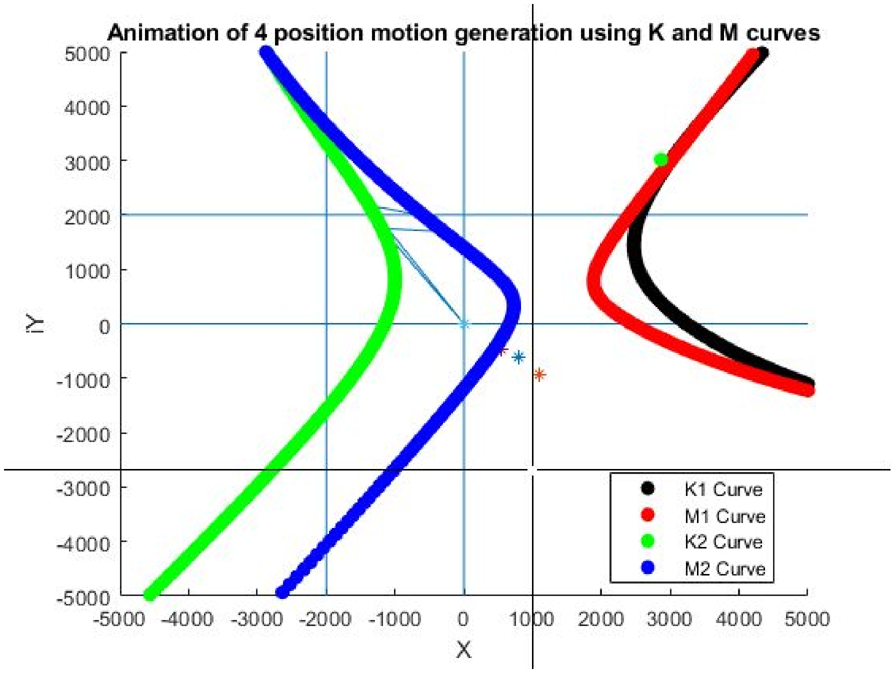

Fig 4: 4 position motion generation using K & M curves

The following equations were used to solve for 3 position synthesis:

$$z1(e^{i\phi 2} - 1) + z2(e^{i\gamma 2} - 1) - \delta 2 = 0$$
$$z1(e^{i\phi 3} - 1) + z2(e^{i\gamma 3} - 1) - \delta 3 = 0$$
$$z1 + z2 = Rp1 - Oa$$
$$z1(e^{i\Psi 2} - 1) + z2(e^{i\gamma 2} - 1) - \delta 2 = 0$$
$$z1(e^{i\Psi 3} - 1) + z2(e^{i\gamma 3} - 1) - \delta 3 = 0$$
$$z3 + z4 = Rp1 - Ob$$

Where z1, z2, z3, z4, z5, z6 are the vectors corresponding to each link,
$\phi 2$, $\phi 3$ are the changes in orientation of input angles
$\gamma 2$, $\gamma 3$ are the changes in orientation of the couplers
$\boldsymbol{\delta}2$, $\boldsymbol{\delta}3$ are the changes in location of coupler position
Rp1 is the location of the coupler point
Oa is the location of the first fixed pivot
Ob is the location of the second fixed pivot

The final link lengths of the mechanism were as follows:

Link	Length(m)	Direction(deg)
Crank length l1	0.941	179.18
Dyad 1 length l2	1.976	-54.73
Follower length l3	1.235	-166.32
Dyad 2 length l4	1.351	-42.21
Coupler length l5	0.719	-78.77
Base length l6	0.565	-45.00

Table 1: List of links with lengths & angles with respect to horizontal at initial position

Counterweights to prevent toppling of the mechanism

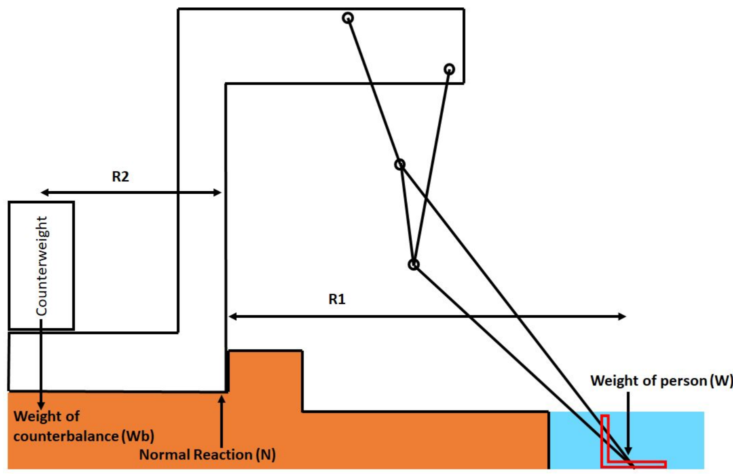

Fig 5: Position of linkage at extreme position(seat lowered into the water)

Gravity balancing is a key component of making the mechanism portable. If the mechanism is not balanced, it will have to be bolted to the ground to prevent toppling when the person is seated making it non-portable.

To counterbalance the proposed mechanism, we took 2 extreme scenarios-

1. The person is seated & the mechanism is at its extreme position into the water
2. There is no one sitting on the mechanism & the mechanism is at its initial position

In the first scenario the counterweight will provide a moment which will balance the weight of the person. The normal reaction will be at the rightmost edge of the base of the mechanism. The masses of the links & the frames are assumed to be negligible as compared to the mass of the person & the counterweight.

$$\Sigma F_y = 0 \Rightarrow R = (W+Wb)*g, \quad \textit{(Eq. 4.1)}$$
$$\Sigma M_z = 0 \Rightarrow W*R1 = Wb*R2, \quad \textit{(Eq. 4.2)}$$

As the mechanism has to be compact, the maximum length of R2 is restricted to 1m. If we calculate the mass of the counterweight required as per these constraints, it is found to be around 150 kgs. This is not **feasible**.

An alternate solution which we can follow is to insert buoys into the water which are connected to the frame through rigid links. These buoys need to be placed into the pool only when the lift is in use & can be removed out of the pool when the lift is not operated. In this way, we can reduce the weight of the counterbalance required. Now the equilibrium equations can be written as follows:

$$\Sigma F_y = 0 \Rightarrow R + (\varrho_w-\varrho)*V*g = (W+Wb)*g, \quad \textit{(Eq. 4.3)}$$
$$\Sigma M_z = 0 \Rightarrow W*g*R1 = Wb*g*R2 + (\varrho_w-\varrho)*V*g*R3, \quad \textit{(Eq. 4.4)}$$

The buoy is assumed to be hollow with very low density of around 1 kgm^{-3}. At the extreme position, if we restrict the weight of the counterbalance to 20 kgs, R2 to 1m, & R3 to 2m, we find the volume of the foam required to be 0.065 m^3. This means we need to displace about 65 litres of water to balance the moments.

The buoy link system could be lowered into the pool with an actuation mechanism that is similar to the linkage used to lower the disabled person into the pool. It can also be linked to the same actuation mechanism as well. As we have control over the amount of distance the buoy is lowered into the pool, we can ensure that the mechanism does not topple in the other direction when no person is sitting in the lift. One limitation is that if there are sudden waves in the water, perhaps due to someone jumping into the water, the system may start rocking.

Spring Balancing

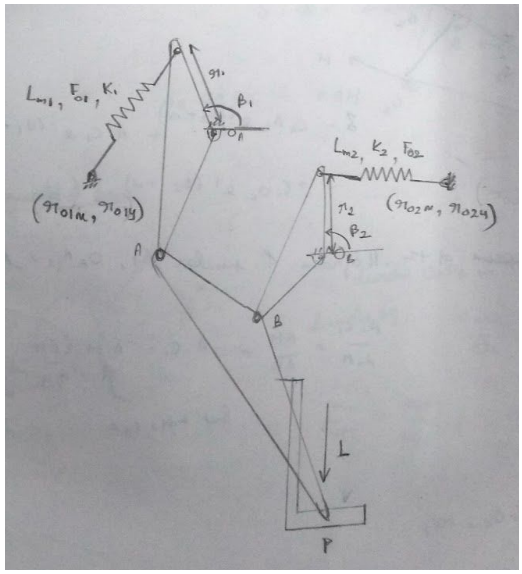

Fig 6: Attachment of springs to links

The mechanism needs to be balanced so as to minimize the force of actuation required. Gas springs are used for this purpose due to their damping properties,compactness and availability of a range of fittings for mounting

<u>Formulation of Optimization Problem</u>:

Potential Energy $P = f(\theta 2)$, *(Eq. 6.1)*

Discretization of $\theta 2 = \{\theta min + d\theta * i,\ 0 < i < (\theta max - \theta min)/d\theta\}$, *(Eq. 6.2)*

Torque $T(i) = (P(\theta 2) - P(\theta 2 + d\theta))/d\theta$, *(Eq. 6.3)*

Mean Square Torque $G = \Sigma T(i)^2/N$, *(Eq. 6.4)*

A gas spring was connected to both the input & output links. The point of connection to the links & the fixed pivots were constrained to be within a feasible range. The potential energy of the system P was calculated as a function of discrete input angle values*(Eq. 6.2)* for the working range of the mechanism. Then the derivative of the potential energy*(Eq. 6.3)* was calculated. This was squared to make the values positive for the working range. This was summed with limits as the minimum & maximum values of the input angle and divided by the total number of steps*(Eq.6.4).* The spring constants, minimum force of the spring, stroke of the spring & minimum length of the spring were varied for different springs & the optimization solver was run each time to find the minimum value of *G* as the output.

Case	RMS Value of Input Torque(Nm)
Without balancing	364.92
With SL06 & SL08 gas spring series	319.97
With SL10 gas spring series	14.93
With SL14 gas spring series	28.60

Table 2: Comparison of RMS values of Input torques for different cases

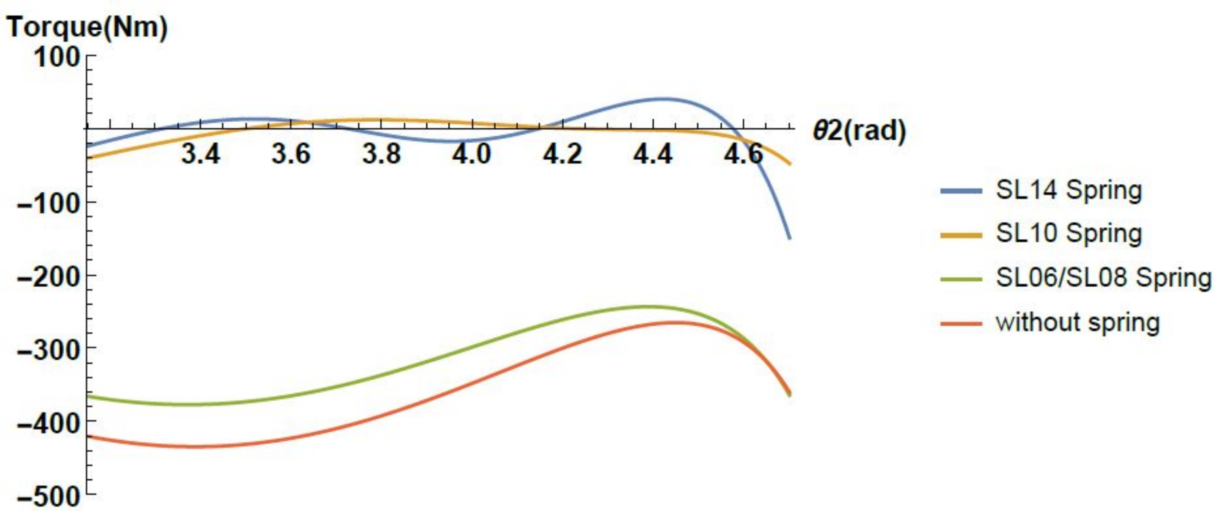

Fig 7: Torque vs angle profile for diff. cases

The springs in SL10 series provide the minimum RMS value of input torque. The chosen springs are SL10-500-1360-S5-B4-750 & SL10-500-1440-S5-B4-620

Force Analysis

The force analysis for the four bar and the driver dyad four bar has been performed with quasi-static approximations i.e. all the velocities and accelerations are taken as zero. The linear mass density of the links is taken to be 1kg/m. The algorithm for the force analysis is as follows:

- The initial configuration is found and the operational range of angle is given as input, along with the spring parameters
- Over a loop iterate on the following-
    - Calculate the force and moments using the force analysis equations.
    - A*F=B

      B= input matrix (accelerations of links)

F= force matrix [τ F_{ox} F_{oy} F_{1x} F_{1y} F_{2x} F_{2y} F_{3x} F_{3y}]^T

A= coefficient matrix

Driver Dyad synthesis

The driver dyad synthesis aimed to optimize the mechanical advantage within the range of the link lengths specified based on the ergonomic considerations. The link lengths has a cap of 0.6m for the links. The optimization algorithm works as follows:

- Iterates over this range of link lengths, for a fixed input torque on the driver dyad, compute the output torque of the driver dyad.
- Compare the output torque of driver dyad with the input torque required for the four bar, selecting the combinations for which the torque output of driver dyad is greater than the input required over the entire range operational angle and for a fixed input driver dyad torque.
- Select the combination which has the highest root-mean-square torque as the optimal solution.

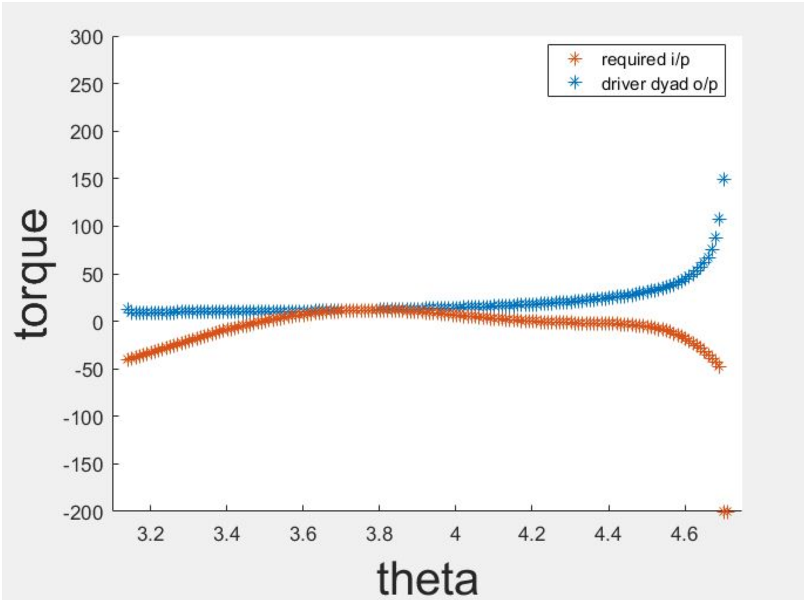

Fig 8: Torque vs theta for driver dyad synthesis

Link	Length(m)
Rocker	0.3
Coupler	0.6
Crank	0.1
Base	0.4

Table 1: List of links of driver dyad with lengths

References

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3. Sushant Veer, S. Sujatha, "*Approximate spring balancing of linkages to reduce actuator requirements",* Mechanism and Machine Theory 86 (2015) 108–124