Optimal Synthesis of a 4-Bar Simple Toggle

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Abstract: Optimal synthesis of mechanisms is a successful approach for mechanism design to satisfy all the desired characteristics of the designed mechanism. Toggles have wide industrial applications such as riveting, punching, pressing, and clamping.

The toggle optimal design problem is a constrained multi-dimensional problem. Powell optimization technique is used to maximize the mechanical advantage of the toggle. 2 functional constraint functions are used to perform a successful optimization.

The toggle force analysis in the static mode is performed in a dimensionless form. The results are tabulated for an easy reference to them without any calculations for any desired mechanical advantage of the toggle. Mechanical advantage in the range of 3.9 to 340 is selectable for specific constraints on the toggle input link length and operating conditions of the toggle.

Using the optimal design table could satisfy the toggle objectives with errors less than 0.3 %.

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1. Introduction

Mechanical toggles represent the muscles of machinery required for some important processes such as riveting, punching, pressing, bonding and clamping. Successful synthesis of toggles leads to a successful machine design with minimum input effort either manual of mechanical. On the other hand, optimal toggle design leads to satisfying desired operation constraints such as coupler inclination and slider (tool) position from the fixed pivot of the toggle.

The presented approach in this work is essential for small industries especially in the developed countries.

Design of toggles has gained some interest among international researchers. **Mostofi (1985)** investigated the dynamic performance of a toggle mechanism. He showed that the toggle performance under Coulomb friction depends highly upon the input energy of the system [1]. **Yossifon and Shivpuri (1993)** optimized the design of a double knuckle toggle linkage for mechanical presses using kinematic simulation and an enumeration search procedure [2]. **Howell and Midha (1995)** studied the compliance of the work-piece on the input / output characteristics of a rigid-link toggle mechanism [3]. **Fung et.al. (1997)** used a constrained multi-body technique to calculate the position, velocity and acceleration of the toggle mechanism [4]. **Fung and Yang (2001)** studied the motion control of a toggle mechanism actuated by an electro-hydraulic system. The control system was a nonlinear time-varying one [5]. **Fung et.al. (2001)** investigated the dynamic problem of the control of a toggle mechanism driven by a linear synchronous motor. They considered Coulomb friction in the toggle joints [6**]. Tso and Liang (2002)** proposed a 9-bar linkage for a toggle used in in mechanical forming presses. They optimized the toggle dimensions using linkage synthesis and the trial and error method [7]. **Lin and Wai (2002)** studied the dynamic response of a hybrid computed torque controlled toggle mechanism driven by a permanent magnet synchronous motor [8]. **Lin and Chang (2002)** proposes a force transmissivity index for planar linkage mechanisms. They concluded that the proposed index can be used as a better measure of force transmissivity for planar linkage mechanisms [9**]. Wai (2003)** proposed a robust control system using a Takagi – Sugeno – Kang type fuzzy-neural network to control a nonlinear toggle mechanism driven by a permanent magnet synchronous servomotor [10**]. Lin and Hsiao (2003)** proposed an analytical formulation of the thrust of a 5-point double-toggle clamping mechanism during mold clamping. The effect of friction at in joints is investigated [11]. **Englender (2007)** studied reducing the cycle time of an injection molding machine by operating its clamping unit with minimum time. He proposed a nonlinear controller having a cascade structure [12]. **Chuang et.al. (2008)** studied numerically and experimentally the dynamic motion of an adaptive feedback-controlled punching machine. The machine was made of a toggle driven by a permanent magnet synchronous servomotor [13]. **Huang et.al. (2009)** derived the dynamic equations of a punching machine toggle mechanism using Hamilton's, Lagrange multiplier , geometric constraints and partitioning method. They used the recursive least squares method to identify the motor-toggle unknown parameters [14]. **Huang et.al.(2011)** explored the effect of the key design parameters on the performance of a 5-point double-toggle clamping mechanism. They used the genetic algorithm to obtain the optimal solution of the clamping mechanism [15].

2. Analysis

Assumptions:

- Neglecting element weight.
- The design problem is static (neglecting inertia forces and moments).

Links orientation and positions: See Fig.1:

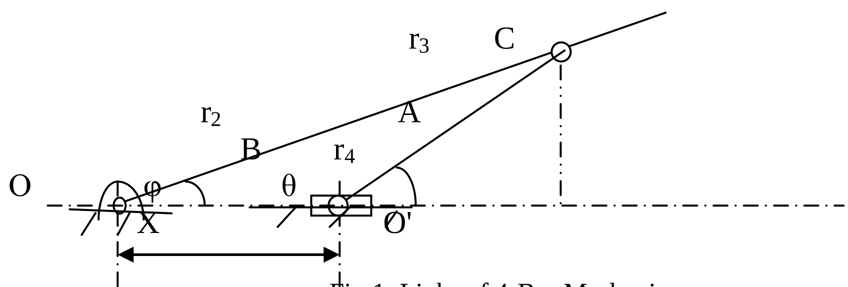

Fig.1: Links of 4-Bar Mechanism

Notations:

r_2:	length of input link OA.
r_3:	length of AC.
r_4:	length of coupler link AB.
X:	slider position relative to origin O.
θ:	orientation of coupler.
φ:	orientation of input link.

Known parameters:

- Coupler angle, θ.
- Slider position, X.

Normalized design parameters:

- Input force portion link, r_{3n}.
- Coupler link, r_{4n}.

Input link orientation, φ:

In ΔOAO' and ΔBAO' of Fig.1, φ is given by:

$$\varphi = \sin^{-1}\{r_{4n} \sin\theta\} \quad (1)$$

Toggle force analysis:

The free body diagrams of the input link 2 are constructed below as in Fig.2

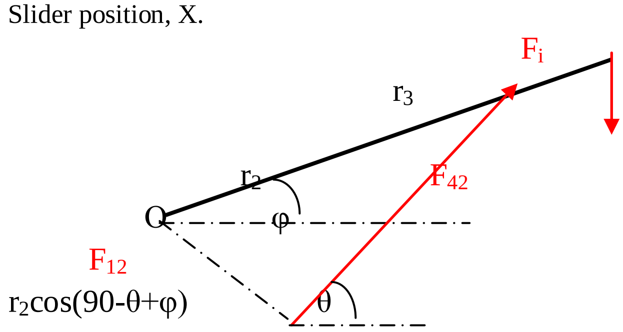

Fig.2: Free body diagram of Link 2

- Moment about O gives:

$$F_i\,[(r_2 + r_3)\cos\varphi] = F_{42}\, r_2 \cos(90\text{-}\theta+\varphi)$$

- Giving:

$$F_{42} = \frac{(r_2 + r_3)\cos\varphi}{r_2 \cos(90-\theta+\varphi)} F_i \quad (2)$$

- Normalizing the dimensions and force through:

$r_{3n} = r_3/r_2$, $r_{4n} = r_4/r_2$, $F_{42n} = F_{42} / F_i$

- Eq.2 becomes:

$$F_{42n} = \frac{(1 + r_{3n})\cos\varphi}{\cos(90-\theta+\varphi)} \quad (3)$$

free body diagram for the toggle slider show in Fig.3

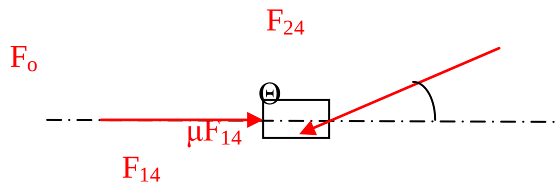

Fig.3: Free body Diagram of 4-bar Mechanism's slider

Using $\sum F_y = 0$:

$F_{14} = F_{24} \sin\theta$ (4)

Using $\sum F_x = 0$:

$F_o = F_{24} \cos\theta - \mu F_{14}$ (5)

Combining Eqs. 3, 4 and 5 with $F_{24} = F_{42}$ gives:

$$F_o = \frac{(\cos\theta - \mu\sin\theta)(r_2 + r_3)\cos\varphi}{r_2 \cos(90-\theta+\varphi)} F_i \quad (6)$$

Mechanical advantage, MA:

Definition: $MA = F_o / F_i$

Equation: Using Eq. 6 and the normalized parameters:

$$MA = \frac{(\cos\theta - \mu\sin\theta)(1 + r_{3n})\cos\varphi}{\cos(90-\theta+\varphi)} F_i \quad (7)$$

3. Optimal toggle design

Objective function, F: The objective function of the toggle design problem is selected as the mechanical advantage (MA) which has to be maximized.

Mechanism design variables: r_{3n} and r_{4n}.

Design inputs:

- Normalized slider position: X_n (X/r_2)
- Coupler angle: θ
- Coefficient of friction: μ

Coefficient of friction, μ: The coefficient of friction depends on the surface material, sliding speed, normal force and lubrication oil temperature **[16].** Depending on the above parameters the coefficient of friction for lubricated sliders lie in the range: $0.04 \leq \mu \leq 1.20$ **[17].**

3.1. Functional constraints:

The functional constraints of the optimization problems are set to obtain a successful optimization process. In the toggle optimization problem, the functional constraints are:

- Functional constraint 1: r_4 has to be greater than the projection of r_2 on the vertical. Thus:

$r_{4n} > r_2 \sin\varphi$

Using the normalized variables, the first functional constraint is:

$FF(1) = r_{4n} - \sin\varphi > 0$ (8)

- Functional constraint 2: It is about the slider position X from O (see Fig.1). X is related to the toggle parameters through:

$X = r_2 \cos\varphi - r_4 \cos\theta$

Using the normalized dimensions:

$X_n = \cos\varphi - r_{4n} \cos\theta$ (9)

Eq.9 represents the second functional constraint:

$FF(2) = \cos\varphi - r_{4n} \cos\theta$ (10)

It has an upper limit defined by the desired position of the slider during processing (it is set as a fraction of r_2).

4. Optimization results

- The objective function given by Eq.7 is maximized considering the constraints given by Eqs. 9 and 10 using any suitable optimization technique.
- Optimization technique: The Powell optimization technique of unconstrained problems is applied after problem transformation to cope with constrained multi-variables problems without functions differentiation **[18-20].**
- The optimization results using Powell's technique for an 0.08 coefficient of friction and a variable values of the maximum r_{3n} are given in:
  - Tables 1 – 8 for $X_n = 0.1$.
  - Tables 9 – 16 for $X_n = 0.2$.
  - Tables 17 – 24 for $X_n = 0.3$.

Table 1: Optimal toggle design for $X_n = 0.1$ and $\theta = 5^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.1	0.1	0.9	135.753
0.2	0.2	0.9	135.761
0.4	0.4	0.9	158.387
0.6	0.6	0.9	181.006
0.8	0.8	0.9	203.633
1.0	1.0	0.9	226.268
1.2	1.2	0.9	248.882
1.4	1.4	0.9	271.512
1.6	1.6	0.9	294.116
1.8	1.8	0.9	316.776
2.0	2.0	0.9	339.364

Table 2: Optimal toggle design for $X_n = 0.1$ and $\theta = 10^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.901	66.264
0.4	0.4	0.901	77.307
0.6	0.6	0.901	88.351
0.8	0.8	0.901	99.392
1.0	1.0	0.901	110.436
1.2	1.2	0.901	121.479
1.4	1.4	0.901	132.527
1.6	1.6	0.901	143.559
1.8	1.8	0.901	154.609
2.0	2.0	0.901	165.653

Table 3: Optimal toggle design for $X_n = 0.1$ and $\theta = 15^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.3	0.3	0.903	46.159
0.4	0.4	0.903	49.710
0.6	0.6	0.903	56.810
0.8	0.8	0.903	63.912
1.0	1.0	0.903	71.013
1.2	1.2	0.903	78.116
1.4	1.4	0.903	85.215
1.6	1.6	0.903	92.315
1.8	1.8	0.903	99.418
2.0	2.0	0.903	106.519

Table 4: Optimal toggle design for $X_n = 0.1$ and $\theta = 20^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.3	0.3	0.905	32.971
0.4	0.4	0.905	35.508
0.6	0.6	0.905	40.580
0.8	0.8	0.905	45.905
1.0	1.0	0.905	50.725
1.2	1.2	0.905	55.798
1.4	1.4	0.905	60.870
1.6	1.6	0.905	65.941
1.8	1.8	0.905	71.014
2.0	2.0	0.905	76.085

Table 5: Optimal toggle design for $X_n = 0.1$ and $\theta = 25^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.908	22.875
0.3	0.3	0.905	24.779
0.4	0.4	0.905	26.687
0.6	0.6	0.905	30.499
0.8	0.8	0.905	34.311
1.0	1.0	0.905	38.124
1.2	1.2	0.905	41.936
1.4	1.4	0.905	45.749
1.6	1.6	0.905	49.561
1.8	1.8	0.905	53.374
2.0	2.0	0.905	57.185

Table 6: Optimal toggle design for $X_n = 0.1$ and $\theta = 30^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.3	0.3	0.912	19.110
0.4	0.4	0.912	20.581
0.6	0.6	0.912	23.523
0.8	0.8	0.912	26.461
1.0	1.0	0.912	29.404
1.2	1.2	0.912	32.344
1.4	1.4	0.912	35.285
1.6	1.6	0.912	38.224
1.8	1.8	0.912	41.165
2.0	2.0	0.912	44.105

Table 7: Optimal toggle design for $X_n = 0.1$ and $\theta = 35^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.916	13.760
0.3	0.3	0.916	14.909
0.4	0.4	0.916	16.054
0.6	0.6	0.916	18.347
0.8	0.8	0.916	20.641
1.0	1.0	0.916	22.935
1.2	1.2	0.916	25.231
1.4	1.4	0.916	27.521
1.6	1.6	0.916	29.818
1.8	1.8	0.916	32.109
2.0	2.0	0.916	34.402

Table 8: Optimal toggle design for $X_n = 0.1$ and $\theta = 40^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.4	0.4	0.921	12.540
0.6	0.6	0.921	14.331
0.8	0.8	0.921	16.125
1.0	1.0	0.921	17.916
1.2	1.2	0.921	19.705
1.4	1.4	0.921	21.499
1.6	1.6	0.921	23.289
1.8	1.8	0.921	25.083
2.0	2.0	0.921	26.874

Table 9: Optimal toggle design for $X_n = 0.2$ and $\theta = 5^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.3	0.3	0.801	73.590
0.4	0.4	0.801	79.246
0.6	0.6	0.801	90.572
0.8	0.8	0.801	101.893
1.0	1.0	0.801	113.216
1.2	1.2	0.801	124.537
1.4	1.4	0.801	135.859
1.6	1.6	0.801	147.180
1.8	1.8	0.801	158.500
2.0	2.0	0.801	168.823

Table 10: Optimal toggle design for $X_n = 0.2$ and $\theta = 10^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.3	0.3	0.802	35.985
0.4	0.4	0.802	38.753
0.6	0.6	0.802	44.289
0.8	0.8	0.802	49.825
1.0	1.0	0.802	55.361
1.2	1.2	0.802	60.898
1.4	1.4	0.802	66.430
1.6	1.6	0.802	71.975
1.8	1.8	0.802	77.506
2.0	2.0	0.802	83.047

Table 11: Optimal toggle design for $X_n = 0.2$ and $\theta = 15^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.805	21.430
0.3	0.3	0.805	23.215
0.4	0.4	0.805	25.002
0.6	0.6	0.805	28.572
0.8	0.8	0.805	32.141
1.0	1.0	0.805	35.716
1.2	1.2	0.805	39.286
1.4	1.4	0.805	42.861
1.6	1.6	0.805	46.429
1.8	1.8	0.805	50.000
2.0	2.0	0.805	53.571

Table 12: Optimal toggle design for $X_n = 0.2$ and $\theta = 20^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.810	15.378
0.3	0.3	0.810	16.659
0.4	0.4	0.810	17.941
0.6	0.6	0.810	20.504
0.8	0.8	0.810	23.066
1.0	1.0	0.810	25.630
1.2	1.2	0.810	28.192
1.4	1.4	0.810	30.755
1.6	1.6	0.810	33.317
1.8	1.8	0.810	35.883
2.0	2.0	0.810	38.444

Table 13: Optimal toggle design for $X_n = 0.2$ and $\theta = 25^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.815	13.328
0.3	0.3	0.815	14.438
0.4	0.4	0.815	15.549
0.6	0.6	0.815	17.770
0.8	0.8	0.815	19.992
1.0	1.0	0.815	22.212
1.2	1.2	0.815	24.434
1.4	1.4	0.815	26.655
1.6	1.6	0.815	28.875
1.8	1.8	0.815	31.097
2.0	2.0	0.815	33.315

Table 14: Optimal toggle design for $X_n = 0.2$ and $\theta = 30^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.822	10.940
0.3	0.3	0.822	11.851
0.4	0.4	0.822	12.763
0.6	0.6	0.822	14.586
0.8	0.8	0.822	16.409
1.0	1.0	0.822	18.233
1.2	1.2	0.822	20.055
1.4	1.4	0.822	21.879
1.6	1.6	0.822	23.703
1.8	1.8	0.822	25.525
2.0	2.0	0.822	27.350

Table 15: Optimal toggle design for $X_n = 0.2$ and $\theta = 35^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.830	9.201
0.3	0.3	0.830	9.967
0.4	0.4	0.830	10.734
0.6	0.6	0.830	12.267
0.8	0.8	0.830	13.800
1.0	1.0	0.830	15.334
1.2	1.2	0.830	16.867
1.4	1.4	0.830	18.401
1.6	1.6	0.830	19.933
1.8	1.8	0.830	21.468
2.0	2.0	0.830	23.000

Table 16: Optimal toggle design for $X_n = 0.2$ and $\theta = 40^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.838	5.619
0.3	0.3	0.838	6.087
0.4	0.4	0.838	6.555
0.6	0.6	0.838	7.491
0.8	0.8	0.838	8.428
1.0	1.0	0.838	9.363
1.2	1.2	0.838	10.301
1.4	1.4	0.838	11.237
1.6	1.6	0.838	12.173
1.8	1.8	0.838	13.110
2.0	2.0	0.838	14.047

Table 17: Optimal toggle design for $X_n = 0.3$ and $\theta = 5^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.701	45.312
0.3	0.3	0.701	49.089
0.4	0.4	0.701	52.866
0.6	0.6	0.701	60.414
0.8	0.8	0.701	67.970
1.0	1.0	0.701	75.522
1.2	1.2	0.701	83.074
1.4	1.4	0.701	90.623
1.6	1.6	0.701	98.173
1.8	1.8	0.701	105.725
2.0	2.0	0.701	113.272

Table 18: Optimal toggle design for $X_n = 0.3$ and $\theta = 10^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.703	22.197
0.3	0.3	0.703	24.047
0.4	0.4	0.703	25.897
0.6	0.6	0.703	29.596
0.8	0.8	0.703	33.296
1.0	1.0	0.703	36.994
1.2	1.2	0.703	40.695
1.4	1.4	0.703	44.392
1.6	1.6	0.703	48.092
1.8	1.8	0.703	51.792
2.0	2.0	0.703	55.490

Table 19: Optimal toggle design for $X_n = 0.3$ and $\theta = 15^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.707	14.361
0.3	0.3	0.707	15.558
0.4	0.4	0.707	16.755
0.6	0.6	0.707	19.148
0.8	0.8	0.707	21.542
1.0	1.0	0.707	23.935
1.2	1.2	0.707	26.328
1.4	1.4	0.707	28.722
1.6	1.6	0.707	31.115
1.8	1.8	0.707	33.509
2.0	2.0	0.707	35.903

Table 20: Optimal toggle design for $X_n = 0.3$ and $\theta = 20^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.713	10.348
0.3	0.3	0.713	11.210
0.4	0.4	0.713	12.072
0.6	0.6	0.713	13.796
0.8	0.8	0.713	15.521
1.0	1.0	0.713	17.246
1.2	1.2	0.713	18.970
1.4	1.4	0.713	20.696
1.6	1.6	0.713	22.420
1.8	1.8	0.713	24.145
2.0	2.0	0.713	25.869

Table 21: Optimal toggle design for $X_n = 0.3$ and $\theta = 25^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.720	7.866
0.3	0.3	0.720	8.522
0.4	0.4	0.720	9.177
0.6	0.6	0.720	10.488
0.8	0.8	0.720	11.799
1.0	1.0	0.720	13.111
1.2	1.2	0.720	14.422
1.4	1.4	0.720	15.733
1.6	1.6	0.720	17.044
1.8	1.8	0.720	18.354
2.0	2.0	0.720	19.666

Table 22 Optimal toggle design for $X_n = 0.3$ and $\theta = 30^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.729	6.154
0.3	0.3	0.729	6.667
0.4	0.4	0.729	7.179
0.6	0.6	0.729	8.205
0.8	0.8	0.729	9.230
1.0	1.0	0.729	10.256
1.2	1.2	0.729	11.282
1.4	1.4	0.729	12.307
1.6	1.6	0.729	13.333
1.8	1.8	0.729	14.359
2.0	2.0	0.729	15.384

Table 23: Optimal toggle design for $X_n = 0.3$ and $\theta = 35^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.739	4.884
0.3	0.3	0.739	5.291
0.4	0.4	0.739	5.698
0.6	0.6	0.739	6.512
0.8	0.8	0.739	7.325
1.0	1.0	0.739	8.139
1.2	1.2	0.739	8.953
1.4	1.4	0.739	9.767
1.6	1.6	0.739	10.581
1.8	1.8	0.739	11.395
2.0	2.0	0.739	12.209

Table 24: Optimal toggle design for $X_n = 0.3$ and $\theta = 40^o$:

r_{3nmax}	r_{3n}	r_{4n}	MA
0.2	0.2	0.751	3.894
0.3	0.3	0.751	4.218
0.4	0.4	0.751	4.543
0.6	0.6	0.751	5.192
0.8	0.8	0.751	5.841
1.0	1.0	0.751	6.490
1.2	1.2	0.751	7.139
1.4	1.4	0.751	7.788
1.6	1.6	0.751	8.437
1.8	1.8	0.751	9.086
2.0	2.0	0.751	9.735

5. Tables application

The 24 tables of the toggle optimal design covers:

- The slider normalized positions: 0.1 , 0.2 and 0.3.
- The coupler orientation: 5, 10 , 15 , 20 , 25 , 30 , 35 and 40 degrees
    - Maximum normalized input link part: 0.1 – 2

The tables also cover:

- A toggle mechanical advantage from 3.894 up to 339.364 with small increments.
- Small mechanical advantage suits weak materials such as plastics and thin metallic sheets.
- This allows easy location of a desired mechanical advantage without need to curve fitting or interpolation.
- Presenting the results in a normalized form gives the mechanical engineer a good chance to assign the toggle dimensions to suit his application.
- The next section illustrates the use of the optimal design tables in designing a toggle for a specific application.

6. Case Study

A mechanical process requires a force of 5 KN. The operator can exert a hand force of 100 N. We want to find the optimal dimensions and other parameters of the simple toggle studied in this paper.

The desired mechanical advantage is:

MA = 5000 / 100 = 50.

Using Table 11, the toggle parameters are:

- Normalized slider position: $X_n = 0.2$.
- Coupler orientation: $\theta = 15^o$.
- Normalized input force part: $r_{3n} = 1.8$
- Normalized coupler: $r_{4n} = 0.805$

Let $r_2 = 100$ mm.

This gives the toggle dimensions:

- Slider position from O: X = 20 mm.
- Input link part: $r_3 = 180$ mm.
- Coupler: $r_4 = 80.5$ mm.

Calculations using the simple toggle analysis:

- Input link orientation: $\varphi = 12.026^o$
- Mechanism transmission angle: TA = 105^o.
- Coupler force: $F_{42} = 527.77$ N
- Mechanical advantage: MA = 49.886
- Slider position: X = 20.048 mm

6. Discussions

- Optimization is a powerful technique which leads to successful kinematic design of machinery.
- It tries to satisfy all the kinematic constraints assigned by the designer.
- The optimal design process of the simple 4-links toggle is reduced to the assignment of the input link length , coupler length for a desired mechanical advantage.
- Mechanical advantage ranged from 3.894 to 339.364.
- The optimization results is tabulated in 24 table to simplify using them without need to curve fitting or interpolation.

- A range 0.1 – 0.3 is covered for the normalized toggle slider position.
- A range 5 – 40 degrees is covered for the coupler orientation.
- A case study about using the toggle optimal design tables showed that:
  - The error in the desired mechanical advantage is only 0.228 %.
  - The error in the slider position is only – 0.242 %.
  - This error is due to rounding the toggle dimensions in the tables.

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