Investigation on Effect of Design Parameters of Toggle Clamping Mechanism on Output Force

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***Abstract*—Toggle mechanism is commonly used in manufacturing industry for several applications ranging from injection molding machines to tools & fixtures. Toggle clamps are available in numerous types to outfit specific application. This paper explores the design optimization of the toggle clamping mechanism. Toggle mechanism considered here is actuated by hydraulic cylinder. Force amplification ratio is the key design parameter toggle clamping mechanism. Performance of toggle clamp mechanism is based upon the force available at the clamping location which is output link. Clamping force available at the output link is the function of the input cylinder force, geometric position of all the links, coefficient of friction between moving and turning parts. Hydraulic cylinder is available in different standard sizes and is operated on specific system pressure; input cylinder force is the function of cylinder size and the system operating pressure. Mathematical modelling of the toggle clamp mechanism is presented in this paper. Analytical approach and CAD model force analysis is carried out. Resulting clamping force computed from the analytical approach is compared with the clamping force obtained from the CAD model analysis. Design of Experiments (DOE) methodology is obtained to reach out the different combinations of the input variables and overall system design is optimized.**

Keywords: Toggle mechanism, CAD analysis, Clamping force

I. INTRODUCTION

Toogle clamping mechanism is one of the most desired mechanisms in manufacturing industry. It is mostly used for assisting the processes such as bending, welding, fitting, grinding, fitting and other similar metal handling processes. Tools & fixtures industry are the frequent user of the toggle clamp mechanism, metal working and assembly are the areas where this mechanism is seen often.

In the earlier work done in the area [1] kinematic analysis of the toggle clamping mechanism with CAD analysis and analytical approach is presented. Ming-Shyan Haung et.al [2] described that toggle mechanism can produce considerably higher clamping force for the given input force. That is an important feature which makes this mechanism one of the preferred clamping mechanisms. Pei-Lum Tso [3] instructed that decent clamping fixture must be proficient of overcoming the extreme possible force exerted by the work-piece and should be easy to actuate, positioned, or loosened. Burton [4] explains hinge friction in the toggle mechanism. Beer and Johnston [5] utilized virtual work principle to perform analysis of toggle vise. Mechanisms with more than four links are usually fragmented into basic linkages for simplifying the analysis of the complete mechanism. Four bar linkage and Slider – Crank linkage are the most favorite basic linkages for toggle mechanism fragmentation, converting toggle mechanism into four bar linkage and slider crank linkage will simplify the complete linkage and analysis can be done with ease. [6,7]

Lin and Kuo [8] evaluated the thrust requirement for mold-clamping process of five point double toggle clamping mechanism; they also proposed the formula to evaluate thrust of cross head mechanism for given clamping force. Fung et al. [9] applied Hamilton’s principle and Lagrange’s multiplier method for assessment of an expression for the inertial force and the mechanism thrust. The Runge–Kutta integral method was utilized to explore the kinematics and dynamics and compare them with four-point and five-point toggle mechanisms.

Fung et al. [10] observed the kinematics sensitivity of a toggle mechanism, which is reflected as a combination of two slider-crank mechanisms, and shown improved clamping efficiency. To decrease the friction force, Fung et al. [11] put forward a new demonstration of the toggle mechanism which is functioned by a precise permanent magnet and linear synchronous motor instead of gears and other additional mechanisms. Toggle clamp mechanism is a typical example of mechanical advantage utilization. Manually operated toggle clamp are most common in small and mid-scale industries to be operated for fixtures while machining and bending operations. The toggle clamps have the benefit of their favorable power to movement ratio, and easy action.

II. SYTEM DESCRIPTION

Fig. 1 shows the toggle clamping mechanism. Ground link is represented by link C and other details are as follows;

A – Clamping member (output link)
P – Input link (Hydraulic cylinder)
C – Ground link
m – Coupler (Output link)

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n – Crank (Support link)
r,q –Hydraulics lines

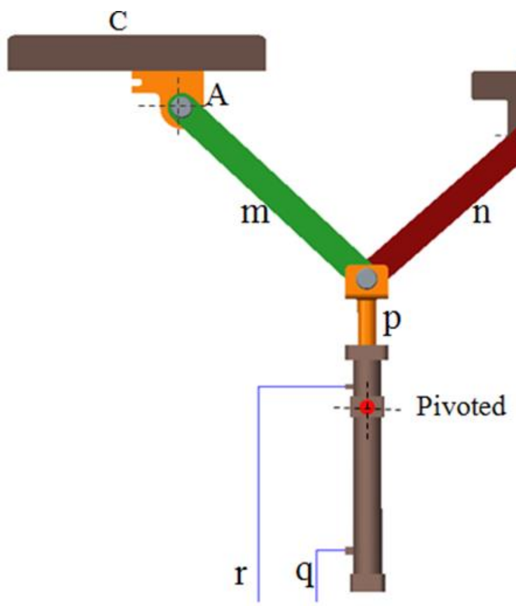

Fig.1: System Description

Input velocity and hence input force for the toggle clamping mechanism is produced by means of hydraulic system pressure. Hydraulic cylinder is an actuator for the complete toggle clamping system. Clamping member A is an output member which grips the clamping jaw. Output link speed and the thrust available at the output link to hold or clamp the work piece is a function of the actuator parameters (system pressure, hydraulic cylinder specifications) mechanism configuration, link position, link lengths, joint friction and.

III. DESIGN METHODOLOGY

The primary purpose of the toggle clamping mechanism design is to generate a higher mechanical advantage and leverage at lower cost of overall mechanism. Design parameters of the toggle clamp mechanism explained here are crucial in expressing the optimization function of the toggle clamping mechanism. This optimization function can be solved using different optimization techniques such as genetic algorithm or artificial neural network and design of experiments (DOE). DOE approach is best suited here to generate the best possible combinations of the input variables to get the maximum possible clamping thrust.

Following parameters are important for toggle clamping mechanism design:

1. Force magnification factor
2. Stroke and velocity of hydraulic cylinder
3. Speed of the clamping/sliding member
4. Pin reaction & friction at slider joints
5. Initial configuration of mechanism
6. Structural strength of the links

1. Force magnification factor is the key feature for the design and optimization of the toggle clamp mechanism, mechanical advantage plays important role minimize the input force and to maximize the output force

2. Stroke and velocity of hydraulic actuator can be set as required hydraulic pressure can be adjusted and fine –tuned at initial setting. Selection of actuator is depend upon the force requirement for mechanism operation

3. Velocity of the clamping member is a function of linkage position, input velocity of hydraulic actuator, frictional effect in sliding members and pin joints

4. Pin reaction at joints is also important parameter to be considered for the performance of the toggle clamp mechanism

Toggle clamping mechanisms is one of the classic examples of the mechanism which utilizes the mechanical advantage. Emphasis is given on generating the maximum torque or movement at the output member with the given input, considering constraints on space available. Input force generated by the actuator is transmitted to the coupler link via pin joints, consideration of pin joint design, material of pin and overall friction in the joint are some of the important considerations in the design of the toggle clamp linkage. Locking of the mechanism is avoided by constraining the joints appropriately and it is ensured that the minimum angle to be maintained between coupler link and crank. The instant when the angle between coupler link and crank becomes 180^0, toggle mechanism get locked. So it is necessary to maintain a minimum angle between these two links in the fully extended condition.

Material selection is one the key aspects in design of any machine components, considering working conditions of the toggle linkages coupler link and crank will experience tensile as well as compressive loads, pin locations are subjected to the shear load.

IV. ANALYTICAL PROCEDURE

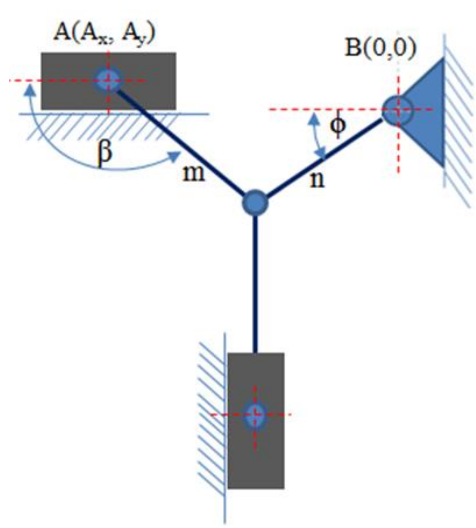

Fig. 2 : Analytical Method

Toggle clamp mechanism considered here is analyzed for the output link member. Analytical approach outcomes are compared with CAD modelling and analysis. For analytical study forces in link m & n are resolved summation of vertical, horizontal forces and moments are consider solving the problem for unknown reactions. Dynamic equilibrium is considered here for this problem. While cylinder is actuated for the initial condition, linkage needs to overcome the self-weight and inertial effect which is a product of mass moment of inertia and the angular acceleration of the linkage.

Output force is evaluated at the extreme position of the linkage while cylinder is completely open cylinder force is multiplied with the help of mechanical leverage or mechanical advantage. Junction 1 is where link m & n are joined together and cylinder is also attached at this junction to actuate the mechanism.

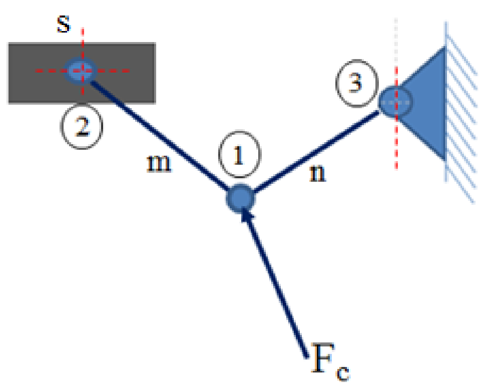

Fig. 3 : Force Resolution

Link m is solved for all the forces in the links junction 1 is common in both the links m and n.

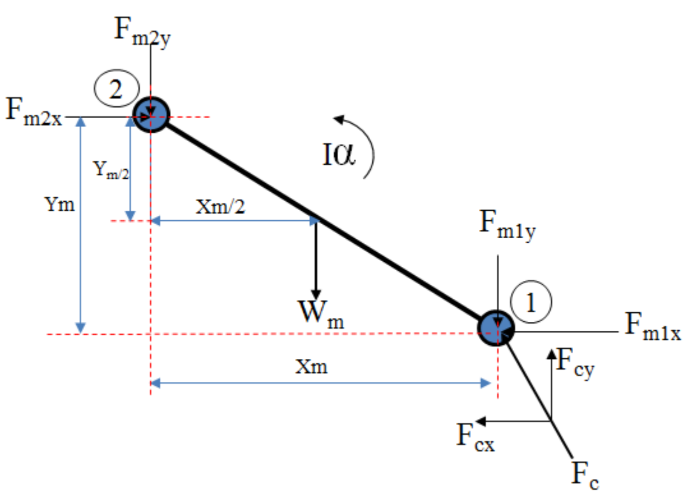

Fig. 4 : Analytical Solution

Solving for reactions at joint 1 & 2 we get the following equation, similar equations are generated for link m as well. Six equations are solved for six unknowns as junction 1 is common in both the links. W_m is the weight of the link and F_c is the input cylinder force. Iα is the inertial effort which needs to be overcome to operate the mechanism. Moment is considered about junction 2 as link is pivoted about junction 2.

Equation 01, 02 & 03 represents the summation of forces in x-direction, y-direction and moments. Rightward & upward forces are treated as positive and anti-clockwise moments are taken positive

$$F_{m1x} - F_{m2x} = F_{cx} \tag{01}$$

$$-F_{m1y} - F_{m2y} = -F_{cy} + W_m \tag{02}$$

$$\begin{aligned} F_{m1y} \times X_m - F m1x \times Y_m &= F_{cx} \times Y_m = \\ F_{cx} \times Y_m - F_{cy} \times X_m &+ W_m \times X_{m/2} - \mathrm{I}_m \times \alpha_m \end{aligned} \tag{03}$$

In similar manner forces in link n are resolved and by doing so six equations are solved for six unknowns and force in the coupler link is computed.

Output clamping force is the force available at the clamping member after deducting the frictional force between sliding member and railing.

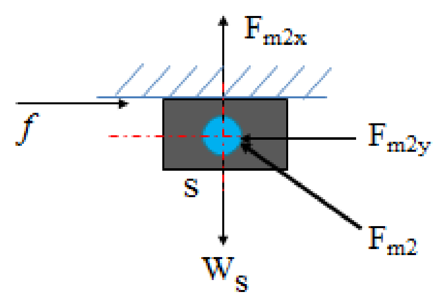

Fig. 5 : Output Clamping Force

Fig. 5 shows the details of slider member “s” which is pivoted at the end of link “m” and supported by the railing to accomplish sliding moment. F_{m2} is the resultant force generated at junction 2. This force is further resolved at a pivot location of slider member. Force “*f*” represents the frictional force available generated at the sliding member and the railing. If μ is the coefficient of friction between slider and the railing member, frictional force can be represented by equ.4

$$f = \mu N = \mu (F_{m2y} - W_s) \tag{04}$$

Output clamping force available for holding the workpiece can be represented as below;

$$F = (F_{m2x} - f) \tag{05}$$

Force *“F”* in equ.5 represents the force available at the clamping member to hold the workpiece. So F is the combination of the linkage configuration, input cylinder force and the frictional resistance between the railing and the slider. Frictional force can be reduced by utilization of the lubrication and selection of material with correct coefficient of friction.

V. CAD Modelling & Analysis

To validate the analytical procedure for computing the output force CAD model is built and analyzed with the help of mechanism package of the CAD software. Equivalent amount of the input cylinder force is generated with the help of the force motor and mechanism is actuated to find the reaction at each joint. Acceleration due to gravity and friction force is also considered while analyzing CAD model. In the extreme open position of the cylinder load cell is assembled and the reaction force is computed.

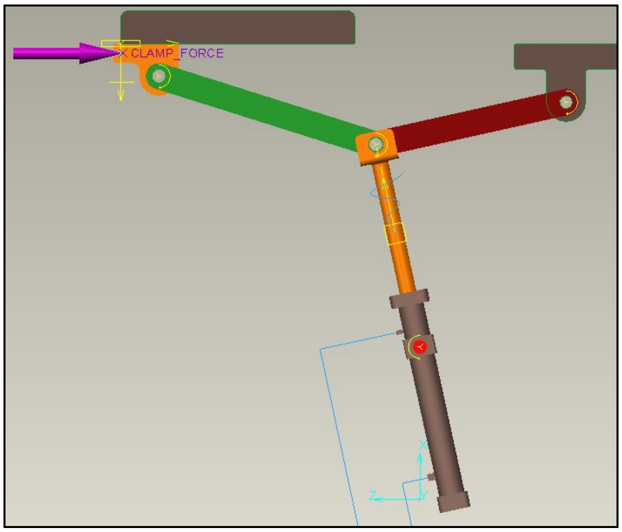

Fig. 6 : CAD modeling & analysis

All the revolving and slider joints are defined and degrees of freedom are restricted accordingly.

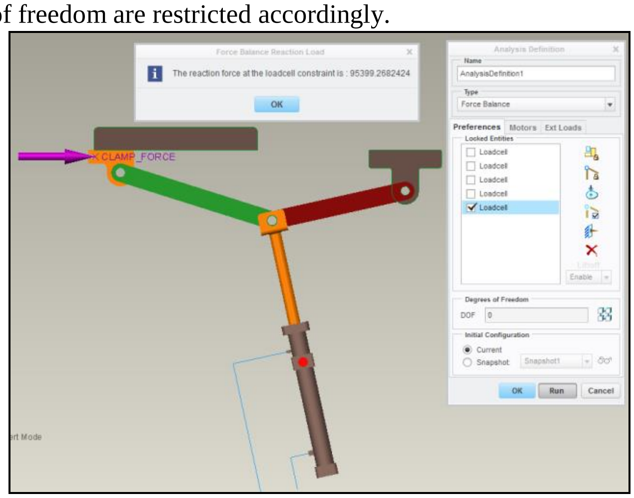

Fig. 7 : Result of CAD analysis

Fig. 7 explains the procedure for linkage analysis using CAD mechanism package in brief. Almost all the CAD mechanism packages are capable of exporting the CAD file or natural format file such as step file. Defining joints and constrains is the key to get the best performance from the mechanism in CAD models. Input forces and motion can be imparted with the help of the motors or actuators available in the tool library.

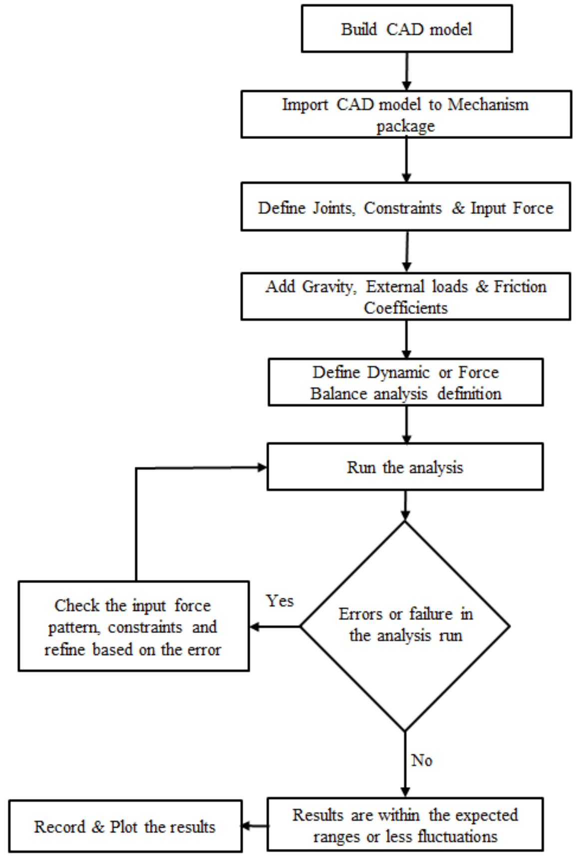

Fig. 8 : CAD Analysis Procedure

VI. System Variables and Selection of Suitable Combination

There are several variables in the toggle clamping mechanism including pivot point location, geometric location of the links and cylinder, offset between pivot location and cylinder force which is a function of system pressure and cylinder size. Out of the above mentioned variables cylinder pressure and cylinder size are most influential input variables. In the existing set up of the toggle clamping mechanism System pressure is the easiest parameter which can be varied to vary the input cylinder force. Replacement of cylinder with the nearest available higher size will also result in the higher clamping force though replacement of the existing cylinder is tough task but can be executed to achieve higher output force with the existing set up of the linkages. Table 1 shows the combination of the cylinder diameter, system pressure, input force and output clamping force. It is obvious that higher the system pressure and cylinder diameter higher is the output clamping force. Table 1 can be extended to have further combination of available cylinder diameter and the system pressure and based on the requirement suitable combination can be opted for the particular toggle clamping mechanism observed from the table that.

Stresses in each link are evaluated to check if they are well below the yield limit for the highest possible force expressed in the table 1.

Pressure (MPa)	Cylinder Diameter (mm)	Input Force (N)
15	63	46759
14	63	43641
13	63	40524
15	70	57727
14	70	53878
13	70	50030

Table 1 : Combination of System Variables

VII. FEA VALIDATION

Existing linkage and newly designed optimized linkage are validated with the help of FEA software. Constraints and Loads are chosen appropriately to replicate the actual environment.Fig.8 shows the model set up for the constraints and the applied load at the junction of two links.

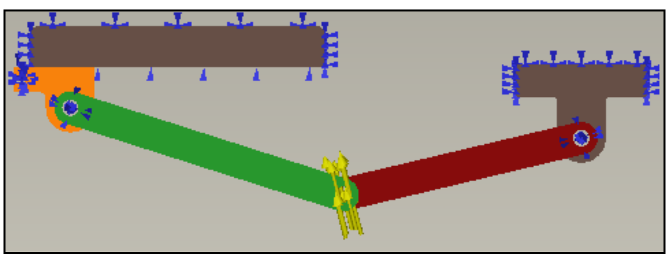

Fig. 9 : FEA Set Up for Validation

Meshing of the model shown in fig.9 is conducted in automated mode but the critical locations such as the pin joints are having more refined meshing. Planer joints and pin joints are defined at respective locations.

Required cylinder force is applied as an input force to the FEA model at an exact angle at which the clamping force is required to be measured or in other words where the maximum output clamping force is measured. With the extended position of the hydraulic cylinder the corresponding positions of the links are imported in the FEA software and analysis is performed. Degrees of freedom are defined as per the configuration of the mechanism. Constrains are also given to replicate the actual mechanism in place. After setting up the model new analysis definition is created and it has been run for the first set up of the input cylinder force and values of max principle stresses and strains and checked.

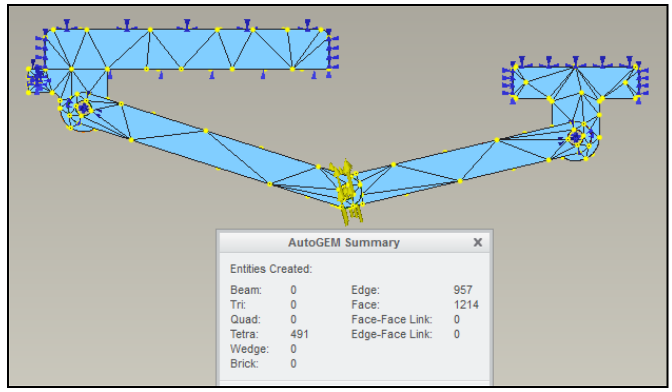

Fig. 10 : Meshing and Refinement

After running the analysis post processing is carried out and stresses at all the joints, maximus stress and stress pattern across the linkages are studied. It's been observed that there is no increment in the stress level in the new design and stresses in both existing and new design are under yield limit.

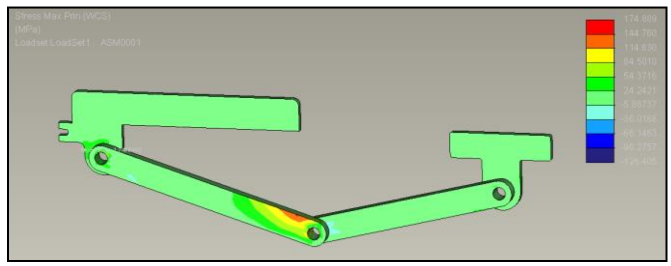

Fig. 11 : FEA Results

Fig. 10 shows the stress pattern in the linkage, pin joint at the junction of two links and edge over the junction of coupler link is observed but still the stress level is within the yield limit of the material.

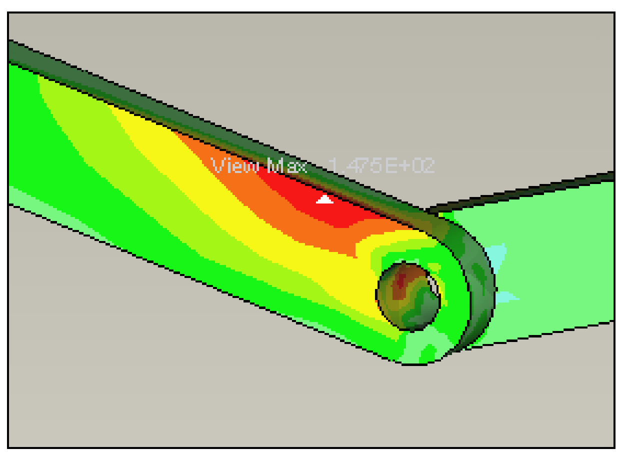

Fig. 12 : High Stress Zone

Fig. 11 depicts the high stress zone near the pin joint and cylinder mounting junction. Maximum stress is observed at the edge of the coupler link is of the order of 147 Mpa. This stress values is well within the limit of yield strength of the material which is 240 MPa.

VIII. Result & Discussion

The toggle clamping mechanism is actuated for the various combinations of the system variables those are possible to vary even with the existing mechanism. Further work is conducted to understand the effect of other parameters including link lengths, link weights and offset between crank link pivot and the slider pivot location on the output force of the toggle clamping mechanism. Mathematical relation is established between the system variables and output force at the clamping member. Table 2 shows the combination of different configuration and the corresponding values of the output force available at the clamping member.

Pressure (MPa)	Cylinder Diameter (mm)	Input Force (N)	Output Force (N)
15	63	46759	93284
14	63	43641	87063
13	63	40524	80843
15	70	57727	115170
14	70	53878	107491
13	70	50030	99811

Table 2 : Output Force with System Variables

Pressure (MPa)	Cylinder Diameter (mm)	Input Force (N)	Output Force By Analytical Calculations (N)	Output Force By CAD Analysis (N)
15	63	46759	93284	95399
14	63	43641	87063	88712
13	63	40524	80843	83119
15	70	57727	115170	119120
14	70	53878	107491	110021
13	70	50030	99811	102341

Table 3 : Comparison of Two Approaches

These values are the evaluated from the mathematical modeling in analytical approach. The values computed analytically are also verified with the help CAD software mechanism analysis as elaborated in CAD analysis section. Table 3 shows the values obtained in both the approaches. Maximum deviation of only 3.3% is observed between analytical approach and CAD analysis using mechanism package. Rests of the values are within 2% deviation between both the approaches. This study is vital for selection of the specific configuration of the toggle clamping mechanism and to understand the possible force available at the clamping member. FEA can also be performed based of the output force to ensure structural rigidity.

IX. Conclusion

The objective of this work is to study the effect of system variables on the output clamping force for the given set of toggle clamping mechanism. This objective is achieved by performing analytical and CAD analysis for computation of output clamping force. Analytical and CAD software results are studied and plotted for validating the degree of closeness. It is observed that the trends of analytical solution and CAD software results are matching closely. The methodology used for analytical study is verified with the CAD software package. From this study suitable combination of system pressure and hydraulic cylinder size can be chosen to generate the required clamping force.

X. Further Work

Further study of effect of all the system variables on the performance of the toggle clamping mechanism and output clamping force is getting conducted mathematically and optimized design of the toggle clamping mechanism with all the possible combination of the input variables is to be worked out.

References

[1] S.A. Bhojne, A.A. Keste, S.H.Gawande, D.H.Thakur, Computer Aided Kinematic Analysis of Toggle Clamping Mechanism, *IOSR Journal of Mechanical & Civil Engineering, Volume 1, page 49 March 2016*

[2] Ming-shyan Huang et.al, Key design parameters and optimal design of a five-point double-toggle clamping mechanism, *Elsevier, applied mathematical modelling 35(2011) 4304-4320.*

[3] Pei-Lum Tso, The kinematic synthesis of toggle clamps, *ASME, Journal of manufacturing science and engineering Aug 1998 Vol. 120/649.*

[4] P. Burton, Kinematics and Dynamics of Planar Machinery, *Prentice Hall, Englewood Cliffs, NJ, 1979*.

[5] F.P. Beer, E.R. Johnston, Vector Mechanics for Engineers – Statics, *McGraw Hill, New York, 1984*.

[6] G.H. Martin, Kinematics and Dynamics of Machines, *McGraw Hill, New York, 1982*.

[7] C.E. Wilson, J.P. Sadler, Kinematics and Dynamics of Machinery, *Harper Collins College Publishers, 1993.*

[8] W.Y. Lin, M.H. Kuo, Investigation of the friction effect at pin joints for the five-point double-toggle clamping mechanisms of injection molding machines, *International. Journa. Mechanical Science. 45 (2003) 913–1927.*
[9] R.F. Fung, C.C. Hwang, C.S. Huang, W.P. Chen, Inverse dynamics of a toggle mechanism, *Comput. Struct. 63 (1997) 91–99.*
[10] R.F. Fung, C.C. Hwang, C.S. Huang, Kinematic and sensitivity analyses of a new type toggle mechanism, *Jpn. Soc. Mech. Eng. Ser. C 40 (1997) 360–365.*
[11] R.F. Fung, J.W. Wu, D.S. Chen, A variable structure control toggle mechanism driven by a linear synchronous motor with joint coulomb friction, *J. Sound Vib. 247 (2001) 741–753.*

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