Design and Optimization of Slider and Crank Mechanism with Multibody Systems

Bhupesh Chandrakar[1], Man Mohan Soni[2]

[1]Christian College of Engineering & Technology, Bhilai C.G. , India

[2]Rungta Engineering College, Raipur C.G., India

Abstract: ***The slider-crank mechanism is considered as one of the most used mechanism in the mechanical field. It is found in pumps, compressors, steam engines, feeders, crushers, punches and injectors. Furthermore, the slider-crank mechanism is central to diesel and gasoline internal combustion engines, which play an indispensable role in modern living. It mainly consists of crank shaft, slider block and connecting rod. It works on the principle of converting the rotational motion of crank shaft to the translational motion of slider block. Over the past two decades, extensive work has been conducted on the kinematic and dynamic effects of the slider and crank mechanism in multibody mechanical systems. In contrast, little work has been devoted to optimizing the performance of mechanical systems. The slider and crank mechanism simulation model is developed using the design software MSC.ADAMS. Different simulations are performed at different crank speeds to observe the response of the reaction forces at joint R2 (joint between crank shaft and connecting rod). An innovative design-of-experiment (DOE)-based method for optimizing the performance of a mechanical system for different ranges of design parameters is then proposed. Based on the simulation model results the design parameters are predicted by an artificial intelligence technique. This allows for predicting the influence of design parameter changes, in order to optimize joint reaction forces and power requirements of the slider and crank mechanisms.***

Keywords: Multibody system, ADAM, Slider Crank Mechanism.

1. Introduction

Multibody dynamics is based on classical mechanics and has a long and detailed history. The simplest multibody system is a free particle which can be treated by Newton's equations published in 1686. D'Alembert considered a system of constrained rigid bodies where he distinguished between applied and reaction forces. A systematic analysis of constrained mechanical systems was established by Lagrange. Modern methods for the dynamic analysis of constrained multibody systems fall into two main categories: differential algebraic equations (DAEs) and ordinary differential equations (ODEs). DAEs employ a maximal set of variable to describe the motion of the system and use multipliers to model the constraint forces. Premultiplying the constraint reaction-induced dynamic equations by the orthogonal complement matrix to the constraint Jacobian results in the governing equations as ODEs. Numerous advances have been made during the last couple of centuries in theory and in methods of formulating the equations of motion.

The slider and Crank Mechanism is considered one of the most used systems in the mathematical field. The purpose of the mechanism is to convert the linear motion of the piston to rotational motion of the crank shaft. BY definition: slider and crank mechanism is one type of four bar linkages which has three revolute joints and one sliding joint. In industry, many applications of planar mechanisms such as mechanism have been found in thousands of devices. A slider–crank mechanism is widely used in gasoline/diesel engines and quick-return machinery. Research works in analysis of the slider–crank mechanism have been investigated due to their significant advantages such as low cost, reduced number of parts, reduced weight and others. It kinematic analysis with multibody dynamics and its parametric optimization has been little studied when compared to the mechanisms.

Assad,(2012) presented the kinematic and dynamic analysis of slider crank mechanism. The slider crank mechanism is simulated in ADAMS software to observe the response of the slider block and the reaction forces at joint R2 (joint between crank shaft and connecting rod). The dynamic analysis has been performed by applying moment of 4.2 Nm at joint R1 (the revolute joint between connecting shaft and connecting plate). The applied moment is removed by imposing rotational motion at joint R1with angular velocity of 6 rad/sec to perform dynamic analysis. These simulations were performed with different time steps and durations. The friction was assumed to be negligible during these simulations. As a result of this work, the longitudinal response of the slider block is observed with applied moment as well as slider block response along with reaction forces at joint R2is investigated in case of imposed rotational motion. [11]

Sharma and Ranjan, (2013) analyzed of a four-bar mechanism is undertaken. In the analysis and design of mechanisms, kinematic quantities such as velocities and accelerations are of great engineering importance. Velocities and displacements give an insight into the functional behavior of the mechanism. The accelerations, on the other hand, are related to forces .The main theme of this paper are the modelling, computer-aided dynamic force analysis and simulation of four-bar planar mechanisms composed of rigid bodies and mass less force and torque producing elements. Modelling of planar four-bar mechanisms will be done by using the ADAMS software. By this software we can simulate their link at different positions and find the velocity and acceleration graph and compared with analytical equations. Motions of the rigid bodies are predicted by numerically integrating Differential-Algebraic Equations (DAEs). ADAMS is more reliable software because it considers mass, centre of mass location and inertia properties on the links.[12]

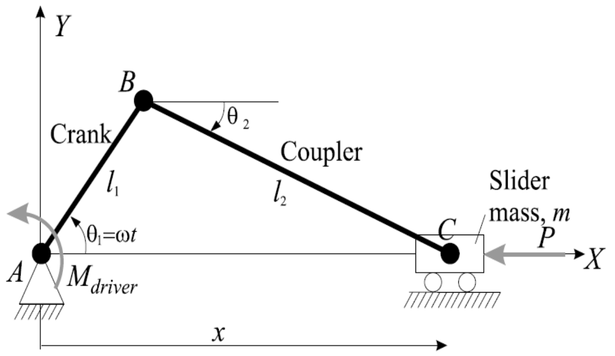

Figure 1: Slider-Crank Mechanisms with Kinematic Coordinates

According to Figure 1, we introduce three coordinates to describe the configuration of the mechanism. In principle, we only need one coordinate, the most obvious choice being θ_1, but since there is not an obvious connection between θ_1 and the complete configuration of the mechanism, we use more coordinates, i.e., θ_1, $\theta_2$and x. The kinematic analysis now aims at finding the relationship between the three coordinates and other required kinematical information, such as motion of centre of mass of the bodies or the like. In this case, we will primarily be interested in the motion of the slider, being the only mass in the system.

Considering the triangle *ABC*, we can set up the following two equations and the third one required for the problem to be determinate is the driver equation specifying constant angular velocity of the crank:

$$l_1\cos(\theta_1)+l_2\cos(\theta_2)=x \quad \ldots(1)$$

$$l_1\sin(\theta_1)+l_2\sin(\theta_2)=0 \quad \ldots\ldots (2)$$

$$\theta_1=\omega t \quad \ldots\ldots (3)$$

Eq. (3) directly gives θ_1, in time and solving Eq. (2), we can find θ_2:

$$\theta_2=\arcsin\left(\frac{l_1}{l_2}\sin(\theta_1)\right) \quad \ldots\ldots (4)$$

Finally Eq. (1) allows to find x from θ_1 and θ_2.

To calculate the forces accurately, we need to find the acceleration of the mass $\ddot{x}$. Equations that determine the acceleration can be found by differentiation of Eqn. (1) to (3) twice with respect to time. The first differentiation gives us equations that can be used to determine the velocities and, it generally is necessary to determine these first. The first differentiation leads to:

$$-l_1\sin(\theta_1)\dot{\theta}_1-l_2\sin(\theta_2)\dot{\theta}_2=\dot{x} \quad \ldots\ldots (5)$$

$$l_1\cos(\theta_1)\dot{\theta}_1-l_2\cos(\theta_2)\dot{\theta}_2=0 \quad \ldots\ldots (6)$$

$$\dot{\theta}_1=\omega \quad \ldots\ldots (7)$$

Where the former two equations can be solved for $\dot{\theta}_2$ and $\dot{x}$:

$$\dot{\theta}_2=\frac{l_1\cos(\theta_1)}{l_2\cos(\theta_2)}\dot{\theta}_1 \quad \ldots\ldots (8)$$

$$\dot{x}=-l_1\sin(\theta_1)\dot{\theta}_1-l_2\sin(\theta_2)\dot{\theta}_2=-l_1\sin(\theta_1)\dot{\theta}_1-l_2\sin(\theta_2)\frac{l_1\cos(\theta_1)}{l_2\cos(\theta_2)}\dot{\theta}_1$$

We differentiate Eqn. (5) to (9) with respect to time, leading to

$$-l_1\sin(\theta_1)\ddot{\theta}_1-l_2\sin(\theta_2)\ddot{\theta}_2-l_1\cos(\theta_1)\dot{\theta}_1^2-l_2\cos(\theta_2)\dot{\theta}_2^2=\ddot{x} \quad \ldots\ldots (10)$$

$$l_1\cos(\theta_1)\ddot{\theta}_1-l_2\cos(\theta_2)\ddot{\theta}_2-l_1\sin(\theta_1)\dot{\theta}_1^2+l_2\sin(\theta_2)\dot{\theta}_2^2=0 \quad \ldots\ldots (11)$$

$$\ddot{\theta}_1=0 \quad \ldots\ldots (12)$$

Where the former two equations are solved for $\ddot{\theta}_2$ and $\ddot{x}$, yielding

$$\ddot{\theta}_2=\frac{l_1\cos(\theta_1)}{l_2\cos(\theta_2)}\ddot{\theta}_1-l_1\sin(\theta_1)\dot{\theta}_1^2+l_2\sin(\theta_2)\dot{\theta}_2^2 \quad \ldots\ldots (13)$$

$$\ddot{x}=\left(-l_1\sin(\theta_1)-l_2\sin(\theta_2)\frac{l_1\cos(\theta_1)}{l_2\cos(\theta_2)}\right)\ddot{\theta}_1-l_1\cos(\theta_1)\dot{\theta}_1^2-l_2\cos(\theta_2)\dot{\theta}_2^2 \quad \ldots\ldots (14)$$

2. Numerical Method

In this section a computer model for the classic slider-crank mechanism is considered to analyze the behavior of the mechanical system for the Figure 2. The multibody model has four ideal joints. In which three are revolute joints and one translational joint. The revolute joints are existed between the ground and the crank, the crank and coupler and at the slider pin and the translational joint between the ground and coupler. The geometric and inertia properties of each body in this system are shown in Table 1

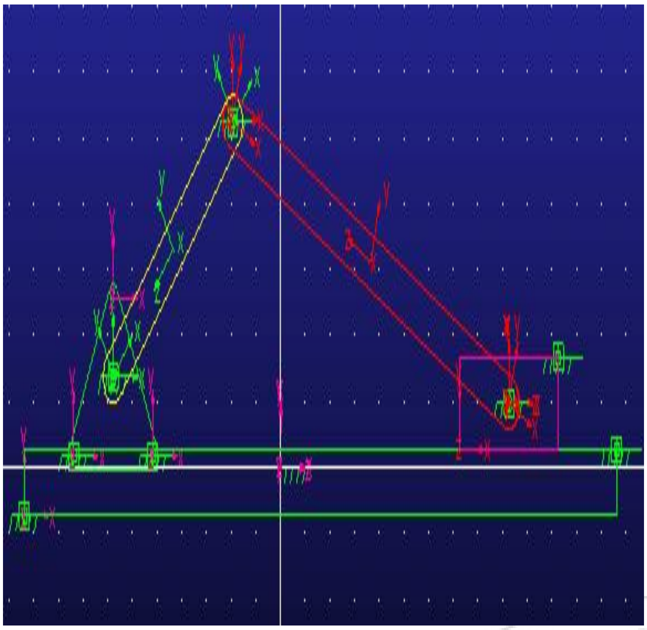

Figure 2: Slider and Crank Mechanism

Table 1: Properties of Mechanism

Body	*Length (m)*	*Height (m)*	*Depth (m)*	*Moment of Inertia (kg-m^2)*	*Mass (kg)*
Crank	0.31	0.04	0.02	0.4	2
Coupler	---	0.04	0.02	0.75	6
Slider	0.2	0.07	0.1	0.75	8
Base	1.2	0.05	0.1	-	-

3. Results

An innovative design-of-experiment (DOE) based method for optimizing the performance of a mechanical system for different ranges of design parameters is proposed in Table 2 to optimize the performance of slider and crank mechanism.

Table 2: Setting simulation model parameters

Set	*Crank length (m)*	*Coupler length (m)*
Set-1	0.31	0.605
Set-2	0.2595	0.577
Set-3	0.2402	0.699
Set-4	0.1701	0.675

Finally, numerical results obtained from two application examples with different design parameters, crank speed are presented for the further analysis of the mechanical system. This allows for predicting the influence of design parameter changes, in order to minimize reaction forces, accelerations, and power requirements. Table 3 shows the simulation results for the slider and crank mechanism.

Table 3: Simulation Results

Set	*Speed (rpm)*	*Joint reaction force in X-Direction (N)*	*Joint reaction force in Y-Direction (N)*	*Power Consumption (N-m/sec)*
Set-1	1000	1000	750	5000
Set-1	2000	5000	3000	40,000
Set-1	3000	10,000	7500	1.5×10^5
Set-2	1000	750	600	3000
Set-2	2000	3000	2300	25,000
Set-2	3000	7500	5000	1×10^5
Set-3	1000	750	350	2500
Set-3	2000	3000	1500	20,000
Set-3	3000	6250	3000	70,000
Set-4	1000	550	225	1100
Set-4	2000	2400	850	9000
Set-4	3000	5000	2000	30,000

Usually the design process is treated as an optimization problem. To each user specified performance requirement is associated a performance index whose value increases with its level of violation. The joint reaction forces and power consumption are considered as input and the outputs are design parameters and crank speed. The data from Table 4 are used to build the NN- model.

Table 4: Setting simulation model parameters

Input data			Output data		
Joint reaction force in X-Direction (N)	Joint reaction force in Y-Direction (N)	Power Consumption (J/sec)	Speed (rpm)	Crank length (m)	Coupler length (m)
1000	750	5000	1000	0.31	0.605
5000	3000	40,000	2000	0.31	0.605
10,000	7500	1.5×10^5	3000	0.31	0.605
750	600	3000	1000	0.2595	0.577
3000	2300	25,000	2000	0.2595	0.577
7500	5000	1×10^5	3000	0.2595	0.577
750	350	2500	1000	0.2402	0.699
3000	1500	20,000	2000	0.2402	0.699
6250	3000	70,000	3000	0.2402	0.699
550	225	1100	1000	0.1701	0.675
2400	850	9000	2000	0.1701	0.675
5000	2000	30,000	3000	0.1701	0.675

In this work, a method of artificial neural network applied for the solution of performance indices to predict the output values. The input layer in NN has three nodes which take the joint reaction forces and power consumption as the input and the output layer also has three nodes to give the outputs as design parameters and crank speed.

Figures 3 - 4 shows the results of comparative designs parameters and crank speeds with those obtained with the multibody model to the NN optimization. The response of the system to the input using the neural network is really good. If it is compared with the output from the ADAMS simulation, there are some differences between them, but the two outputs are really near in almost all points and at peak values of the ADAMS results are also optimized in neural networks. So, this shows that is possible to simulate this system with a dynamic neural network, but the results are really dependent from the hidden layers, the number of neurons in each and the number of epochs.

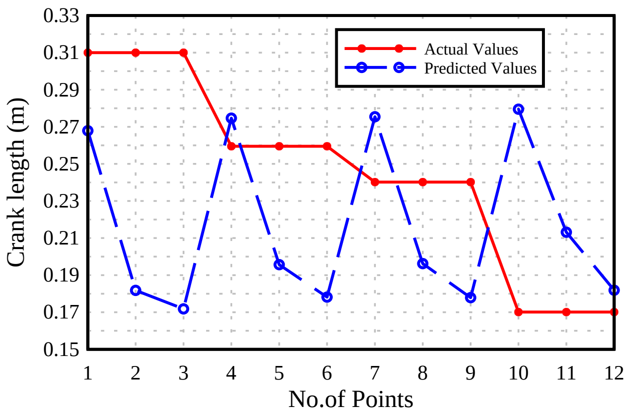

Figure 3: Crank length

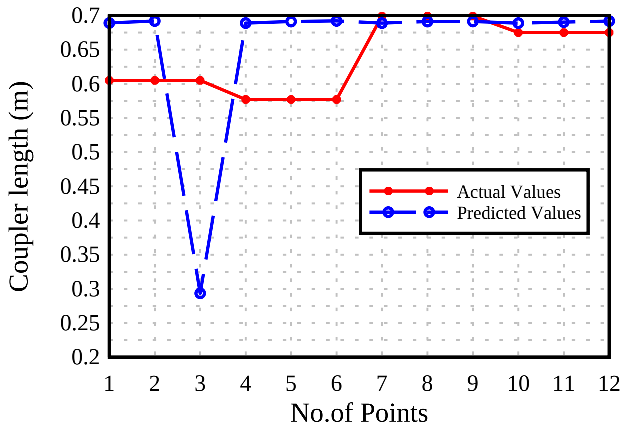

Figure 4: Coupler lengths

4. Conclusions

The NN-model was used to replace the computer simulation experiment as a cost-effective mathematical tool for optimizing the system performance. This research was focused on using the design-of-experiment method to develop a NN-model instead of the computer simulation model. The use of the NN model allowed the prediction of the system's response at other design points with a significantly lower computational time and cost. For the studied mechanism, the predictions were shown to be within5% of the actual values from dynamic simulations, for which close to an hour of computational time is to be spent for each simulation. In addition to the use of the NN model for the prediction of the response at different design points, the scheme allows for the visualization of the trends of the response surfaces when the design variables are changed. The global results obtained from this study indicate that the dynamic behavior of the mechanical system is quite sensitive to the crank speed. The contact force is increased when the crank speed increases and the decrease in crank speed tends to make the results more noisy. The method presented in this thesis can be utilized for optimizing the performance of mechanical systems with joint clearances. By utilizing the NN-model, the computer simulation time can be significantly reduced, while the response of the system can be studied and optimized for a range of input design variables. Thereby based on simulation and analysis by MSC Adams view software and optimization based on NN technique we have attained optimized result based on length of crank and coupler. These results are validated using error found in NN optimization tool, MATLAB.

The optimized results of crank and coupler length helps in achieving less amount of power consumption and joint forces at the joint and relatively lesser cost of material.

References

[1] CHACE, M.A., 1967, "Analysis of the Time-Dependence of Multi-Freedom Mechanical Systems in Relative Coordinates", Journal of Engineering for Industry, 89, pp. 119-125.
[2] UICKER, J.J., 1969, "Dynamic Behaviour of Spatial Linkages Part 1 – Exact Equations of Motion, Part 2 – Small Oscillations about Equilibrium", Journal of Engineering for Industry, 91, pp. 251-265.
[3] PAUL, B., and KRAJCINOVIC, D., 1970, "Computer Analysis of Machines with Planar Motion, Part 1 – Kinematics, Part 2 – Dynamics", Journal of Applied Mechanics, pp. 37, 697-712.
[4] SHETH, P.N., and UICKER, J.J., 1971, "IMP (Integrated Mechanism Program): A computer-Aided Design Analysis System for Mechanisms and Linkages", Journal of Engineering for Industry, Series B 94(2), pp. 454-464.
[5] Soni, A. H., 1974, "Mechanism Synthesis and Analysis", McGraw-Hill Book Co.
[6] ERDMAN A.G., and GUSTAFSON, J.E., 1977, "LINCAGES: Linkage Interactive Computer Analysis and Graphically Enhanced Synthesis Package", ASME paper No.77-DTC-5.
[7] ORLANDEA, N., CHACE, M.A., and CALAHAN, D.A., 1977, "A Sparsity-OrientedApproach to the Dynamic Analysis and Design of Mechanical Systems – Part 1 and 2", Journal of Engineering for Industry, 99, pp. 773-784.
[8] RUBEL, A.J., and KAUFMAN, R.E., 1977, "KINSYN III: A New Human-Engineering System for Interactive Computer-Aided Design of Planar Linkages", Journal of Engineering for Industry, Series B, 99(2), pp. 440-448.
[9] KAUFMAN, R.E., 1978, "Mechanism Design by Computer", Machine Design, 50(24), pp.94-100.
[10] CHACE, M.A., 1978, "Using DRAM and ADAMS Programs to Simulate Machinery, Vehicles, Agricultural engineering, pp. 16-18.
[11] A. Assad, "Simulation of Slider Crank Mechanism Using ADAMS Software," Int. J. Engg. Tech., vol.12, no.04, pp.108-112, 2012.
[12] R. P. Sharma and C. Ranjan, "Modeling And Simulation of Four-Bar Planar Mechanisms Using ADAMS," Int. J. Mech. Engg. Tech., vol. 4, no. 2, 2013.