Static force analysis of planar mechanisms in MechAnalyzer software

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ABSTRACT

A thorough understanding of the forces acting on various components of a machine or mechanism is vital for designing them. Hence force analysis is an important part in the courses related to Theory of Machines and Mechanisms. Force analysis of mechanisms in static equilibrium can be carried out by both analytical and graphical methods. The latter employs scaled free body diagrams (FBD) and force vector polygons in the determination of unknown forces. This method is emphasized in the curriculum of undergraduate students. However, this approach suffers from disadvantages related to time and effort. This is where a computer software as an additional learning tool for graphical approach helps. In this paper, Static Force Analysis (SFA) module, developed as a part of MechAnalyzer is presented. SFA module is helpful in the static force analysis of various planar mechanisms preloaded in it and draws the free body diagrams and force polygons of the links.

Keywords: ***Simulation, Static Force Analysis, Planar mechanisms, MechAnalyzer***

1. INTRODUCTION

The durability of any machine depends on the strength of the links of the mechanisms used in the machine. The design of the links should be in such a way that they can endure the forces exerted on them. This is where Static Force Analysis (SFA) comes into picture. Neglecting accelerations, static equilibrium is applicable to mechanisms where the changes in movement are gradual or mass of the components is negligible. Two major methods to perform SFA are the analytical and the graphical approach. Analytical method involves solving algebraic equations to determine unknown forces and moments whereas graphical method uses geometry and takes the help of free body diagram. Hence, the latter gives the freedom to visualize forces and torque on each link. Eventually this facilitates the students by providing useful insight to the nature of forces and the visual essence helps in correlating forces between different links. Once students are familiar with the graphical methods, they can attempt analytical methods with better understanding and confidence.

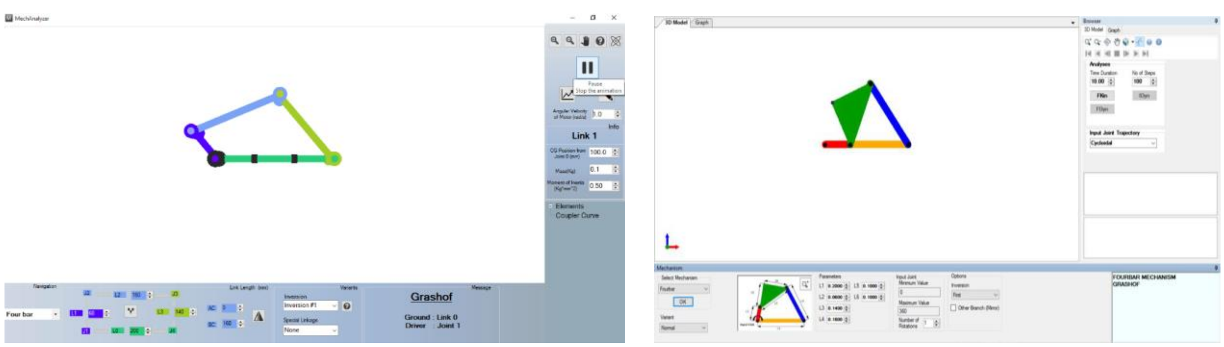
The major drawback of the graphical approach is the time consumed to draw the free body diagram and force polygon for each link. In addition to this, these force polygons have to be redrawn for every different link orientation which is tedious. Teaching this as a part of the curriculum consumes a lot of time which necessitates the use of software. There are various software available for use like SAM (2016), GIM reported by Petuya et al (2014), Universal Mechanism (2016) and MD Adams (2016), of which some are available for free while others are paid. A free software was developed by some of the authors in the form of MechAnalyzer. An overview of the available software for mechanisms and how MechAnalyzer is better at some of the aspects related to teaching are given in Hampali (2014).

After a comparative study, to the best of the knowledge of the authors, none of the software packages perform static force analysis with gaphical method, or have a provision to draw force polygons and free body diagram of links. The authors have developed a new module named Static Force Analysis (SFA) module, as a part of continued development of MechAnalyzer. It performs static force analysis of various planar mechanisms like four-bar, slider crank, Whitworth quick return and others, which are available as preloaded mechanisms. It is used to draw force triangles and force vectors on different links in static force analysis as per the user's input to force magnitude, direction and at what distance on different links. These polygons are redrawn spontaneously for any change in the input parameters. Results obtained after analysis of mechanism are shown to the user. In addition to this, there is a feature to store different input values and retrieve them later for use in order to save time in entering the input repetitively.

This paper is organized in the following manner: Section 2 is dedicated for a brief introduction to the different versions of MechAnalyzer. Section 3 presents a detailed description of SFA module and its specifications. Section 4 gives the methodology of SFA of slider crank mechanism. The validation of the results with a commercial modelling software Autodesk Inventor Professional (student version) is covered in Section 5, followed by the conclusion.

2. AN OVERVIEW OF MECHANALYZER

MechAnalyzer is a 3D model based learning software. It was developed with the intention of serving as a teaching aid for the basic concepts which are a part of undergraduate courses related to Theory of Machines. Hampali et al (2014) reported Versions 1 and 2 of the MechAnalyzer software, used to perform forward kinematic analysis of four-bar, slider crank and five-bar mechanisms. In addition to that, animation of motion was enabled and the graphs of the results were plotted. Mechanisms were preloaded making it easier for the students to start off without any prerequisites. It was developed in Microsoft Visual Studio using Visual C# programming language. The graphics were implemented using OpenTK (a wrapper for OpenGL) and plots were drawn using ZedGraph library. A screenshot of Version 2 of MechAnalyzer is shown in Figure 1(a).



(a) *Version 2* (b) *Version 3*

Figure 1: *Earlier versions of MechAnalyzer software*

In order to have similar user interface like RoboAnalyzer (Rajeevlochana and Saha, 2011), another software developed by some of the authors, Version 3 of MechAnalyzer was reported by Rakshith et al (2015), which had many improvised features. Different variants to the already existing mechanisms were included and some new mechanisms were loaded further. However, this version lacked graph plots. User interface of MechAnalyzer Version 3 is shown in Figure 1(b).

This work was further continued as Version 4 of MechAnalyzer, reported by Verma et al (2016), and an entirely new module called Velocity and Acceleration Diagram (VAD) was added to it. It carried out position, velocity and acceleration analysis of some commonly used planar mechanisms using graphical methods. A screenshot of the VAD Module in Mechanalyzer Version 4 is given below in Figure 2. In Version 5, a new Static Force Analysis (SFA) module is added along with some other extra features from Version 4. This paper discusses the details of implementation of SFA module alone.

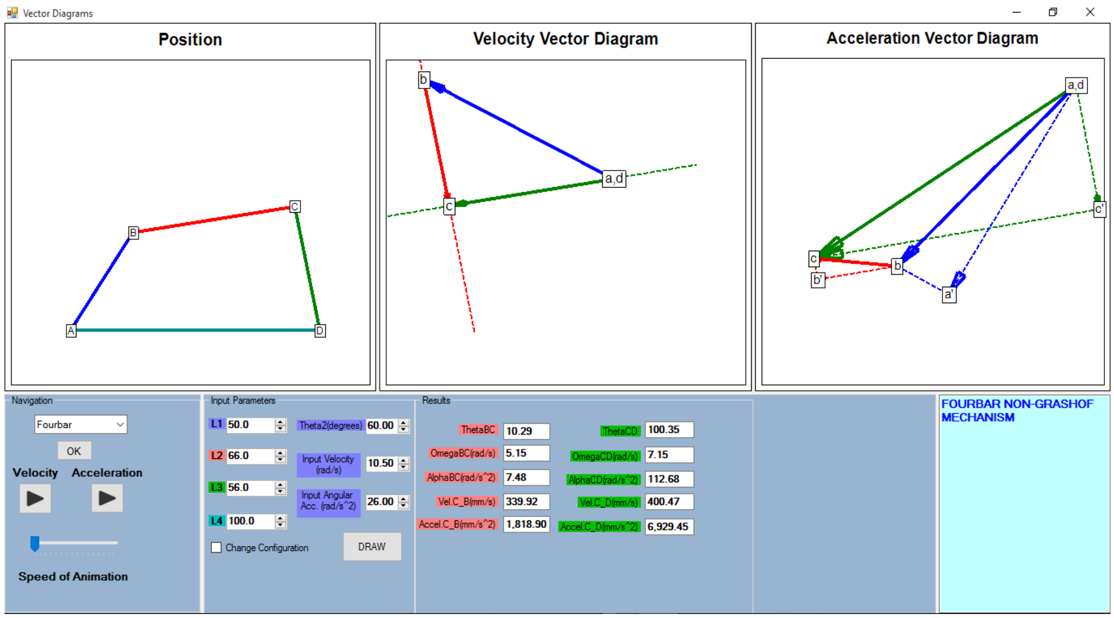


Figure 2: *User Interface of MechAnalyzer Version 4*

3. AN OVERVIEW OF SFA MODULE

SFA module has been developed as a part of MechAnalyzer software. It has a separate tab on the same windows as that of the VAD module. It has been developed as a Windows Form Application using Visual C# as the programming language in Microsoft Visual Studio. An open source library called Zedgraph has been used for drawing free body diagrams and force vector polygons. Primary objectives of SFA module that were considered during its development are:

- It should be capable of performing SFA of common planar mechanisms encountered in the Theory of Machines course
- It should serve as a teaching aid for graphical method of SFA of planar mechanisms
- It should be able to draw force polygons and free body diagrams in order to avoid manual drawing on board

SFA module performs static force analysis of four-bar, slider crank, Whitworth quick return, crank-slotted and four-bar quick return mechanisms. All the mechanisms have one degree-of-freedom (DOF). The input parameters taken are length of links, input crank angle, magnitude and direction of external forces acting on the links and the distance at which these forces act. Result obtained after analysis are displayed in the form of torque acting on the crank. Since the number of inputs required are large and it is therefore time consuming to set them each time when required, an additional feature is provided to save the input parameters. This file with saved input parameters can be retrieved any time later when required. Any number of input details can be saved and retrieved similarly. This is convenient and saves time especially while teaching in a classroom.

Figure 3 shows the graphical user interface (GUI) of the SFA module. It is partitioned into a number of panels which serve different purposes. It consists of a navigation panel which enables the user to choose the required planar mechanism from the five preloaded ones. As soon as a mechanism is selected, SFA is performed for the default input values. This panel also has the additional feature to save and retrieve files with input values. The input panel lets user modify the input parameters. On clicking the draw button, the analysis is performed. The free body diagrams and the force vector polygons are drawn on the FBD diagram window. Once the analysis is done, the results are displayed in the result panel. The message box shows the name of the mechanism being analyzed and will convey any error to the user.

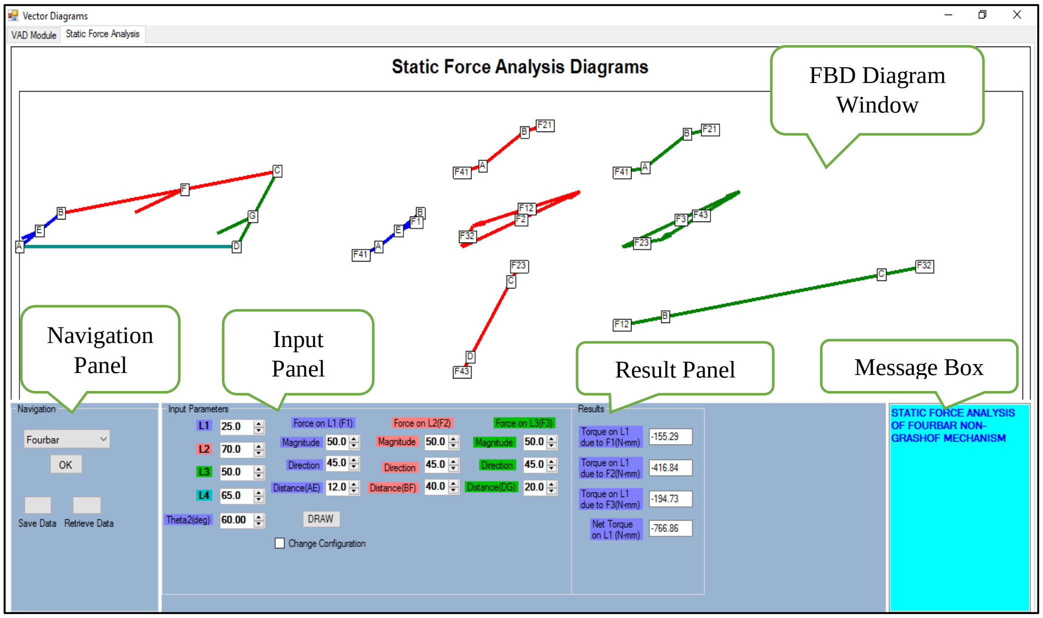


Figure 3: *User Interface of SFA Module for a Four-bar Mechanism*

4. METHODOLOGY OF ANALYSES

The position analysis of the mechanism is done by analytical method. With the input link lengths and crank angle, the position of all the links are calculated using trigonometric relations. These are based on the derivations formulated in Norton (2003). Detailed explanation is given below by taking a mechanism for example and showing its analysis. Here, slider crank mechanism illustrated in Figure 4 is chosen as it contains revolute and prismatic joints, which are typically found in lower-pair planar mechanisms.

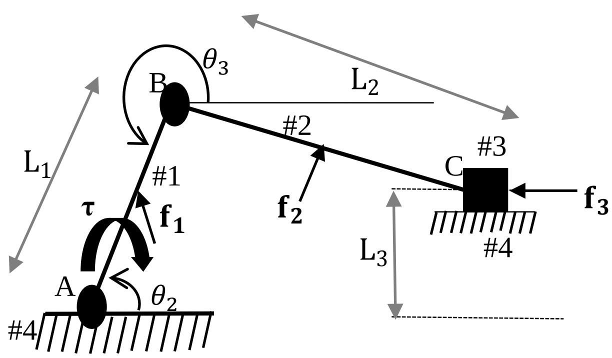


Figure 4: *Nomenclature of links, angles and forces in slider crank mechanism*

Let the length of links 1 (#1) and 2(#2) be $L_1$and L_2, respectively. Slider (#3) position is offset at L_3 from ground. External force $\mathbf{f_1}, \mathbf{f_2}$ and $\mathbf{f_3}$ are applied on links #1, #2 and #3, respectively. Analytical method is applied for the position analysis of mechanism to obtain the position and orientation of each link, as reported by Verma et al (2016).

Once position analysis is complete, static force analysis is carried out following the principle of superposition. Each link is analyzed individually, and required torque (τ) on the crank (#1) is obtained as the vector sum of torques obtained by analyzing each link individually, as explained below:

A) Torque due to force ($\mathbf{f_3}$) on slider (#3):

Slider is under the influence of three forces, i.e., applied force $\mathbf{f_3}$ and constraint forces $\mathbf{f_{43}}$and $\mathbf{f_{23}}$. Free body diagram of slider is drawn followed by the force triangle which gives the magnitude of unknown constraint forces. FBD of slider and other links are shown in Figure 5.

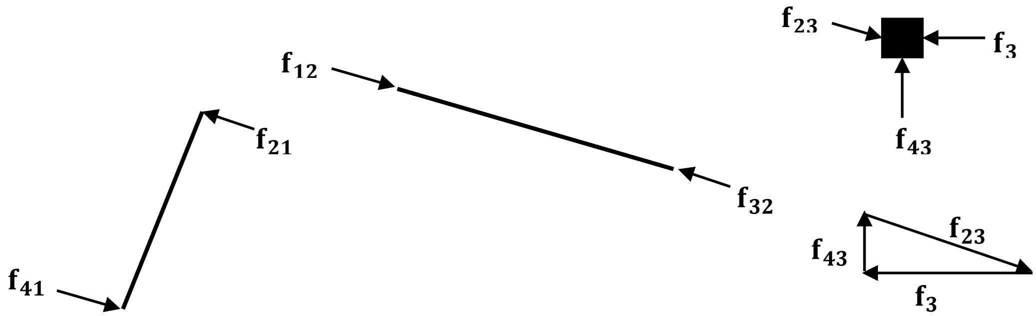


Figure 5: *FBD of slider crank mechanism considering force* $\boldsymbol{f_3}$

Magnitude of forces $\mathbf{f_{43}}$ and $\mathbf{f_{23}}$ are calculated from the force triangle shown in Figure 5. Forces $\mathbf{f_{32}}$ and $\mathbf{f_{23}}$ are constraint pairs, resulting in

$$\mathbf{f_{32}} = \mathbf{f_{23}} \tag{1}$$

Links #2 and #1 are two force members and hence to maintain their static equilibrium,

$$\mathbf{f_{32}} = \mathbf{f_{12}} \tag{2}$$

$$\mathbf{f_{21}} = \mathbf{f_{12}} \tag{3}$$

$$\mathbf{f_{41}} = \mathbf{f_{12}} \tag{4}$$

Since both the forces in Equation (4) are not collinear, they will produce a torque which needs to be balanced by applying an external torque of same magnitude but of opposite sense. Resulting torque is given by

$$\boldsymbol{\tau_3} = \mathbf{f_{12}} \mathrm{L_1} \sin(\theta_2 - \theta_3) \tag{5}$$

B) Torque due to due to force ($\mathbf{f_2}$) on link #2:

Free body diagram of the links is drawn followed by the force triangle which gives the magnitude of unknown constraint forces. FBD of slider and other links are shown in the Figure 6.

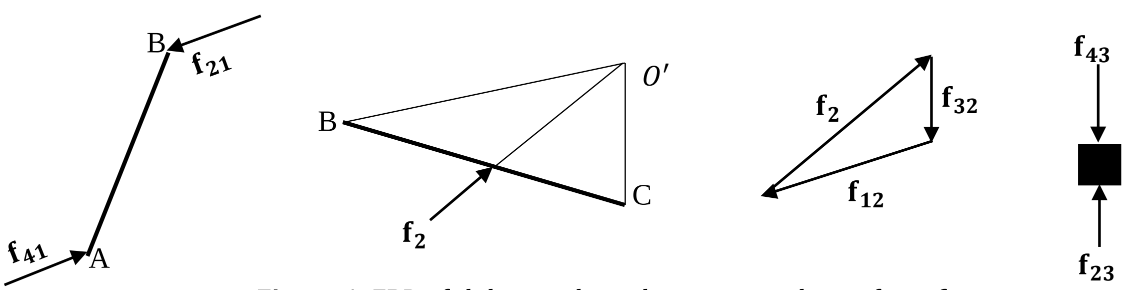


Figure 6: FBD of slider crank mechanism considering force $\mathbf{f_2}$

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Link #3 is a two force member and for its static equilibrium,

$$\mathbf{f_{34}} = \mathbf{f_{43}} \tag{6}$$

Forces $\mathbf{f_{32}}$ and $\mathbf{f_{23}}$ are constraint pairs which result in

$$\mathbf{f_{32}} = \mathbf{f_{23}} \tag{7}$$

Link #2 is a three-member force and the direction of forces $\mathbf{f_3}$ and $\mathbf{f_{32}}$ are known. The point of concurrency is obtained as O', the intersection of the lines along these two known directions and the force triangle is constructed. Magnitude of forces $\mathbf{f_{32}}$ and $\mathbf{f_{12}}$ are calculated from the force triangle shown in Figure 6. The constraint forces between link #1 and #2 are equal and opposite,

$$\mathbf{f_{21}} = \mathbf{f_{12}} \tag{8}$$

Considering the link #1 which is a two force member,

$$\mathbf{f_{41}} = \mathbf{f_{12}} \tag{9}$$

Since both the forces are not collinear, it will result in a torque which needs to be balanced applying external torque of same magnitude but of opposite sense, given by

$$\boldsymbol{\tau_2} = \mathbf{f_{12}} \mathrm{L}_1 \sin(\theta_2 - \theta_3) \tag{10}$$

C) Torque due to force ($\mathbf{f_1}$) on link #1:

The FBD of all the links are shown in Figure 7 and it can be clearly noticed that $\mathbf{f_{43}}$and $\mathbf{f_{23}}$ should be equal but the directions of both are different. So for both forces to be in static equilibrium, the magnitude of both should be zero, i.e.,

$$\mathbf{f_{43}} = \mathbf{f_{23}} = \mathbf{0} \tag{11}$$

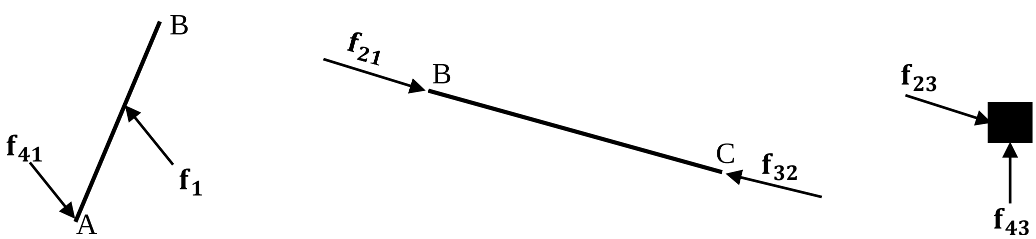

Figure 7: *FBD of slider crank mechanism considering force $\boldsymbol{f_1}$*

Analyzing reaction or constraint forces at B and C for link #2, the forces acting on this two force member also have to be zero, i.e.,

$$\mathbf{f_{21}} = \mathbf{f_{12}} = \mathbf{f_{32}} = \mathbf{f_{23}} = \mathbf{0} \tag{12}$$

Link #1 (crank) is a two force member and hence reaction force $\mathbf{f_{41}}$ is obtained as

$$\mathbf{f_{41}} = \mathbf{f_1} \tag{13}$$

Since both the forces are not collinear, it will result in a torque which has to be balanced by an external torque of same magnitude but of opposite sense, given by

$$\boldsymbol{\tau_1} = \mathbf{f_1} \mathrm{L}_1 \sin(\theta_2 - \theta_3) \tag{14}$$

Net torque on crank will be the sum of $\boldsymbol{\tau_1}, \boldsymbol{\tau_2}$ and $\boldsymbol{\tau_3}$, given by

$$\boldsymbol{\tau} = \boldsymbol{\tau_1} + \boldsymbol{\tau_2} + \boldsymbol{\tau_3} \tag{15}$$

The SFA for slider crank mechanism is illustrated in Figure 8, where the principle of superposition has been used. Three sets of vector diagrams are created for the three external forces acting on the links #1, #2 and #3. The torques calculated, individual and the total sum, are shown to the user in the 'Result Panel' shown in Figure 8.

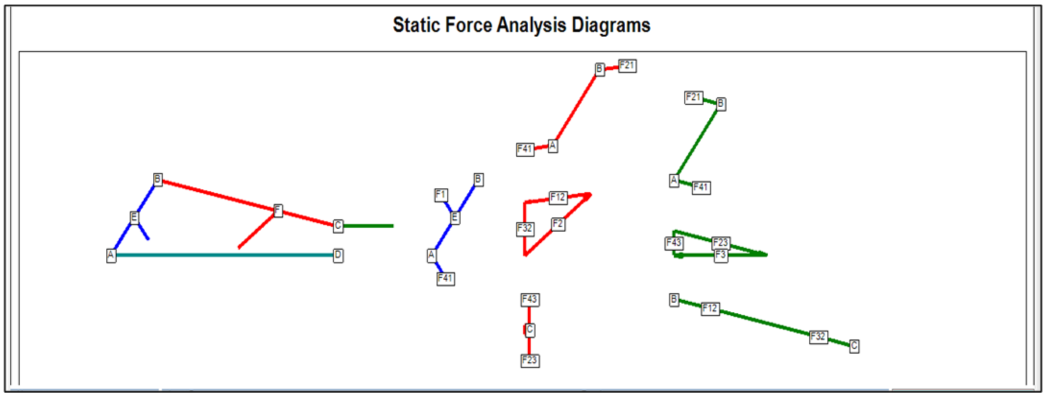

Figure 8: *Static Force Analysis diagrams of Slider Crank mechanism*

The formulation for the SFA of the other mechanisms is carried out in similar manner. The screenshot of the SFA of Whitworth mechanism is shown in Figure 9.

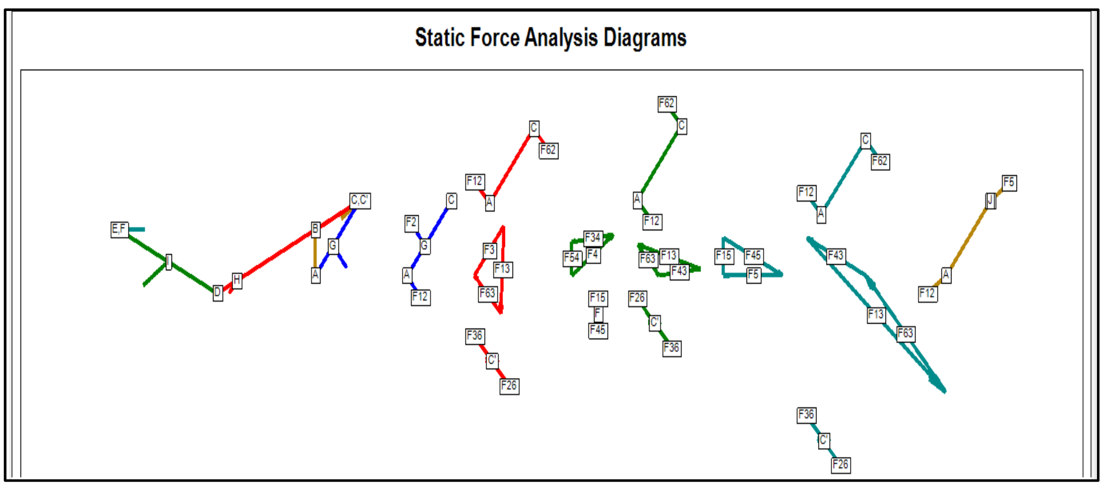

Figure 9: *Static Force Analysis diagrams of Whitworth mechanism*

5. VALIDATION OF RESULTS

All the mechanisms were individually modeled in Autodesk Inventor Professional (student version). 'Dynamic Simulation' environment in it allows static force analysis by assigning external forces acting on different links of a mechanism and obtaining the torque/moment at the crank joint due to the external forces. Equal and opposite torque at the crank results in static equilibrium and hence was used to validate the results obtained using SFD module of MechAnalyzer software. These input parameters for slider crank mechanism are shown in Figure 10.

For validation, results were compared at several discrete input angles and parameters but for the sake of brevity, only one comparison table for input in Figure 10 is shown in Table 1. The values obtained using Autodesk Inventor and SFA module match thus validating the results of MechAnalyzer software.

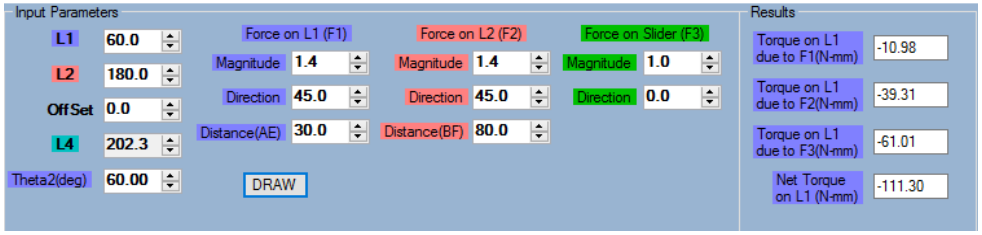

Figure 10: *Input parameters and results taken for validation of slider crank mechanism*

Table 1: *Comparison of results for validation*

Results / Software	Torque on crank due to $\mathbf{f_1}$(N-mm)	Torque on crank due to $\mathbf{f_2}$(N-mm)	Torque on crank due to $\mathbf{f_3}$(N-mm)	Net Torque on crank (N-mm)
SFA Module	**-10.98**	**-39.31**	**-61.01**	**-111.30**
Autodesk Inventor	**-10.9808**	**-39.315**	**-61.0069**	**-111.303**

6. CONCLUSION

A module dedicated to Static Force Analysis (SFA) developed as a part of MechAnalyzer is presented in this paper. It allows students and teachers to select from a set of default planar mechanisms such as four-bar, slider crank and quick return mechanisms, and enter input parameters in the form of length of the links and external forces acting on the selected mechanism. The software draws the mechanism and determines the forces acting on each link by drawing free body diagrams (FBD) and solving for static equilibrium of the mechanism. It can be readily used in a classroom environment to teach SFA easily and effectively. Students can also benefit from the software by learning at a pace suitable to them, outside the classroom. The results obtained have been validated with those obtained using Autodesk Inventor. SFA module is available in MechAnalyzer Version 5 for free from http://www.roboanalyzer.com/mechanalyzer.html. We are planning to implement static force analysis taking joint friction into consideration in the releases to come.

7. REFERENCES

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