Scotch-Yoke mechanism for a syringe pump – A case study

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Abstract. Syringe Pump is mainly used in microfluidics, where precise flow rate is required. Precise flow rate is achieved by using minimum torque and at low speed, for such requirements a mechanism has to be constructed. The input is from a stepper motor, so a rotary to linear motion converting mechanism is required, which will work efficiently on such low torque applications. This work mainly looks into feasibility of scotch yoke rather than conventionally used crank and slider mechanism. Scotch yoke is a rotary to linear conversion mechanism. It contains mainly two parts i) a rolling scotch and ii) a sliding yoke. The yoke is driven by a pin eccentrically placed on the scotch. Since proximity of the mechanism is nearer to the source, the loss accounted is less in the case of scotch yoke. In this work both crank-slider and scotch-yoke are examined through simulation using MSC ADAMS software and the maximum velocity of that can be achieved is obtained analytically through Kinematic analysis of scotch-yoke mechanism.

1. Introduction

Syringe Pump plays an important role in Controlled Titration of Chemicals, Infusion of vital fluids through blood and in Micro Electro Mechanical Systems. Syringe pump is mainly used in applications where fluid flow is to be regulated and maintained at appropriate level. [1] and [2] quoted that fluctuations are induced mainly due to the torque and speed of motor that is used. The effect of flow rate on drug delivery of systems was found by [3] and the authors suggested that precise flow rate could minimize unaccounted fluctuations on syringe pump. For precise and controlled fluid flow, the torque has to be minimum and the speed is to be maintained as low as possible. A mechanism has to be designed for such low torque and low speed applications. This work mainly focuses on two mechanisms namely slider crank mechanism and scotch yoke mechanism.

1.1 Slider-Crank Mechanism

Slider crank consists of a rotating crank and slider attached to it. The torque is applied to the crank and syringe pump is connected through slider. A parametric study of slider-crank mechanism was done by [4] and the authors analyzed the effect of input speed and torque over the slider crank. It was stated that slider crank would have oscillations due to the eye-gap in the joint of slider-crank. A dynamic model was constructed by [5] for slider crank and the various forces affecting the resultant force was analysed. The swaying of the joints create a main problem in slider crank and [6] suggested an optimal model for slider crank with slider as flexible link. The effect of variable speed in slider crank mechanism was studied [7]. It was found that slider-crank needs high amount of torque to overcome the initial inertial force of links and the link sways against gravity. Due to reaction force of gravity the link tend to bend decreasing the quality of the power to be transmitted. The dynamic stability of slider crank with flexible link was found out by [8] based on the analysis and it was found that bending in link was minimized when using flexible link.
The self-weight of the slider decides the critical speed of the system and also determines the bending moment due to gravity. Hence flexible link’s weight also accounted to losses. Even though modifications were made to optimize slider crank, the inertial torque required to initiate the mechanism is very high and this high torque can also induce fluctuations in output. In any transmission system the source and destination should be as near as possible to minimize the unaccounted losses in transmission distance. Slider crank minimum length of transmission is decided through length of the crank. The length should be as optimum as possible. Also the length of the transmission induces swaying couple in motor shaft which is undesirable and hence the length of crank plays an important role in power transmission.

1.2 Scotch-Yoke Mechanism

Scotch is one of the rotary to linear conversion mechanism. It consists of two main parts mainly i) a rotating scotch and ii) a sliding yoke. Sliding yoke is driven by a pin that is eccentrically placed on the rolling scotch. In this mechanism the number of links and joints are less hence reliability of the mechanism is more. There is no link in the mechanism that works against its self-weight. [9] found that scotch yoke transmission was optimal in low torque and low speed applications. The main disadvantage of scotch yoke was that it was rolling and sliding friction acts directly on to the shaft of motor. In such cases low speed operation would reduce the effect of these forces in the shaft. [10] found that the back and forward motion of scotch yoke is synchronously equal and so it was obvious that this mechanism could drive two syringes and synchronously at the same time with equal force. [11] found that scotch yoke mechanism behaves well even in vertical transmission. The disadvantage of scotch yoke was that its transmission efficiency depended on the eccentrically placed pin and due to sliding contact the pin may wear out easily. To avoid this a rubber bush can be provided at the contact point.
2. Simulation and Analysis

Both Slider-Crank and Scotch-Yoke is simulated using MSC's multibody simulation software ADAMS. In this case both are operated at the same torque level of 0.9 N-mm for such a low torque the fluctuations may be neglected as in case of fluid flow operations. The above shown prototype (Figure 3) is simulation model of scotch yoke constructed using MSC ADAMS. The pin placed eccentrically is assumed to be forged or casted along with the scotch to reduce losses. The frictional losses between pin and the yoke are neglected. The Kinematic Model of the Scotch yoke

Figure 2. Scotch yoke mechanism

Figure 3. A prototype of Scotch-Yoke Mechanism
1. Torque element 2. Screw joint b/w yoke and pin 3. Sliding joint b/w yoke and ground

**Figure 4.** Analytical model of Scotch-yoke

For torque of 0.9 N-mm the results obtained are:
Velocity = 0.25 m/sec, Displacement = 50mm. The graphs obtained is shown in Figure 5.

**Figure 5.** Time Vs Displacement and Velocity of yoke
The prototype of slider crank constructed in ADAMS is shown in Figure 6.

![Prototype of Slider Crank](image)

**Figure 6.** Prototype of Slider Crank

![Time vs. Displacement and Velocity of slider](image)

**Figure 7.** Time vs. Displacement and Velocity of slider
When self-weight of the linkages are taken in to account, the slider sways in the space which is undesirable as it is driven by a motor it may cause serious trouble which is shown in Figure 7. However by neglecting self-weight of the linkages the result obtained is shown in Figure 8.

![Figure 8](image)

**Figure 8.** Time vs. Displacement and Velocity of Slider (neglecting self-weights of linkages)

### 3. Analytical model

![Figure 9](image)

**Figure 9.** Kinematic Model of Scotch-Yoke

Let the Angular displacement of scotch is \( \omega t \). The yoke gets displaced sinusoidal at an angle \( \omega t \). Hence Displacement ‘X’ of yoke for \( \omega \) rotation of scotch of radius x is

\[
X = x \sin \omega t
\]  

(1)
Velocity \( (V) = dx / dt \)

\[ V = -x \omega \cos \omega t \]  

Hence \( V \) at \( \omega t = 90 \)

\[ V = -x \omega \cos 90 = 0 \]  

and maximum velocity occurs at \( \omega t = \pi \)

which is \( V = x \omega \)  

Thus a rotary motion of angular velocity \( \omega \ t \) is converted to a reciprocatory motion of linear velocity \( V = x \omega \)

Hence for a positive displacement, the velocity will be negative. Since \( \sin \omega t \) is a periodic function, the fluctuation will be less and the accuracy is maintained.

Acceleration \( (A) = \frac{d^2x}{dt^2} \)

\[ A = -X \omega^2 \sin \omega t \]  

And maximum acceleration = \(-X \omega^2\)

Force maximum \( (F) = \) mass \* acceleration

Where mass implies mass of the fluid to be ejected

\[ F = -mX \omega^2 \]  

From simulation it is noted that \( \omega = 8.72 \) rad/sec and for unit Kg mass of fluid and substituting X and \( \omega \) values the force exerted is

\[ F \text{ (mag)} = 0.436 \text{ N} \]

Negative sign indicates that the force acts in opposite direction of that of velocity.

4. Results and discussion

Slider-Crank mechanism is highly limited by its own self-weight and it does not work at low torque level as required. Scotch-Yoke on the other hand is independent of its self-weight and it will yield good results practically. The reliability of a mechanism depends on the number of linkages and joints used in the mechanism. Lesser the members and linkages higher the reliability is. Slider-Crank consists of 3 links and 4 joints, reliability of each joint is high but cumulatively this accounts in reducing reliability of the mechanism. Scotch yoke on the other hand consists of 2 members and 3 joints, hence cumulatively reliability of Scotch Yoke is high.

When it comes to closed cover operations, compactness plays an important role. Slider-Crank is limited by its slider length and may acquire large space and for continuous operation, the length to radius ratio of Slider: Crank must be at least 2:1. This will increase space requirement of the mechanism. Scotch-Yoke requires less space than Slider-Crank.

Since the slider crank mechanism is not working for very low torque of 0.9N-mm due to its self-weight, the scotch yoke mechanism for the same input torque has been analyzed in this work. It has been observed that the crank could not complete a revolution for the same 09N-mm torque due to the gravitational pull on the crank as well as links. It requires more torque to overcome this force. Thus an additional power loss takes place apart from frictional loss due to the slider, whereas scotch yoke is a good alternative for low torque applications, since the loss is only due to the friction. The results are as follows:

Input torque: 0.9N-mm, Force obtained at the end of yoke: 0.436N, Velocity at the end of yoke: 0.3 m/s.
5. Conclusion

In the present work a slider crank and scotch yoke mechanisms are simulated using MSC’s ADAMS software. The results show that for a given low torque, scotch yoke mechanism yields better results as its self-weight does not affect much the power transmission. On the other hand, the self-weight of slider crank mechanism plays a vital role. It requires a considerable amount of speed to overcome the reaction force due to gravity due to its self-weight. Scotch yoke mechanisms don’t require self weight and low torque and low speed can be effectively achieved.

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