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An Automated Scotch Yoke Mechanism

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Abstract
This paper addressed the relationship between linear velocity of a scotch yoke mechanism during motion. Understudying the working principle of the scotch yoke mechanism as regards to how it converts circular motion into linear motion. Experimental apparatus were set up which involves calibrating of the motor speed, calibrating of the motor speed, calibrating the timing of the circuit from theoretical knowledge which led to the scotch yoke mechanism model construction. Mono–stable multi–vibrator and DC motor speed controller circuits were introduced into the design. Linear velocity produced independently by Tachometer and Timer circuit experiment was determined. There is close relationship between the angular speed and linear velocity produced from the Tachometer experiment and the timer circuit experiment, which helps to have a model for demonstrating the motion conversion characteristics of the scotch yoke mechanism. These findings demonstrated the motion characteristics of the scotch yoke mechanism; also the model will be useful in teaching and research purposes.

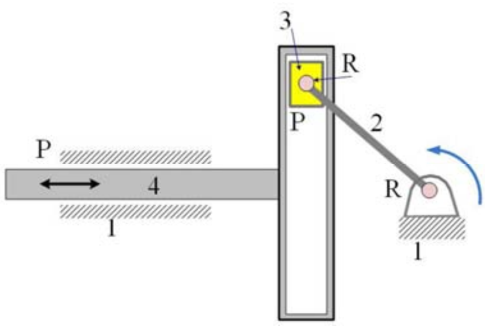
1. Introduction

The Scotch Yoke Mechanism is a fairly simple mechanism for converting the linear motion of a slider into rotational motion or vice-versa. The parts of this device include a sliding bar, a yoke on the bar with a slot cut out, and a smaller bar connected to the yoke and affixed by a pin through the yoke slot to the sliding bar. As the bar slides back and forth, or reciprocates, the smaller bar is forced to slide up and down in the yoke slot, creating a rotational movement. The converse of this motion relationship is also true; as the pin initiates a rotational movement, the slider correspondingly generates a reciprocal or back and forth movement. In operation, the reciprocating part is directly coupled to the sliding bar or yoke with a slot that engages the pin on the rotating part. The motion of the Scotch Yoke Mechanism is such that pure simple harmonic motion is produced by the mechanism when driven by an eccentric or crank. Because velocity and acceleration are derivatives of the displacement time curve these graphs also have a perfect wave form.

Scotch Yoke Mechanism is most commonly used in control valve actuators in high-pressure oil and gas pipelines. Although not a common metalworking machine nowadays, crude shapers also use Scotch yokes. It has been used in various internal combustion engines, such as the *Bourke engine, SyTech engine, and the Waissi engine. Some other contemporary uses include Can Crusher Machines, Power Operated Hairbrushes, and Medical/Dental aid robots.* Junzhi, et al., (2009), addressed the design, construction, and motion control of an adjustable Scotch yoke mechanism generating desired kinematics for dolphin-like robots. Since dolphins propel themselves by dorsoventral oscillations following a sinusoidal path with alterable amplitudes, a two-motor-driven Scotch yoke mechanism is adopted as the primary propulsor to produce sinusoidal oscillations, where a certain combination of a leading screw mechanism and a rack and pinion mechanism driven by the slave motor are incorporated to independently change the length of the crank actuated by the master motor. Meanwhile, the output of the Scotch yoke, i.e., reciprocating motion, is converted into the up-and-down oscillations via a rack and gear transmission. A DSP-based built-in motion control schemeis then brought forth and applied to achieve dolphin-like propulsion. Their preliminary tests, in a robotics context, confirmed the feasibility of the devised mechanism severing as a dedicated propulsor for bio-inspired movements. Manthan, et al., (2015), presents the automation of elliptical trammel mechanism by applying rack and pinion and DC Motor arrangement on the rod of the trammel which moves on the channel. The power was supplied by batteries and the entire system was carried out to have its operation by making ellipses of varying sizes. Moreover, a compass system attached at the end of the pinion made it easy to fix and remove the cutting tools of every kind. Equations relating the position of two sliders with the position of drawing or cutting element provided at the end of connecting rod were derived. The results were experimentally verified by fabricating an elliptical trammel and drawing ellipses from it. The sliders of the mechanism move perpendicular to each other and the drawing or cutting element produces the ellipse on the required surface and of the required major and minor axes which in turn provides a very convenient mechanism for cutting out elliptical pieces of whatever sizes out of any kind of material.

Galinski and Zbikowski, (2005), described the rationale, concept, design and implementation of a fixed-motion (nonadjustable) mechanism for insect-like flapping wing micro air vehicles in hover, inspired by two-winged flies. This spatial (as opposed to planar) mechanism was based on the novel idea of a double spherical Scotch yoke. The mechanism was constructed for two main purposes: (i) as a test bed for aeromechanical research on hover in flapping flight, and (ii) as aprecursor design for a future flapping wing micro air vehicle. Insects fly by oscillating (plunging) and rotating (pitching) their wings through large angles, while sweeping them forwards and backwards. During this motion the wing tip approximately traces a ‘figure-of eight’ or a ‘banana’ and the wing changes the angle of attack (pitching) significantly. The kinematic and aerodynamic data from free-flying insects were sparsed and uncertain, and was not clear what aerodynamic consequences different wing motions have. Since acquiring the necessary kinematic and dynamic data from biological experiments remains a challenge, a synthetic, controlled study of insect-like flapping is not only of engineering value, but also of biological relevance. For this application, insect-like flapping wings are an attractive solution and hence the need to realize the functionality of insect flight by engineering means. Since the semi-span of the insect wing is constant, the kinematics are spatial; in fact, an approximate figure-of-eight/banana was traced on a sphere. Hence a natural mechanism implementing such kinematics should be (i) spherical and (ii) generated mathematically convenient curves expressing the figure-of-eight/banana shape.

Scotch Yoke is equivalent to the slider crank mechanism of conventional reciprocating compressors when the connecting rod is imagined to have an infinite length. Since pure harmonic motion is generated, shaking forces occur only at the fundamental running frequency of the compressor and perfect dynamic balance is possible. This feature plus a compact design are the major advantages of a Scotch-yoke mechanism in compressor design. Until recently, Scotch-yoke mechanisms have been utilized only in compressors of relatively small capacity. For the application discussed herein, a Scotch-yoke mechanism has been employed in a line of four cylinder hermetic compressors ranging in capacity from 90,000 BTIJH to 145,000 BWH. With this design, two pair of opposed pistons are employed perpendicular and in slightly offset planes, Elson and Amin, (1974). Gregory, et al., (2003), developed a model which was initially non dimensional and simplified under conditions of large numbers of cycles, to predict the importance of including coupling based solely on a ratio of maximum allowable wear depth to the crank radius. Experiments show a linear progression of wear over two distinct regions, suggesting a sudden transition in wear modes just after 1.5 million cycles. The need for cycle or time dependent wear rates in analysis, which is a potentially far more significant source of error, is clearly illustrated by the experiment and discussed. Objectives of this experimental paper is to determine what relationship exists between linear Angular Speed and Linear Velocity of a Scotch yoke Mechanism as it engages in motion by: (i) Understudy the working principle of the Scotch yoke mechanism and study how it converts circular motion into linear motion, and (ii) To construct a model as a means of experimental evaluation of the output motion of the Scotch Yoke mechanism.



1 – Crank, 2 – link, 3 – Pivot, 4 – Slider.

Figure 1. *Scotch Yoke Mechanism.*

Figure 1 above shows the pure simple harmonic motion produced by the Scotch Yoke mechanism when driven by an eccentric or crank. There are many derivatives of it which are used in computing simple harmonic motion. The Scotch Yoke Mechanism above is also a slider crank mechanism in which the linear motion of a slider are converted to rotational motion of the crank and vice versa. Crank is a rotary element, while a piston is fitted with millimetre scale. A vertical pivot links the rotary element (crank) and the piston. When the piston generates the input motion (for example, a piston in a car's engine), the crank rotates. A millimetre scale is fitted to measure the linear motion of the converting rod.

2. Materials and Methods

The theoretical relationships employed in the course executing the experimental evaluation for the procedure implemented include: Determination of Linear Velocity from Angular Speed Measurements;

$$\omega = \frac{2\pi \times RPM}{60} \tag{1}$$

$$V = s_o \text{ x } \omega \tag{2}$$

Determination of Linear Velocity from Distance – Time Measurements;

$$V = \frac{DistanceMeasured}{Timetaken} \tag{3}$$

2.1. Design Computations

Torque rating was determined in (4), selection of electric motor warranted- the torque rating according to the idealised experimental set up, which needs to be computed.

Motor Torque: the value of torque for a horizontal travel on a contact surface is given by

$$\frac{1}{2} D \times \mu M g \tag{4}$$

Slider Design: the shaft in this application is subjected to axial loading only (very negligible torsional and bending loads). Therefore, the properties of its construction can be adequately specified by applying the equation in (5).

$$S_a = 4F_a / \pi d^2 \text{ (for solid shafts)} \tag{5}$$

Sliding force: the force overcome by the scotch yoke mechanism in order to set the sliding member in motion was calculated from the assumption that minimum force to be overcome for sliding force required to cause the member to slide along the rails = Static friction force.

$$\text{Static Friction} = F = \mu R \tag{6}$$

Weight of the sliding member is determined by the density relationship

$$\rho = \frac{m}{v} \tag{7}$$

$$m = \rho v \tag{8}$$

$$W = \rho v g \tag{9}$$

Experimental Set Up: having constructed the Scotch Yoke experimental apparatus to suitable standard, the following preparations for the experimental purpose were carried out in order to achieve results: *Calibrating the Motor Speed:* the system was placed on a completely flat/horizontal surface and the tachometer was also placed such that it is longitudinally perpendicular to the flat rotating surface of the crank. A piece of paper was marked off and graduated from 0°to 360°. The paper was placed over the potentiometer to serve as a scale. The potentiometer was then turned to its first extreme position, which coincided with 0°on the paper; then the circuit was left to run. The tachometer was also left to measure the rotational speed of the motor as measured on the crank and recorded. Then the potentiometer knob was turned to its other position and the rotational speed was measured off the crank and recorded. With the assumption that linear distribution of the motor speed varying with potentiometer knob position, the speed of the motor was determined, then taking readings of the crank using the tachometer which ensures that the assumption was evaluated experimentally. A congruence in the tachometer reading and previously estimated motor speed value signified that the motor speed was successfully calibrated. The motor speed was computed at the different marked points over the graduated scale, which allowed selection of suitable motor speed as desired in order to perform the experiment.

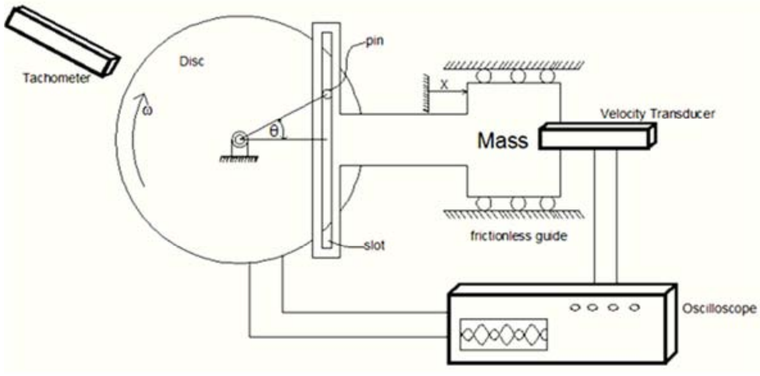


Figure 2. *The ideal experimental setup.*

Calibrating the timing of the Circuit: by varying certain resistances on the project circuit board, the amount of time that current flow into the motor was determined by allowing its rotation for a desired amount of time. Using a stopwatch, the electric motors operating time was up to 2 seconds and timing was verified continuously which guaranteed that experimental set up is accurate.

2.2. Construction of the Model

The model built is a miniature prototype for the purpose of demonstrating the operation of the Scotch yoke mechanism with regards to its conversion of angular velocity to linear velocity. The specifications of the components that are used in its construction are as follows:

The Base plate and Vertical Frame: the base plate and vertical frame was constructed from soft plywood material made of redwood. The dimensions of the vertical frame are 700mm by 400mm; with thickness of ½ inch and with a density per cubic foot ($0.028317m^3$) of $3.47kg/m^3$, while that of the base plate are 750mm by 400mm. The Scotch yoke mechanism: the Scotch yoke mechanism consists of following singular members conjoined and assembled in the appropriate manner: Linear slider, yoke or slot, Crank pin, and crank. The assembly was in simple imitation of the real demonstrational models. The linear slider was affixed to the yoke member in a rigid manner by welding the yoke or slot engaged a small crank pin that is also very rigidly connected to the crank of the mechanism at some point along its diameter which makes it free to move along the hollow of the slot. The crank has a recess into which the motor shaft of the electric motor entered and rigidly fitted. A small bracket was used to hold the slider to the frame of the whole model.

Based on the design of the model at hand, the dimensions and properties of these members are as follows: The Slider: made of1/8 inch thick steel with rectangular cross section of 30mm height with overall length of 330mm. It was selected chiefly due to its availability, and the minimal weight it constitutes to the overall apparatus. The Yoke/Slot: was constructed with 1/8 inch steel. It is basically a flat, hollow rectangular block with *the* dimensions of the inner hollow, similar to the outer measurements. The inner hollow has a length which is equal to twice the distance of the crank pin from the centre of the circular crank. The Crank pin: being a small circular pin joined to the crank, has quite little need for exact specification but only needs to be joined rigidly enough to the crank to be able to transmit the rotary force from the crank to the slider. It is machined such that it can easily fit into the inner hollow of the yoke and slide up and down with minimum friction. It is circular in cross section and has a total length just a little longer than the thickness of the yoke and connecting shaft. The Crank: also a fairly simple member, it is simply a flat cylindrical member; the thickness of this member is ⅛ inch with diameter of 200mm. A recess was provided at the centre through which the shaft from the electric motor passes and bolted.

Figure 3a and 3b illustrates 3 dimensional drawing of the model, describing the actual model in space and the front view of two dimensional schematic drawing of the model respectively.

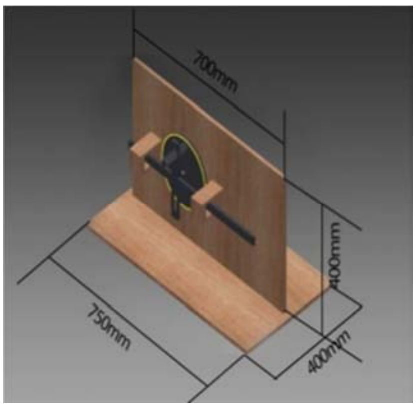


Figure 3a. *Dimensional view of the model.*

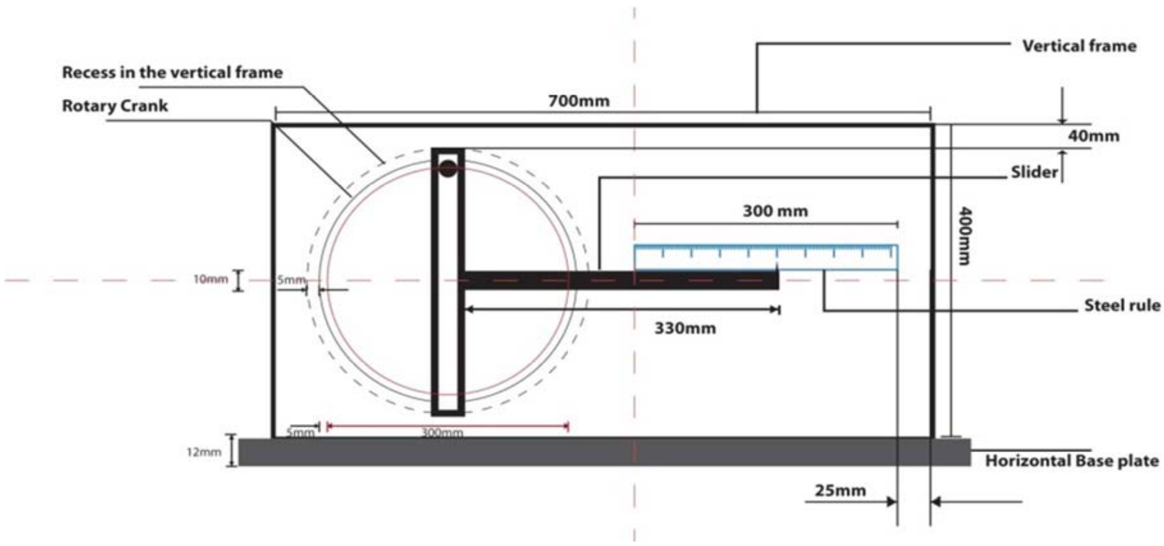


Figure 3b. *Front view drawing of the model.*

The Electric Timer and Motor Circuit: the circuits incorporated into the design are of two types: Mono-stable multi-vibrator and DC motor speed controller.

The Mono-stable/Astable Multi-vibrator Circuit: the mono-stable multi-vibrator circuit is a retrigger-able mono-shot pulse generator. The term"mono-stable" indicates that it has only one stable state, the unstable state is called the quasi stable state or astable state. The duration of the stable state or the pulse width is determined by the charging time constant of the RC network. Multi-vibrator from stable state to quasi stable state can be transferred by using a trigger switch.

Components required: *IC 555, *Resistors (1MΩ, 100Ω), *Capacitors (1μF, 0.001μF), Thrysistors, *Transistor, *Transformer, *Diodes, and *LED push button/ trigger switch.

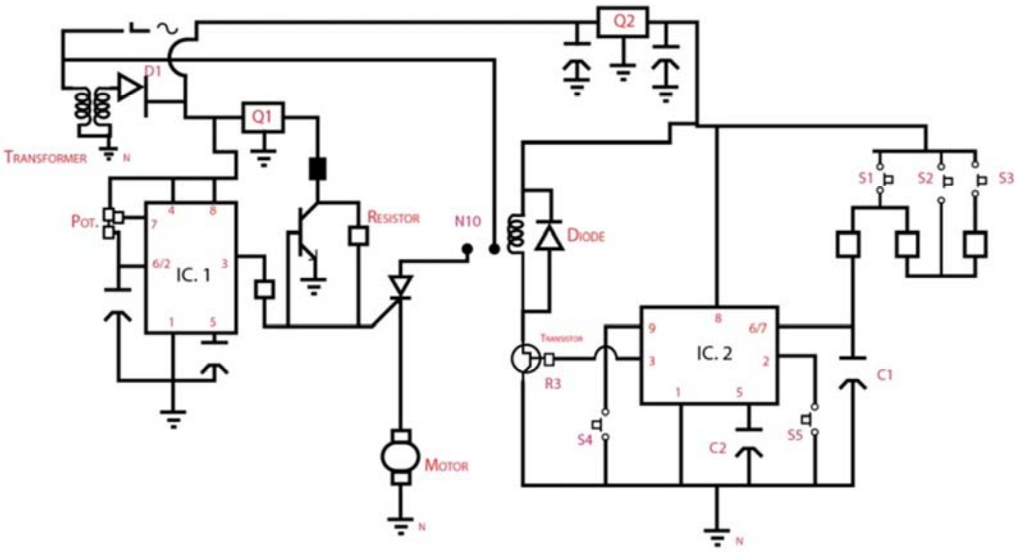


Figure 4. *A mono stable multi vibrator circuit diagram.*

Working principle of a Mono-stable Multi-vibrator: the output of Mono-stable multi-vibrator remains in its stable state until it gets a trigger. Primarily, the transistor and capacitor are shorted to ground, this state is considered as the stable state of the mono-stable 555 multi-vibrator. When the voltage at the second pin of the 555 IC goes below 1/3 Vcc, the output becomes high. This state is known as the quasi stable or astable state. The trigger causes the transition from stable to astable state so when the trigger is activated, the voltage at the 2nd pin becomes less than 1/3Vcc (disconnected from Vcc) and hence the output becomes high. Then the discharge transistor is cut off and the capacitor starts charging towards Vcc. Charging of the capacitor is through the resistor R1 with a time constant R1C1. As the capacitor voltage increases and its finally exceeds 2/3 Vcc, it will reset the internal control flip flop, thereby turning off the 555 timer IC (more than 2/3 voltage at the threshold pin causes the IC to reset). Thus the output goes back to its stable state from Quasi stable state. Design equation for mono-stable multi-vibrator ON time,

$$T = 1.1\ R1\ C1 \tag{10}$$

2.3. Experimental Methodology

The experimental Setup incorporated a locally fabricated reproduction of the Scotch Yoke Mechanism, incorporating a steel rule, and an electrically operated AC motor with which results were generated, a Tachometer, a timer circuit and motor controller circuit representing an improvisation in the original experimental procedure which incorporated a Linear Velocity Transducer, and an Oscilloscope together with the Tachometer. The circuit used is a mono-stable/astable multi-vibrator circuit which is a retrigger-able mono-shot pulse generator. It allows for the operation period operation of an electric motor to be timed, such that the motor automatically ceases operation at pre-set time durations. Also, the circuit allows for the rotational speed of the motor to be regulated according to calibrated range of speeds. The experimental procedure, as previously mentioned, involved testing to determine the angular speed–linear velocity relationship with two different setups and procedures viz: an experiment with a Tachometer, and an experiment with the Multi Vibrator Timer Circuit. The former, being subjectively labelled the hypothetical experiment, while the other was the confirmatory experiment. The procedures for both experiments are as detailed below

(i) *Experiment with the Tachometer*: a suitable range of rotational speeds was selected to test. The tachometer sensor was placed in an orientation whereby it was longitudinally perpendicular to the flat rotating surface of the crank of the constructed mechanism, and the corresponding readings of the crank rotational speed were taken and recorded. From the recorded values, computations were then made to determine the hypothetical resultant values of linear velocity that should be obtained or matched if reading were to be taken directly from the slider.

(ii) *Experiment with the Timer Circuit:* this experiment was the confirmatory one in which the true value of the linear velocity imparted unto the slider member by the crank component was verified against the previously computed value from the tachometer readings. The time setting on the mono stable circuit remaining constant, the slider marker was set to the zero position along the linear distance measure; the speed of the electric motor was set on earlier determined points, varying from 5 rpm, to 30 rpm in steps of 5. Then the switch of the circuit was turned on to allow motion commence on the apparatus. The timer circuit ran for a pre-set period of two seconds before it came to a halt, irrespective of the selected motor speed. The linear distance through which the slider moved (indicated by the slider marker which reads along the distance measure) was then determined for the given rotational speed.

3. Results and Discussion

Table 1 and Table 2 with corresponding graphs in Figure 5 and Figure 6 are the results obtained from the two experimental set ups and procedures.

Table 1. *Readings taken from the tachometer.*

Rotation (min^{-1})	Angular velocity, ω (rad/s)	Linear Velocity (m/s)
6.40	0.67	0.10
12.80	1.34	0.20
18.10	1.90	0.29
21.40	2.24	0.34
27.30	2.86	0.43
34.80	3.64	0.54

Table 2. *Readings taken from the timer circuit and linear distance measurement.*

Rotation (min^{-1})	Time (seconds)	Distance travelled (m)	Velocity (m/s)
6.40	2.00	0.13	0.07
12.80	2.00	0.25	0.13
18.10	2.00	0.39	0.20
21.40	2.00	0.51	0.26
27.30	2.00	0.73	0.37
34.80	2.00	0.87	0.44

The corresponding graphs resulting from the values obtained are also presented below:

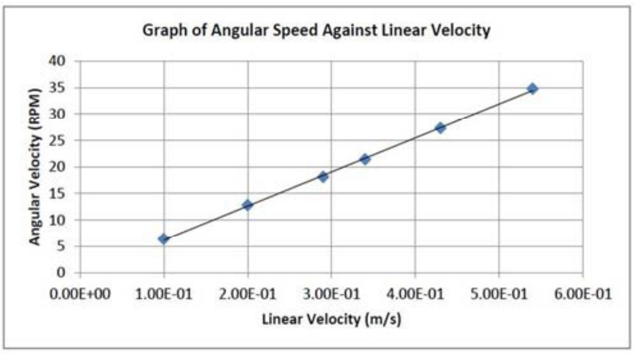


Figure 5. *Relationship between Angular speed against linear velocity as using Tachometer.*

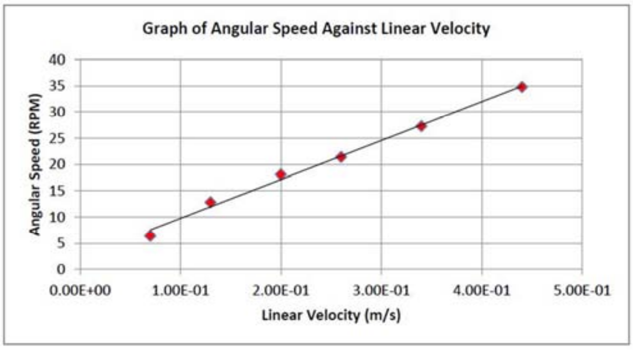


Figure 6. *Relationship betweenAngular speed against linear velocity using timer circuit.*

It can be deduced from the results presented here that the values of velocity obtained from the tachometer readings (which serve as a hypothetical base of sorts) are closely similar to those obtained from using the timer circuit and distance measure. The relationships were obtained using two varied procedures such that a correlation between both obtained results are confirmatory evidence establishing the findings obtained for the relationship between Angular Speed and Linear Velocity of the Scotch Yoke Mechanism as it is engaged in motion. There are, however slight discrepancies in values and these may be attributed to the following factors:

a) The initial resistance needed to be overcomed by the electric motor when it is switched on at lower speeds,
b) Reduction in speed due to the frictional resistance posed by metallic moving parts of the apparatus,
c) Human error in the timing of the circuit,
d) Human error in the reading of values of the distance measure, and
e) Infinitesimal design flaws that collectively resulted in errors such as imperfections in the alignment of connecting points such as the motor and shaft, or yoke and pin.

However, the overarching conclusion herein is that; in a scotch yoke mechanism, there is a direct relationship between the angular or rotational speed and corresponding linear speed produced. The relationship simply implies that angular speed is directly proportional to the linear velocity as regards to the two cases tested.

4. Conclusion

In conclusion, a model for demonstrating the motion conversion properties of the Scotch Yoke mechanism, particularly with respect to conversion of angular velocity to linear velocity was fabricated with parts specified, and an improvisation of a standard experimental procedure was constructed to achieve our objective of verifying the linear velocity of the slider component in the mechanism as against that obtained from the crank using a tachometer. It was found that the angular speed is directly proportional to linear velocity of the Scotch yoke mechanism, under normal motion. This experimental finding helps to elucidate current knowledge where the operation of the Scotch Yoke mechanism is concerned. It is recommended however, that further confirmatory work should be done on this subject.

Acknowledgement

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Notations

S_o	radius of the crank (m)
ω	Angular Velocity (rad/s)
V	Linear Velocity (m/s)
RPM	Revolutions per Minute (min^{-1})
ρ	Density (kg/m^3)
M	Mass (kg)
W	weight (N)
g	acceleration due to gravity (m/s^2)
F	Frictional force (N)
μ	Coefficient of friction
R	Normal reaction to the sliding surface (N)
S_a	Axial stress (tension or compression) (N/m^2)
F_a	Axial load (N)
d	diameter of the shaft (m)
D	diameter of the crank to be rotated (m)

Appendix

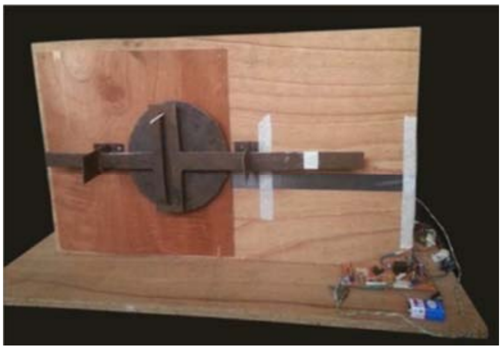

Figure A1. *Front view of the Scotch Yoke mechanism during construction.*

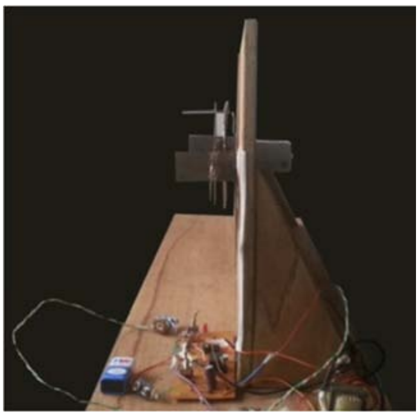

Figure A2. *Side view of the Scotch Yoke mechanism during construction.*

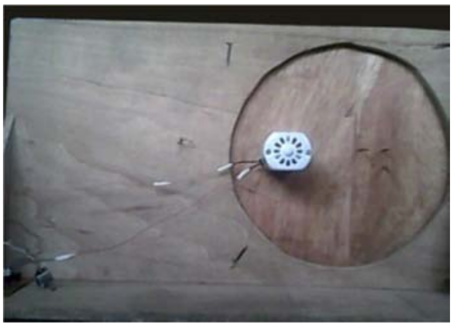

Figure A3. *Back view of the Scotch Yoke mechanism during construction.*

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