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Experimental Data Based Model for Time to Exhaust Flywheel Energy in a Human Powered Flywheel Motor Driven System having a Novel Gearbox

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Abstract

Use of fossil fuels has increased environmental pollution, which is posing a threat to the environment. So research is going on for harnessing human power because it is one of the resources of renewable energy. This research paper presents mathematical modeling of a novel gearbox for the human powered flywheel motor for total time required to exhaust energy stored in a spinning flywheel when it coupled to process unit through a newly developed Novel Gear box.

Keywords: *Human Power, Pedal Power, Flywheel Motor, Novel Gearbox, Mathematical Modeling, Constant Speed.*

1. Background of the Present Research

In the age of fossil fuels the human power was neglected but hazardous environmental pollution caused by fossil fuels again brought the human power in the mainstream of renewable power resources. So in recent past vast research is going on for harnessing human power. A stationery system similar to a bicycle having flywheel is conceptualized as Human Powered Flywheel Motor (HPFM) [1-6] in which a human being spins a flywheel at about 600 RPM to store energy. It can be a replacement for the electric motor in processes which requires power in the range 3 to 9 HP for very short durations of time even though the human energy input rate to the flywheel is only 75 watts [7]. The operator stops pedaling and clutches the HPFM through a torque amplification gear pair to a process unit. Due to the process resistance of clutched process unit speed of flywheel goes on continuously diminishing. This puts a limitation for the use of such a HPFM energized process machine to only those applications in which product quality doesn't get affected because of variations of the speed of process unit. A gearbox called as 'Novel Gearbox' [9, 10] in which output speed can be maintained reasonably constant by using fly ball governor even though the input speed is varying has been developed to eliminate the most important limitation i.e. dropping speed of the output shaft of HPFM. The experimentation with the novel gearbox is carried out with the involvement of some parametric variations to validate the performance. Rope brake dynamometer was used to simulate the process load. The experimentally obtained results were used to formulate a mathematical model for the performance validation of Novel Gearbox for HPFM.

2. Experimental Setup

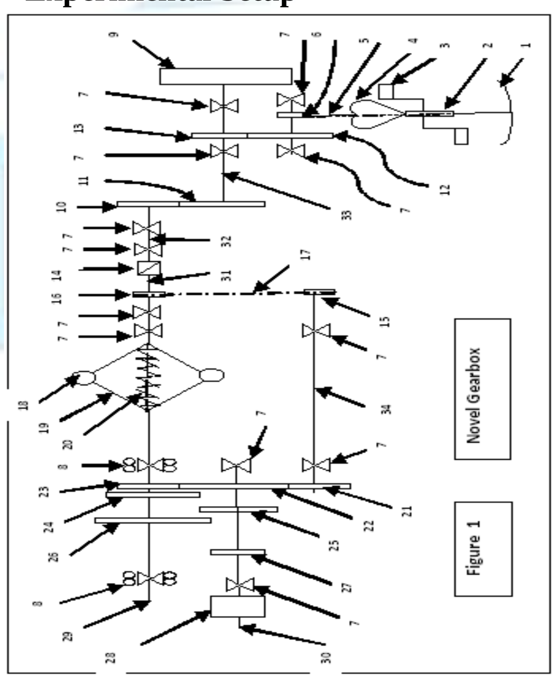

Figure 1 Experimental Setup

Schematic Experimental Setup & Parts are shown in Figure 1 & Table 1 respectively.

Table 1 Setup Parts

Part No.	Setup Part Name	Part No.	Setup Part Name
1	Handle Bar	18	Fly ball
2	Front sprocket	19	Fly ball link
3	Pedal	20	Spring
4	Rider Seat	21	Pinion
5	Chain	22	Gear
6	Freewheel	23	Pinion
7	Ball Bearing	24	Pinion
8	Bearing	25	Gear
9	Flywheel	26	Pinion
10	Pinion	27	Gear
11	Gear	28	Brake Drum
12	Gear	29	Shaft
13	Pinion	30	Shaft
14	Dog Clutch	31	Shaft
15	Freewheel	32	Shaft
16	Sprocket	33	Shaft
17	Chain	34	Shaft

2.1. Subsystems of Experimental Setup

1) **Human Powered Flywheel Motor (HPFM)**
   a) Bicycle Mechanism --- Part No. 1 to 7
   b) Energy Unit --- Part No 9 to 1
2) **Transmission Unit**
   c) Dog clutch -Part No. 14
   d) Partial Synchronization and Automatic Clutching Assembly --- Part No. 15 to 17 & 21
   e) Fly ball Governor --- Part No. 18 to 20
   f) Sliding Cluster Pinions --- Part No. 23, 24, & 26
   g) Speed Maintaining Gears -- Part No. 22, 25 & 27
3) **Rope Brake Dynamometer** --- Part No. 28

2 .2. Operation Principle of Setup

As a rider stops pedaling and engages clutch-14 to flywheel rotating at 600 RPM which in turn spins fly ball governor to its maximum speed, so that the first gear pinion pair-22-23 get engaged, due to the resistance offered by rope brake drum-28 the flywheel speed goes on continuously diminishing and so the fly ball governor slides to mesh the second gear pinion pair-25-24, likewise third gear pinion-27-26 get meshed. Which result in change of gear ratio from 3, 2.33 & 1.86 at first, second & third gear-pinion pairs respectively, its ultimate result is maintained output speed fairly constant at the brake drum shaft. During the time span between the disengagement of first gear-pinion pair & engagement of second gear-pinion pair (similarly for second pair & third gear-pinion pair) the power is transmitted through sprocket-16 to chain-17 to freewheel-15 to pinion-21 and finally to gear-22 [9].

Partial speed synchronization for gear mesh & automatic clutching-declutching of freewheel-is achieved due to the difference of RPM between cluster pinion shaft-29 & freewheel shaft-34 [9].

2.3. Experimental Procedure

The riders were of age, height and weight ranges 25-38 years, 165- 175 cm & 55-70 kg respectively. All the tests are carried out at 100, 200, 300,400,500 & 600 RPM of the flywheel with variations of following parameters.

1) Governor Spring with Stiffness 476.77N/m.
2) Fly ball Mass- 500 grams
3) Lubricant Oil Viscosity in sliding Gears and sliding Bearings 0.05133 Ns/m^2 at 40° C
4) Brake load of 12.753 Nm
5) Gear ratio of gear-pinion pair I, II & III is 3, 2.33 & 1.86 respectively & Fixed values for the following variables (Table 1a)

Table 1a Fixed Variables

n	**C (m)**	**W_p (m)**	**W_g (m)**
3	0.15875	0.028	0.028
***Fl* (m)**	**C (m)**	**I ($Kg.m^2$)**	**g (N/s^2)**
0.25	0.15875	3.351897	9.81

2.4 Data Acquisition

The data acquisition system was designed to record process time with respect to flywheel RPM & output shaft RPM.

Table 2 Recorded Data

Flywheel RPM	Process Time (Sec)	Flywheel RPM	Process Time (Sec)
606	56.5	301	26.5
588	54.5	273	24.5
571	52.5	252	22.5

550	50.5	227	20.5
535	48.5	203	18.5
512	46.5	180	16.5
491	44.5	154	14.5
468	42.5	134	12.5
441	40.5	114	10.5
422	38.5	94	8.5
397	36.5	70	6.5
375	34.5	48	4.5
357	32.5	31	2.5
342	30.5	31	0.5
322	28.5	--	--

3. Mathematical Model

Buckingham's pi theorem [8] is used to formulate the model. The variables affecting the total time to exhaust flywheel energy are shown in Table. 3

Table 3 Variables in the Process

Sr. No.	**Name of Variable**	**Symbol**	**Unit**	**Dimension**
Independent Variables				
1	Gear Ratio – I^st^ Pair	G_1	---	---
2	Gear Ratio – II^nd^ Pair	G_2	---	---
3	Gear Ratio – III^rd^ Pair	G_3	---	---
4	Number of Gear-Pinion Pairs	n	---	---
5	Width of Cluster Pinions P_1, P_2, P_3	Wp	m	$[L^1]$
6	Width of Gears G_1, G_2, G_3	Wg	m	$[L^1]$
7	Angular velocity of Flywheel	ω_F	rad/sec	$[T^{-1}]$
8	Fly ball Mass	F_m	Kg	$[M^1]$
9	Fly ball Link Length	Fl	m	$[L^1]$
10	Spring Stiffness	K_S	N/m	$[M^1T^{-2}]$
11	Lub. Oil Viscosity	μ	Ns/m^2	$[M^1L^{-1}T^{-1}]$
12	Brake Load Torque	T_B	Nm	$[M^1L^2T^{-2}]$
13	Equivalent Mass M.I.of Flywheel	I	Kgm^2	$[M^1L^2]$
14	Acceleration due to Gravity	g	m/s^2	$[L^1T^{-2}]$
15	Centre Distance Between Gear-Pinion Shaft	C	m	$[L^1]$
Dependent Variable				
01	Time to Exhaust Flywheel Energy	t_p	sec	$[T^1]$
Repeating Variables				
1	Equivalent Mass M.I. of Flywheel	I	Kgm^2	$[M^1L^2]$
2	Acceleration due to Gravity	g	m/s^2	$[L^1T^{-2}]$
3	Center Distance Between Gear-Pinion Shaft	C	m	$[L^1]$

Repeating variables can be rewritten as below:

$C = [L^1]$ i.e. $[L^1] = C$ ………… (a)

$g = [L^1T^{-2}]$ i.e. $[T^1] = \frac{C^{1/2}}{g^{1/2}}$ ……….. (b)

$I = [ML^2]$ i.e. $[M^1] = \frac{I^1}{C^2}$ ……… . (c)

Formation of Pi (Π) term for Lub. Oil Viscosity (μ):

Lub. Oil Viscosity is represented by symbol (μ) & dimension $[M^{+1}L^{-1}T^{-1}]$

Therefore (μ).$[M^{-1}L^{+1}T^{+1}]$ is dimensionless term, which can be considered as Pi (Π) term for Lub. Oil Viscosity,

Therefore $\Pi = (\mu) \cdot [M^{-1}L^{+1}T^{+1}]$ Substituting the values of [M] , [L] & [T] from equations (a), (b) & (c)

$$\Pi = (\mu) \cdot \frac{C^2}{I^1} \cdot C \cdot \frac{C^{1/2}}{g^{1/2}}$$

$$\Pi = \frac{C^{7/2}}{I\ g^{1/2}} \cdot \mu$$

Similarly pi terms for all the variables are shown in the table 3a below

Table 3a of pi terms

Sr.	**Name of Variable**	**Pi (Π) Term**
1	Gear Ratio - I^st^ Pair	$\Pi_1 = G_1$
2	Gear Ratio – II^nd^ Pair	$\Pi_2 = G_2$
3	Gear Ratio – III^rd^ Pair	$\Pi_3 = G_3$
4	Number of Gear-Pinion Pairs	$\Pi_4 = n$
5	Width of cluster Pinions P_1, P_2, P_3	$\Pi_5 = \frac{Wp^1}{C^1}$
6	Width of Gears G_1, G_2, G_3	$\Pi_6 = \frac{Wg^1}{C^1}$

7	Angular velocity of Flywheel	$\Pi_7 = \frac{C^{1/2}}{g^{1/2}} . \omega_F$
8	Fly ball Mass	$\Pi_8 = \frac{C^2}{l^1} . F_m$
9	Fly ball Link Length	$\Pi_9 = \frac{Fl}{C^1}$
10	Spring Stiffness	$\Pi_{10} = \frac{C^2}{L\ g^1} . K_S$
11	Lub. Oil Viscosity	$\Pi_{11} = \frac{C^{7/2}}{L\ g^{1/2}} . \mu$
12	Brake Load Torque	$\Pi_{12} = \frac{C^1}{L\ g^1} . T_B$
01	Time to Exhaust Flywheel Energy	$\Pi_{01} = \frac{g^{1/2}}{C^{1/2}} . t_p$

Dimensional Equation for Time to Exhaust Flywheel Energy (t_p)

$f(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7, \Pi_8, \Pi_9, \Pi_{10}, \Pi_{11}, \Pi_{12}, \Pi_{01}) = 0$

Multiplying pi terms $\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6$, and Π_9 and renumbering pi terms as below

$\Pi_{01} = \varnothing(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6)$

Substituting values of pi terms

$$\left(\frac{g^{1/2}}{C^{1/2}}.t_p\right) = K_1\left[\left(G_1.G_2.G_3.n\frac{Wp^1.Wg^1.Fl^1}{C^2}\right)^{a1}.\right.$$
$$\left(6.2832\frac{C^{1/2}}{g^{1/2}}.N_F\right)^{b1}.\left(\frac{C^2}{l^1}.F_m\right)^{c1}.\left(\frac{C^2}{L\ g^1}.K_S,\right)^{d1}.$$
$$\left.\left(\frac{C^{7/2}}{L\ g^{1/2}}.\mu\right)^{e1}.\left(\frac{C^1}{L\ g^1}.T_B\right)^{f1}\right]$$

Where N_F – Flywheel RPM & K_1 is curve fitting constant.

Indices of various pi terms & curve fitting constant are determined by matrix method.

The exact mathematical model is as shown below

$$\left(\frac{g^{1/2}}{C^{1/2}}.t_p\right) = 0.22305\ x\left(G_1G_2.G_3.n\frac{Wp^1.Wg^1.Fl^1}{C^2}\right)^{0.0115} x$$
$$\left(6.2832\frac{C^{1/2}}{g^{1/2}}.N_F\right)^{1.1378} x\left(\frac{C^2}{l^1}.F_m\right)^{-0.0147} x\left(\frac{C^2}{L\ g^1}.K_S\right)^{0.2333}$$
$$x\left(\frac{C^{7/2}}{L\ g^{1/2}}\ \mu\right)^{0.0173} x\left(\frac{C^1}{L\ g^1}\ T_B\right)^{-0.5013}$$

4. Results and discussions

The output results Mathematical Model and Experimentally observed total process time to exhaust flywheel energy are shown in tabulated form in the Table 4, graphical plot is shown in Figure 2. From the graph it can be seen that all are almost coinciding showing that there is less percentage of error.

The mathematical model is showing more error at higher RPM of the flywheel.

Table 4 Comparison of Process Time

Flywheel RPM	Total Time to Exhaust Flywheel Energy (Seconds)		Flywheel RPM	Total Time to Exhaust Flywheel Energy (Seconds)	
	Math. Model	Experiment.		Math. Model	Experiment.
606	59.9	56.5	301	27.0	26.5
588	57.8	54.5	273	24.2	24.5
571	55.9	52.5	252	22.1	22.5
550	53.6	50.5	227	19.6	20.5
535	52.0	48.5	203	17.2	18.5
512	49.4	46.5	180	15.0	16.5
491	47.1	44.5	154	12.6	14.5
468	44.6	42.5	134	10.8	12.5
441	41.7	40.5	114	8.9	10.5
422	39.7	38.5	94	7.2	8.5
397	37.0	36.5	70	5.1	6.5
375	34.7	34.5	48	3.3	4.5
357	32.8	32.5	31	2.0	2.5
342	31.2	30.5	31	2.0	0.5
322	29.2	28.5			

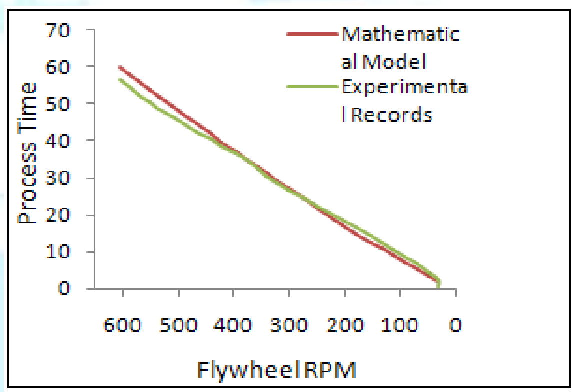

Figure 2 Graph Process Time Versus Flywheel RPM

5. Conclusions

The process time to exhaust flywheel energy predicted by mathematical model is very much close to the values observed during experimentation and values of ANN simulation. So proves the authenticity of the mathematical model that it predicts very accurately.

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