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Design of experimentation for establishing empirical relationship of chaff cutting phenomenon energized by human powered flywheel motor (HPFM)

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A R T I C L E   I N F O

A B S T R A C T

In India, animal husbandry is an integral part of the rural economy. Almost every farmer's family keeps at least a cow and two oxen. The forge scarcity is always faced in dry season, means the available forage must be properly used and waste minimized. The chaff cutter always suggested for optimum use of forage. But the availability power is not reliable and hand operated chaff cutter results in high tiredness to the operator. The human powered chaff cutter is developed without any design data. The set-up consists of three main systems namely, (i) Human powered driven flywheel motor, (ii) Transmission between flywheel shaft and process unit shaft, (iii) Process unit i.e. chaff cutter.

This paper presents detailed design of experimentation to be performed for establishing empirical relationship of chaff cutting phenomena energized by human powered flywheel motor. It includes identification of variables, dimensional analysis, test envelope, test point, test sequence, measurements and instrumentation, data checking and rejection and method of data analysis.

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1. Introduction

The literature survey revels that several attempts have been already made to develop various aspects of man-machine system of human powered flywheel motor used in bricks making machine (Modak, J. P. 1982, Askhedkar R. D. and Modak J. P. 1994), generation of electrical energy (Deshpande S. B et al. 2009), wood turning process (Modak, J. P. and Bapat, A. R. 1993),drum type algae formation (Modak, J. P. and Katpatal A.A., 1994),oilseed presser(Dhale A. and Modak, J. P. 2012), optimization of conversation of human energy into rotational kinetic energy (Modak J. P. and Bapat A. R. Spring 2003). The literature survey conclusively revels that the system for pumping the muscular energy in the flywheel has not yet given enough consideration.

Since this is a man-machine system, it is rather difficult and unreliable to adopt total theoretical approach for this system, instead an experimental approach is adopted (H. Schenk Jr., 1961). Thus it is necessary to establish the empirical relationship model by applying the methodology of experimentation for chaff cutter energized by human powered flywheel motor by varying all possible physical variable encountered in the process.

In this paper, the detailed design of experimentation for this purpose is addressed which includes the detailed dimensional analysis of the system, deciding test envelop, test points, test sequence for the independent π terms, instrumentation& measurement, method of test data checking and rejection and the method of data analysis.

2. Materials and methods

2.1. Experimental plan design

The Experimentation Plan includes following steps:
1. Dimensional analysis of the system
2. Test Planning
3. Instrumentation & measurements
4. Test data checking and rejection
5. Method of data analysis

2.1.1. Dimensional analysis

Dimensional analysis is carried out in two steps (i) Identification of Physical quantities affecting the process, (ii) dimensional consideration & (iii) dimensionless similarity parameters.

Identification of physical quantities: These are the process variables which are independent and dependent.

A. Independent Variables: The variables which can be changed without changing other variables of the process. The identified independent variables are - Hub Diameter of blade d, Width of cutting blade W_b , Thickness of cutting blade t_b , Tip diameter of blade D, Acceleration due to gravity g, Moment of inertia of flywheel I, Young's modulus of elasticity of cutting blade E, Cutting blade angle α , Gear ratio G, Number of blades n, Kinetic energy of flywheel e, Angular velocity ω. The Dimensional matrix given in Table1.

B. Dependent Variables: The variables which can only be changed by varying one or more independent variables. These variables are - Instantaneous torque on cutting blade T_c , Number of cuts during cutting C_p , Process time for cutting t_p , listed in Table1.

Dimensional consideration: Next we list the dimensions of dependent variables and independent variables. All quantities have dimensions of the form

$(Qi) = L^{li} \ M^{mi} \ T^{ti}$

Where the exponents li, mi and ti are dimensionless numbers that follow from each quantity's definition. Q is particular physical quantity. The Dimensional Matrix of variables is given in Table 1.The variable listed in table were combined to form the dimensionless π terms are obtained by using the Buckingham π Theorem. The π terms are arranged according to the nature of basic physical quantities and presented in Table 2.

Each dependent π term (π_{D1}) is assumed to be function of available π terms.

$$\frac{D}{gI} \ T_c \ = f \ (\pi_1, \pi_2, \pi_3, \pi_4 , \pi_5 , \pi_6 , \pi_7 , \pi_8) \ \text{---------(1)}$$
$$Cp = f \ (\pi_1, \pi_2, \pi_3, \pi_4 , \pi_5 , \pi_6 , \pi_7 , \pi_8) \ \text{---------(2)}$$

$$\sqrt{\frac{g}{D}}\ t_p = f\ (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)\ \text{---------(3)}$$

In the present work it is intended to establish the exact empirical form of equations 1, 2, 3 based on experimental data. It is assumed that this form comes out to be -

$$\pi_{D1} = K_1\ (\pi_1)^{a1}\ (\pi_2)^{b1}\ (\pi_3)^{c1}\ (\pi_4)^{d1}\ (\pi_5)^{e1}\ (\pi_6)^{f1}\ (\pi_7)^{g1}\ (\pi_8)^{h1}\quad (4)$$

$$\pi_{D2} = K_2\ (\pi_1)^{a2}\ (\pi_2)^{b2}\ (\pi_3)^{c2}\ (\pi_4)^{d2}\ (\pi_5)^{e2}\ (\pi_6)^{f2}\ (\pi_7)^{g2}\ (\pi_8)^{h2}\quad (5)$$

$$\pi_{D3} = K_3\ (\pi_1)^{a3}\ (\pi_2)^{b3}\ (\pi_3)^{c3}\ (\pi_4)^{d3}\ (\pi_5)^{e3}\ (\pi_6)^{f3}\ (\pi_7)^{g3}\ (\pi_8)^{h3}\quad (6)$$

Now the ultimate aim is to establish the values of K, a, b, c, d, e, f, g and h based on experimental data. Thus π_{D1}, π_{D2} & π_{D3} are the dependent dimensionless group of variables for this process and there are eight independent dimensionless groups of variables. The experimentation will be performed by varying one of independent π term at a time, while holding all other π terms constant and observing the resulting changes in the dependent variables.

2.1.2. Test planning

A classical plan of experimentation for this experimentation may at the outset appear obvious. Many discrete extraneous variables like different sensors, instruments and different geometric variables can be taken care of by concept of randomized block like Latin Square, which are among the general family of functional plans [15] plans viz. classical plan or full factorial and factorial plan are available.

Test planning for this experimentation would be carried out by deciding the following terms.

Test envelop: The Test Envelop is a range in which variable is varied during the experiment. This is decided on the following consideration:

a**.** Funds and time available.

b. Previously established data about the under study.

The range of variation in which the variable has significant effect on the variation of dependent variable should be selected. In the proposed experimentation, the rear ratio, number of blades, terminal velocity of flywheel was varied. The summery of experimentation plan is given in Table 3.

Test point: Test points are the discrete values of independent variables of which experiments are conducted. The selection of the test points depends on approximate variation in dependent variable as independent variable varies. This variation can be constant, linear, non-linear or combination of above.

Test sequence: Test sequence is the order in which test points are varied during the proposed experimentation.

The experimental set-up as shown in figure 1. In this set-up there is provision made to change gears, cutting blades for ease of experimentation.

2.1.3. Test envelop, test points and test sequence for

1. π term gear ratio:

The gear ratio is maintained between flywheel shaft and process unit shaft. The gear ratio tried was 1:2, 1:3 and 1:4 in this experimentation. Each gear ratio would be considered as test point, each gear ratio, and number of blades varied 2 & 3the terminal speed of flywheel is also varied from 300 RPM to 600 RPM in step of 100 RPM. At gear ratio 1:2 the speed of the process unit is higher as compared to 1:4 but the torque increase as the gear ratio increases. It means that at 1:2 gear ratio torque is minimum whereas at 1:4 gear ratio torque is maximum and speed is less.

The Test Sequence for gear ratio would be in increasing order i.e. 1:2, 1:3 and 1:4.

2. π term related to No. of blades:

The cutting blades are mounted on cutter head wheel. This wheel is mounted on process unit shaft. Two cutter head were used for mounting two and three cutting blades respectively for each gear ratio two and three blades tried with varying the speed of flywheel.

3. π terms related to Terminal Velocity of Flywheel:

The flywheel is speeded by the bicycle mechanism. Then the energy stored in the flywheel is used cutter. The flywheel speed increases there is increase in the energy store in the flywheel. It was decided to vary the flywheel speed from 300, & 600 rpm, its corresponding angular velocity would be 31.45 & 62.83.

The test points for the flywheel speed would be 300, 400, 500; 600 rpm for each speed different gear ratio is tried. For each selected gear ratio the number of blades would be 2 and 3. The test envelop, test point and test sequence is given in Table 1.

Table 1
Dimensional matrix.

	W_b	t_b	D	g	I	E	α	n	ω	t_c	e	G	T_c	C_p	t_p
M	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0
L	1	1	1	1	1	-2	0	0	0	0	2	0	2	0	0
T	0	0	0	-2	-2	-1	0	0	-1	1	-2	0	-2	0	1

Table 2
Independent dimensionless ratio.

Sr. No.	Independent dimensionless ratio or π terms	Nature of basic physical quantities
1	$\pi_1 = \dfrac{d w_b t_b}{D^3}$	Geometric Variables
2	$\pi_2 = \dfrac{D^4}{gI} E$	Material of blade
3	$\pi_3 = \sqrt{\dfrac{D}{g}}\, \omega_c$	Instantaneous Terminal velocity of cutter
4	$\pi_4 = G$	Gear Ratio
5	$\pi_5 = \alpha$	Cutting blade angle
6	$\pi_6 = n$	No. of cutting blade
7	$\pi_7 = \sqrt{\dfrac{g}{D}}\, t_c$	Cutting time
8	$\pi_8 = \dfrac{D}{2g} \omega_f{}^2$	Terminal speed of flywheel
9	$\pi_{D1} = \dfrac{D}{gI} T_c$	Resistive torque
10	$\pi_{D2} = C_p$	No. of cuts by cutter
11	$\pi_{D3} = \sqrt{\dfrac{g}{D}}\, t_p$	Process time

Table 3
Experimentation plan.

Sr. No	Ratio	Test Envelop Range	Test Point	Test Sequence							
				1		2		3		4	
01	$\pi_1 = dWbtb/D^3$	5.33×10^{-3}	Constant								
02	$\pi_2 = (D^4/gI)E$	1.46×10^9	Constant								
03	$\pi_4 = G$	2,3,4		2.3.4	2.3.4	2.3.4	2.3.4	2.3.4	2.3.4	2.3.4	2.3.4
04	$\pi_5 = \alpha$	0.122	Constant								
05	$\pi_6 = n$	2,3		2	3	2	3	2	3	2	3
06	$\pi_8 = (D/2g)\omega f^2$	31.428-62.857		31.426		41.904		52.380		62.857	

Note: π_3 = It can't be predefined as the angular velocity change during experimentation. The reading will be noted during experimentation.
π_7 = The specific time instant during cutting is a dynamic term. It is noted during experimentation.

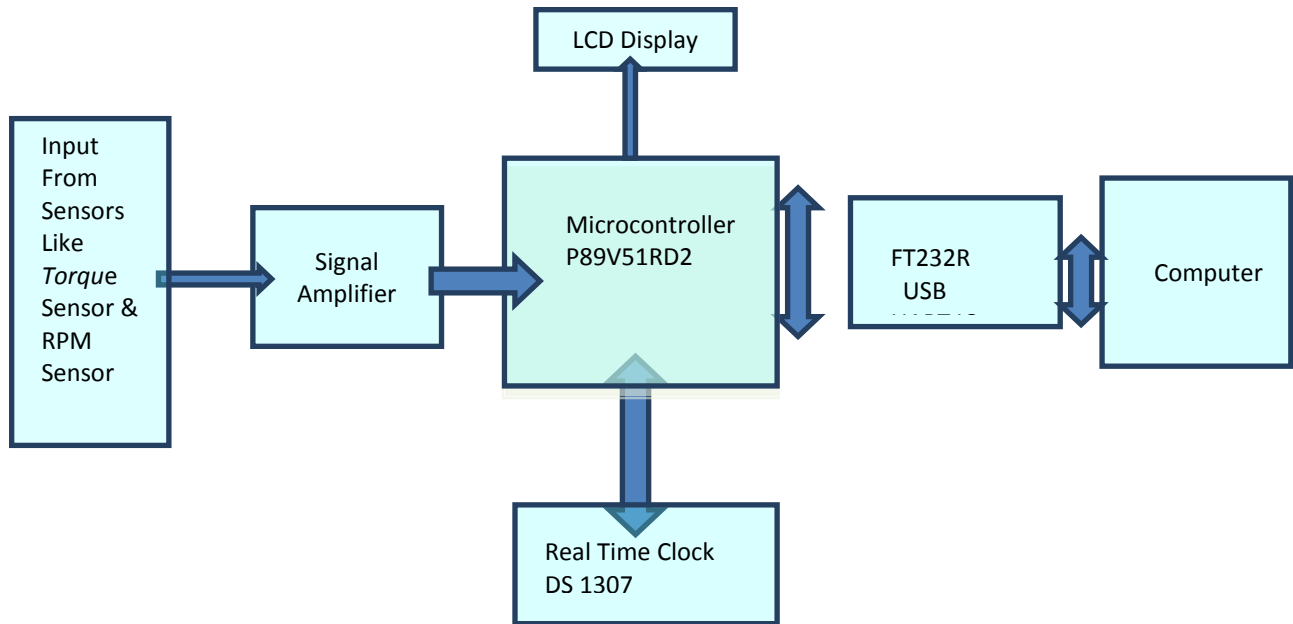**Fig. 1.** The block diagram for data acquisition system.
Intended for color reproduction on the web and in black-and-white in print.

Fig. 2. Experimental set-up.

2.1.4. Instrumentation and measurement

a. **Linear Measurement:** For linear measurement digital calipers and micrometers were used. The blade angle is measures by bevel protector.
b. **Angular Velocity:** Angular velocity of cutter shaft and flywheel shaft is to be measured. The slotted opto-couplers were mounted on the shaft. These sensors measure the angular velocity with real time clock. This angular velocity is recorded and stored via micro controller P89C51 RD2 which is

connected to personal computer through FT232R USB UART(universal asynchronous receiver / transmitter) IC. The block diagram for data acquisition system is presented in Figure 2.

c. **Variation in torque:** The variation of torque on cutter shaft will be evaluated on the basis of speed plots of cutter speed verses time.

d. **Number of cuts:** It was decided to evaluate number of cuts on the basis of speed of cutter obtained during experimentation.

No. of cuts = No. of blade X No. of revolution.

e. **Process time:** It can be evaluated on the basic of π terms obtained from dimensional analysis.

$$\text{Process time} = \pi_{D3} = \sqrt{\frac{g}{D}}\ tp \qquad (7)$$

Where tc = Time required for cutting between two fixed time interval.

2.1.5. Test data checking and rejection

In spite of careful planning and execution of experiments, the probabilities of error are always present. The only way to safeguard against such occurrence is to plan for one or more checks on accuracy and sensibleness of data. The data which lies outside the trend of the graph represents the process i.e. outliers. It is justified to reject such outliers.

2.1.6. Method of test data analysis

The experimentation is to be of a mixed plan. Hence, the method of multiple regressions will be adopted for the purpose of data analysis.

3. Results and discussion

As the flywheel speed increases, the kinetic energy stored in flywheel increases. The bicycle mechanism with speed rising gear pair is used to speed up the flywheel. The operator requires minimal efforts to speed up flywheel. The ratio of speed rising gear pair is maintained 1:5. During speeding of flywheel the process unit is disengaged due to which operator do not feel the process resistance. The flywheel speed may be increased up to 700-800 rpm but there would be excessive vibrations that may affects the sensors used for measuring different variables. The test sequence is from minimum to maximum speed i.e. 300 to 600 rpm and gear ratio 2:1 To 4:1 for torque amplification, whereas the number of blades 2 & 3. This test sequence would be appropriate for establishing empirical relationship of chaff cutting process energized by human powered.

The speed and torque available on the process unit shaft can be varied by varying gear ratio between flywheel shaft and process unit shaft.

4. Conclusion

The design of this experimental work has lead to the following conclusion.

1. Although it is proposed to establish empirical relationship for chaff cutting phenomena in view of a short duration test in systematic way, it is however very necessary to formulate establish generalized experimental empirical relationship model for this process for operation time of about 20 minutes to 30 minutes. This can be treated as one possible extension of the present work.

2. The experimental plan of a man- machine system should be always a mixed one, i.e. at a time more than one independent π terms are bound to vary when π terms other than the one involving the parameters of human energy input is being varied.

3. In this experimentation different riders, of course of same age group will be selected to average out the effect of extraneous variables like variation in physique, variation in psychological factors, attitude/ enthusiasm and environmental conditions associated with rider.

4. The effect of extraneous variables associated with rider which alter his biological capacity is not included in this experimentation plan. This can be treated as one possible extension of present work.

Acknowledgement

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