Design of Experimentation for Formulation of Experimental Data Based Model for Bamboo Sliver Cutting Operation Using HPFM

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Abstract - The design of experimental set up gives a direction towards planning of experimentation. This paper presents design of experimentation for formulation of an experimental data based model for sliver cutting from bamboo using human powered flywheel motor (HPFM) which describes the phenomenon under investigation more reliably, accurately and precisely. It is the integral part of engineering research and implementation of design of experiments (DoE) by systematically executing experimental plans and conducting actual test run. In this paper, the various steps of design of experimentation like dimensional analysis, identification of variables in human powered bamboo sliver cutting phenomenon, reduction of variables and the formation of mathematical models’ equations are presented in detail. The evolution of bamboo sliver cutting using human power is a complex phenomenon. There are many factors affecting the performance of bamboo sliver cutting. In this paper the attempt is made to present the adopted design of experimentation in detail and to generate design data in the form of evolving experimental data based models for various dependant/ response variables of human powered bamboo sliver cutting by carrying out experimentation.

Key Words: Experimentation, DoE, Dependent Variable, Independent Variable, Dimensional Analysis, Buckingham’s pi theorem, Bamboo Sliver, HPFM, Sliver cutting.

1. INTRODUCTION
Design of Experimentation (DOE) is planning process in a research study to meet specific objectives. The proper planning of an experiment is very much important consideration in order to achieve the research objectives clearly and efficiently with the right type of data and appropriate sample size.

Adoption of basic laws of mechanics could be applied for correlation of various dependant and independent parameters of human powered bamboo sliver cutting in theoretical approach. A theoretical approach can be adopted in a case if known logic can be applied correlating the various dependent and independent parameters of the system. Though qualitatively, the relationship between dependant and independent variables could be known based on available literature data, the generalized quantitative relationship may not be known sometimes due to complexity of phenomenon.

The kinematics of transmission of rotational motion from the input shaft to output shaft in bamboo sliver cutting unit for the human powered flywheel motor is a complex phenomenon. Hence the formulation of quantitative relation based on logic is not possible in case of such a complex phenomenon. On account of no possibility of formulation of theoretical model i.e. logic based model, only alternative is left to formulate experimental data based model. This reasons cause to adopt an experimental approach to establish the experimental data based model. Hence it is proposed to formulate such model in this investigation. [1-5]

2. OPERATION OF BAMBOO SLIVER CUTTING BY HPFM
The operator drives the bicycle by pedalling the mechanism while clutch is in disengage position. The human power operated flywheel motor is energy source. This energy source energizes the process unit i.e. bamboo sliver cutting unit through clutch and transmission. The flywheel is accelerated and energized which stores some energy inside it. When the pedalling is stopped, clutch is engaged and stored energy in the flywheel is transferred to the process unit input shaft by means of clutch.

The process unit is sliver cutting unit which comprises of feeder, two pairs of spring loaded rollers, sliver cutter, adjusting knobs etc. When the energy from flywheel is transferred to the sliver cutting unit by engaging the clutch, the split bamboo is fed through feeder. It enters the first pair of push-in rollers, then comes out of push-out roller pair and strikes the sliver cutter which is kept fixed and the sliver is cut. The sliver cutting immediately commences upon the clutch engagement it continues for 5 to 20 seconds until the flywheel comes to rest.
There is a provision of operating the system at the speeds by properly choosing the gear ratio of a torque amplification provided on the sliver cutting unit shaft. The figure 1 shows the schematic diagram of bamboo sliver cutting unit driven by human powered flywheel motor (HPFM). The figures 2 and 3 show the CAD Model of Actual Experimental Set Up and Actual Experimental Set Up respectively.

3. DESIGN OF EXPERIMENT
Design of experiment involves following steps:

- Based on the known qualitative physical characteristics of the phenomenon, identifying the independent and dependant variables which affect the phenomenon and establishing the dimensional equations for human powered bamboo sliver cutting is of prime importance. The experimentation becomes time consuming, tedious and costly if system involves large number of independent variables. So with the help of dimensional analysis one can reduce the number of variables and hence these reduced number of dimensional equations are the targeted form of mathematical models.

- Test planning consists of deciding test envelope, test sequence and plan of experimentation for the set of deduced dimensional equations.

It is necessary to evolve the physical design of experimental set up in setting up the test points, adjusting the test sequence, execution of proposed experimental plan, noting down the responses and provision for necessary instrumentation for deducing the relation of dependent pi terms of the dimensional equation in terms of independent pi terms. Experimental set up is designed in such a way that it can accommodate the ranges of independent and dependant variables within the proposed test envelope of experimental plan. After noting down the responses and obtained dimensional relations of dependant pi terms of dimensional equations, the exact mathematical model can be formed within the specified test envelope. [6-10]

4. DIMENSIONAL ANALYSIS
Dimensional analysis is an extremely useful mathematical technique used in reduction of variables by forming non-dimensional groups of the variables which are called as pi (π) terms. Deducing the dimensional equation for a phenomenon reduces number of independent variables pi terms in the experiment. The exact mathematical form of this dimensional equation is the targeted model. Thus this method of dimensional analysis provides a systematic experimental planning and permits the presentation of results in more useful and concise format.[1]

4.1 Identification of Variables
Depending upon the working operation of the bamboo sliver cutting phenomenon by HPFM, the various dependent or response variables, independent variables and extraneous variables affecting the phenomenon are identified and the data purification is carried out to remove the extraneous variables to avoid their unwanted effect on the phenomenon. Table 1 shows various dependent and independent variables involved in the phenomenon with their symbols, units, dimensions, nomenclature and nature.
It is seen from table 1 that there are total seventeen variables which affects the phenomenon of bamboo sliver cutting by human powered flywheel motor (HPFM). The fundamental physical dimensions to express all these seventeen variables are only three i.e. Mass (M), Length (L) and Time (T). Out of these total seventeen variables the first three variables are the dependant/response variables and the later fourteen variables are independent variables.

### 4.2 Formation of Pi (Π) Terms (Application of Buckingham’s Π-Theorem)

The Buckingham’s Π-Theorem method is used to form the pi (π) terms for all dependant/response and independent variables affecting the phenomenon of human powered bamboo sliver cutting.

#### 4.2.1 Formation of pi (π) terms for independent variables:

The process of dimensional analysis is followed step by step as explained below:

1. The processing time, \( t_p \) is a function of Flywheel Energy \((E_f)\), Angular speed of flywheel \((\omega_f)\), Time required to speed up the flywheel \((t_r)\), Gear Ratio \((G)\), Acceleration due to Gravity \((g)\), Length of Bamboo split \((L_b)\), Width of Bamboo split \((W_b)\), Thickness of Bamboo split \((t_c)\), Horizontal Center Distance between Roller Pairs \((C_h)\), Vertical center distance between roller pairs \((C_v)\), Distance between Roller Center to Cutter Tip \((L_c)\), Modulus of Elasticity of Bamboo \((E_b)\), Modulus of Elasticity of Cutter \((E_c)\), and Cutting Angle of Cutter \((\Phi_c)\).

\[
t_p = f(E_f, \omega_f, t_r, G, g, L_b, W_b, C_h, C_v, L_c, E_b, E_c, \Phi_c)
\]

2. Or, \( t_b \) (equals \( t_p \)) is determined by equating the \( \Pi \) term.

\[
t_b = f(E_f, \omega_f, t_r, G, g, L_b, W_b, C_h, C_v, L_c, E_b, E_c, \Phi_c) = 0
\]

3. \( g \) = Acceleration due to Gravity \((m/s^2)\)

4. \( h \) = Horizontal Center Distance between Roller Pairs \((mm)\)

5. \( b \) = Thickness of Bamboo split \((mm)\)

6. \( c \) = Vertical center distance between roller pairs \((mm)\)

7. \( d \) = Distance between sides as given below:

\[
\begin{align*}
M & \rightarrow 0 = c_1 + 1 \\
L & \rightarrow 0 = a_1 + b_1 - c_1 + 2 \\
T & \rightarrow 0 = 2a_1 - b_1 - c_1 + 2
\end{align*}
\]

Substituting the values of \( a_1 \), \( b_1 \), and \( c_1 \) in the eq. of \( \Pi_1 \) term, we have:

\[
\Pi_1 = (g)^{a_1}(L_b)^{b_1}(E_b)^{c_1}E_f^{d}
\]

The values of \( a_2 \), \( b_2 \), and \( c_2 \) are computed by equating the powers of \( M \), \( L \), and \( T \) on both sides as given below:

<table>
<thead>
<tr>
<th>For 'M'</th>
<th>For 'L'</th>
<th>For 'T'</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M \rightarrow 0 = a_1 + b_1 - c_1 + 2 )</td>
<td>( L \rightarrow 0 = a_1 + b_1 - c_1 + 2 )</td>
<td>( T \rightarrow 0 = -2a_1 + 2b_1 - 2c_1 - 2 )</td>
</tr>
</tbody>
</table>

Hence \( a_1 = 0, b_1 = -1 \) and \( c_1 = 3 \).

Substituting the values of \( a_1 \), \( b_1 \), and \( c_1 \) in the eq. of \( \Pi_1 \) term, we have:

\[
\pi_1 = \frac{E_f}{L_b^2E_b^3}
\]

### Second Π term:

\[
\Pi_2 = (g)^{a_2}(L_b)^{b_2}(E_b)^{c_2}E_f^{d}
\]

The values of \( a_2 \), \( b_2 \), and \( c_2 \) are computed by equating the...
powers of M, L & T on both sides as given below:

<table>
<thead>
<tr>
<th>For 'M'</th>
<th>For 'L'</th>
<th>For 'T'</th>
</tr>
</thead>
<tbody>
<tr>
<td>M → 0 = c₂</td>
<td>L → 0 = a₂ + b₂ - c₂</td>
<td>T → 0 = -2a₂ - 2c₂</td>
</tr>
</tbody>
</table>

Substituting the values of a₂, b₂ and c₂ in the eq. of Π term, we have:

\[ \Pi = \left( \frac{g^{1/2}}{(E_b)^{0.10}} \right) \]

In the similar way the all remaining pi (π) terms for independent variables are calculated by dimensional analysis and are listed in the following table 2. The table 2 shows total eleven pi terms for independent variables:

<table>
<thead>
<tr>
<th>Table -2: Pi terms for independent variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pi terms</strong></td>
</tr>
<tr>
<td>( \pi_1 )</td>
</tr>
<tr>
<td>( \pi_2 )</td>
</tr>
<tr>
<td>( \pi_3 )</td>
</tr>
<tr>
<td>( \pi_4 )</td>
</tr>
<tr>
<td>( \pi_5 )</td>
</tr>
<tr>
<td>( \pi_6 )</td>
</tr>
<tr>
<td>( \pi_7 )</td>
</tr>
<tr>
<td>( \pi_8 )</td>
</tr>
<tr>
<td>( \pi_9 )</td>
</tr>
<tr>
<td>( \pi_{10} )</td>
</tr>
<tr>
<td>( \pi_{11} )</td>
</tr>
</tbody>
</table>

In the similar way, the dimensional analysis for dependent variables is performed by applying again Buckingham’s Π-Theorem.

\[ \Pi_{D1} = (g)^{3/2} (L_b)^{3/2} (E_b)^{1/2} \]

The values of a₁, b₁ and c₁ are computed by equating the powers of M, L & T on both sides as given below:

<table>
<thead>
<tr>
<th>For 'M'</th>
<th>For 'L'</th>
<th>For 'T'</th>
</tr>
</thead>
<tbody>
<tr>
<td>M → 0 = c₁</td>
<td>L → 0 = a₁ + b₁ - c₁</td>
<td>T → 0 = -2a₁ - 2c₁</td>
</tr>
</tbody>
</table>

\[ \Pi_{D1} = (g)^{3/2} (L_b)^{3/2} (E_b)^{1/2} \]  
\[ \Pi_{D1} = (g)^{3/2} (L_b)^{3/2} (E_b)^{1/2} \]

4.3 Reduction of Variables

To reduce the complexity and to obtain the simplicity in the behaviour of the phenomenon, the pi terms of independent variables are reduced by reduction of variables method as suggested by Schenk Jr. The pi terms related to the independent variables like width of bamboo split(Wb), thickness of bamboo split (tb), Horizontal Centre Distance between Roller Pairs (C_b), vertical Centre Distance between Roller Pairs (C_v), and Distance between Roller Centre to Cutter Tip (L_m) are reduced to form a new pi term. The following table 4 shows the new pi terms of independent variables in reduced form. Thus the total eleven pi terms of independent variables are reduced to seven new pi terms as shown table 4.

4.2.2 Formation of pi (π) terms for dependent variables:

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Table -3: New Pi terms in reduced form for independent variables

<table>
<thead>
<tr>
<th>( \pi_i )</th>
<th>( \pi_i ) terms equations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_1 )</td>
<td>( \pi_1 = \frac{E_f}{L_b^2 E_b} )</td>
<td>The term related to energy of flywheel</td>
</tr>
<tr>
<td>( \pi_2 )</td>
<td>( \pi_2 = \omega_f \frac{L_b}{g} )</td>
<td>The term related to angular speed of flywheel</td>
</tr>
<tr>
<td>( \pi_3 )</td>
<td>( \pi_3 = t_f \sqrt{\frac{g}{L_b}} )</td>
<td>The term related to time required to speed up the flywheel</td>
</tr>
<tr>
<td>( \pi_4 )</td>
<td>( \pi_4 = G )</td>
<td>The term related to gear ratio</td>
</tr>
<tr>
<td>( \pi_5 )</td>
<td>( \pi_5 = \frac{W_b t_b C_y C_v L_{rc}}{L_b^2} )</td>
<td>Machine's geometrical parameters</td>
</tr>
<tr>
<td>( \pi_6 )</td>
<td>( \pi_6 = \frac{E_c}{E_b} )</td>
<td>The term related to elasticity of materials</td>
</tr>
<tr>
<td>( \pi_7 )</td>
<td>( \pi_7 = \phi_c )</td>
<td>The term related to cutting angle of cutter</td>
</tr>
</tbody>
</table>

Similarly for number of slivers (\( n \)) and resistive torque (\( T_r \)), the dimensional equations are found as follows:

\[
\begin{align*}
n &= f_2 \left( \left( \frac{E_f}{L_b^2 E_b} \right) \left( \omega_f \sqrt{\frac{L_b}{g}} \right) \left( t_f \frac{E}{E_b} \right) \left( G \right) \right) \\
T_r &= f_3 \left( \left( \frac{E_f}{L_b^2 E_b} \right) \left( \omega_f \sqrt{\frac{L_b}{g}} \right) \left( t_f \frac{E}{E_b} \right) \left( G \right) \right)
\end{align*}
\]

The equations (1), (2) and (3) are the mathematical equations for three response variables (viz. processing time \( t_p \), number of slivers \( n \) and resistive torque \( T_r \)) of bamboo sliver cutting phenomenon operated by human powered flywheel motor (HPFM) which are used for formation of mathematical models of these variables for sliver cutting phenomenon.

5. TEST POINTS, TEST ENVELOPE & TEST SEQUENCE

Test Envelope: Deciding the end points or limits comprises the test envelope and it is obvious and best way to select or fix the test points. All such test points are covered in the test envelope. So it is obvious to ascertain the complete range over which the entire experimentation is carried out.

Test Points: The spacing of the test points within the test envelop is selected not for getting a 'symmetrical' or a 'pleasing' curve but to have every part of our experimental curve map the same precision as every other part. The conceptual proper spacing of test points is replaced by permissible spacing of test points.

Test Sequence: In classical or sequential plan, the variables are varied from one extremity to the other in a sequential manner, in the random plan those are varied in random fashion. The classical plan or sequential plan is essentially opted for irreversible experiments or where there is no scope for randomization. The majority of engineering experiments use partial randomized plan and hence it is used for testing the phenomenon. [1, 12-16]

The table 5 shows test envelope, test points for Sliver cutting operation by HPFM.
The table 6 shows the sample observations for bamboo sliver cutting operation by human powered flywheel motor (HPFM)

Table 6: Experimental Plan and observations for Bamboo Sliver Cutting Operation by HPFM

6. CONCLUSIONS

Though the bamboo sliver cutting by HPFM is complex phenomenon due to effect of various independent parameters, due to the method of experimentation adopted in this work it made possible to achieve generalized quantitative relationship between the variables affecting the phenomenon. Due to the method of DoE applied in this process, it became easier for proper planning of an experiment in order to achieve the research objectives clearly and efficiently with the right type of data and appropriate sample size. As there is no possibility of formulation of theoretical model i.e. logic based model, only alternative is left to formulate experimental data based model. Adoption of an experimental approach to establish the experimental data based model in this investigation made it possible.
Through the formation of test points and test envelopes, it made possible to ascertain the complete range over which the entire experimentation is to be carried out and spacing the independent variables in a predetermined manner and most effectively helped to constitute efficient and compact experimental plan.

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