Simulation of the Dynamic Behaviour of LEC Based Controller to Ensure Operational Continuity of a Low Cost Automation Device Energised by Human Powered Flywheel Motor (HPFM)

KEYWORDS
HPFM, Finger Type Clutch, LEC based Controller

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ABSTRACT
In our previous attempt stress was given on modeling and control of a phenomenon to enhance the operational reliability of a process unit. In that we have suggested that for enhancing the operational reliability we can use a LEC based controller. But the point of discussion was whether this controller will be capable of changing the control from one clutch to another in a shortest possible time may be in terms of µsec. In the present paper the solution of this problem is approached by replacing the motor connected to the clutches by their non-linear models. These models could be actuated by designing a linear electronic circuit simulating their behavior.

A. HPFM Energized Process Machine:
Modak and his associates [1 &2] have developed a HPFM energized process machines for various applications [3 &4] which are rural based and necessary to improve the life of the people of the third world. The machine consists of three subsystems namely, HPFM (Human Powered Flywheel Motor), comprising of a flywheel F, speeded up through speed amplification gears G’ and a conventional bicycle operated by a human operator, Spiral jaw clutch SJC and torque amplification gear G & Process unit. The schematic arrangement of the machine in its plan view is as described in the Fig 1.

![Fig (1): Schematic Arrangement of the machine](image)

B. Machine parameters, Operation & Operational Characteristics:
A flywheel is arranged (1 m rim Φ & 10 cm rim width, 2cm rim thickness) in which a man pumps the energy at a rate convenient to him (human power approximately 0.13 hp continuous) for about a minute's time by operating a pedaling mechanism through a speed rise gear pair having speed ratio equal to 4.5:1. At the end of a minute's duration, flywheel is accelerated to about 700-800 rpm speed. Then the pedaling is stopped, spiral jaw clutch is engaged and the kinetic energy stored in the flywheel is communicated to a process unit through a pair of torque amplification gear [G=4.1].

Process unit exhausts the energy stored in the flywheel during a very small time 3-10 seconds (Process HP up to 3) depending on the resistance of the process unit. Thus the processes which could be of an intermittent nature and needing power far in excess of human capacity can be energized manually by such machine concept. The concept is tried for various applications such as water lifting, wood turning, wood strip cutting, potter's wheel, brick making, algae formation etc.

C. The need for development of Torsionally Flexible Clutches:
During the period of clutch engagement the mechanical system is subjected to severe shock due to instantaneous momentum exchange. On account of this, spiral jaw clutch is subjected to unpredictable malfunction. This is one of the serious drawbacks of this system.

The basic reason for the spiral jaw clutch failure is, it does not have torsional flexibility very much needed in this situation. A clutch with torsional flexibility will permit momentum exchange at a slow rate. The exhaustive literature survey [5 &6] shows that clutches with torsional flexibility are not developed excepting the attempts of Modak and his research scholars [7 to 10]. These types of clutches permit momentum exchange at a fairly slow rate. Though literature indicates development of plate clutches with axial flexibility [5 &6] these are not useful for the present purpose.

The present research addresses to the generation of design data through the development of generalized experimental model for a finger tip load and subsequent vibrations of fingers in a finger type torsionally flexible clutch. It also details inclusion of LEC based [14] controller for getting operational velocity of process unit.

II. FINGER TYPE TORSIONALLY FLEXIBLE CLUTCHES:
A. Construction:
Clutch comprises of two members. Member I is connected to the flywheel shaft through splines. Multiple numbers of fingers 3, 4, 6 are provided integral with the hub of the member I. Fingers have rectangular section as shown. Member II is carrying jaws J (3, 4, 6, depending on the number of fingers provided, but no. of jaws equals no. of fingers). Member II is integral with the jaw which provides drive to the process unit.

![Fig (2): Schematic of Finger Type Clutch](image)
B. Working:
When the flywheel $F$ of the main machine is being accelerated, member $I$ is so located on the flywheel shaft that fingers $F$ do not have contact with jaws $J$ and the clutch is in dis-engaged position. After getting the desired flywheel speed, peddling is stopped, member $I$ is axially slided over flywheel shaft. The moment when fingers dash on jaws $J$, the process of momentum transfer from flywheel shaft to load shaft commences. Fingers $F$, structurally behave as short cantilever having spring like action because of its elasticity. Thus the fingers provide relative angular displacement between load shaft and the flywheel shaft during the period of clutch engagement. This is how torsional flexibility is provided by this type of clutch.

III. DYNAMICS OF THE CLUTCH:
Clutch engagement duration is defined to be the time interval in which the flywheel shaft and the load shaft attain the identical speeds after first contact of fingers with the jaws. During this period, flywheel shaft speed & load shaft speed are different. Applying De-Alembert's formulation, the general equations of motion for the flywheel shaft and the load shaft respectively can be derived as –

\[ -I_F \ddot{\theta}_F - b_F \dot{\theta}_F - K \alpha t = 0 \]  
(1)

\[ K \alpha t - I_L \ddot{\theta}_L - b_L \dot{\theta}_L - T_L = 0 \]  
(2)

In equations (I) & (II) $I_f$ and $I_L$ are moment of inertia's of flywheel and load shaft. $b_F$ and $b_L$ are bearing friction torque constants of flywheel and load shaft respectively. $T_L$ = Load Torque on the load shaft as imposed by the process resistance. $K$ = Stiffness of the fingers, $\alpha_t$ = instantaneous slope of the finger at its fixed end. Careful examination of Equas (I) & (II) shows that these equations are not solvable unless experimental feedback of the behavior of the system is known.

Hence, it amounts to establishing the generalized experimental data based models for & or eventually of finger tip load and finger vibrations which can be considered to be a function of &

IV. DESIGN OF EXPERIMENTATION
Generalized experimental models for $W$ & $S$ (maximum stress induced in the fingers due to finger load and vibrations) are established adopting methodology of experimentation [13].

As per this methodology all independent parameters and / or physical quantities are varied over widest possible range. Huge response data is collected. Based on this entire data Generalized models are formed. The detailed steps are (1) Establishing the dimensional equations of the mechanics of a clutch (2) Test envelopes, Test points and Test sequence (3) Design and building up of an experimental set up, (4) Performing experimentation (5) Publication of Experimental Data(6)Establishing the exact mathematical function of the dimensional equation based on Experimental Data.

A. Dimensional Equations:
Applying Buckingham-II theorem and a Raleigh's method [13], the dimensional equations for $(WD/T_L)$ & $(SD^3/T_L)$ are formulated as under:

\[ \frac{WD}{T_L} = f \left( \frac{I_F}{T_L \cdot T_{T_f}}, \frac{I_L}{T_L \cdot T_{T_L}}, \frac{b_F}{T_L \cdot T_{T_f}}, \frac{b_L}{T_L \cdot T_{T_L}}, \frac{D}{T_L \cdot T_{T_f}}, \frac{U}{T_L \cdot T_{T_L}}, \frac{(U)(N)}{T_L \cdot T_{T_f}} \right) \]  
(III)

\[ \frac{SD^3}{T_L} = f \left( \frac{I_F}{T_L \cdot T_{T_f}}, \frac{I_L}{T_L \cdot T_{T_L}}, \frac{b_F}{T_L \cdot T_{T_f}}, \frac{b_L}{T_L \cdot T_{T_L}}, \frac{D}{T_L \cdot T_{T_f}}, \frac{U}{T_L \cdot T_{T_L}}, \frac{(U)(N)}{T_L \cdot T_{T_f}} \right) \]  
(IV)

Where

$I_F$ = Moment of Inertia of Flywheel Shaft

D. Generalised Models:

Using the principle of (I) force balance & (II) energy balance variation of $W$ verses time is established as depicted in Fig 5 by the curves (a) & (b) respectively corresponding to the experimental data of Fig 4.

Fig 5 shows erratic variation of $W$. This appears to be because of unpredictable bearing friction torque. This situation may be perhaps due to much more severe loading on the flywheel shaft & load shaft. Hence hereafter the anticipated finger tip load based on force balance concept is no more considered. The vibration response is evaluated approximating the finger as a single degree of freedom spring-mass-damper system. $\zeta$ is assumed to be 0.9 in view of the fact that the system damping is due to the friction between the finger and the jaws due to axial siding of fingers under severe tip load during the period of engagement is not reflected in Equations I & II. To account for this $\zeta$ is assumed to be very high and of the order of 0.9.
VI. FORMULATION OF THE PROPOSED MODEL:

Equation (VI) can be rearranged to deduce necessary number of fingers for the specified $T_i$ and specified material of the fingers. However since the reliability of estimation of clutch performance based on equation (VI) being not adequate it is necessary to change the mathematical form of the model. What follows is this change in the form of the model.

$$S=f(I_F,I_L,T_L)$$

where $S$ is the stress under vibrations. Finger type clutch.

V. DISCUSSION OF RESULTS

In this section it is proposed to discuss the mechanics of energy transfer from flywheel shaft to the load shaft through this finger type clutch.

Further interesting observation is at times $\delta$ is increasing and at times reducing during $\delta t=t_1-t_2$. This solidly confirms that load shaft at times demands energy from fingers and at times pumps the energy in the fingers. This should cause severe superimposed oscillation over and above that caused by variation of $W$ vs time. Finger vibrations during $\delta t=t_1-t_2$ and also $\delta t=t_3-t_2$ are subjected to transient vibrations. On the whole therefore fingers are subjected to vibrations which need estimation of stress under vibrations.

Curves a of Fig 5 shows higher value of $W$ as compared to those of curve b. This is obvious because frictional energy loss is not assumed for information presented by curve a. Bearing friction phenomenon appears to be pretty erratic because curve b shows $W=0$ for some instants. This is because at those instants frictional resistance itself is enough to impose necessary retardation even if not reaching to limiting value of friction.

The experimental set up may need additional instrumentation to solidify ascertain the influence of friction.

In the estimation of vibration response over simplifying assumptions are made which are as under:

1. Entire finger mass is assumed to be at the tip.
2. Finger elasticity is assumed to be linear. In fact it may be non-linear leading to the sever finger oscillations.
3. $\zeta$ is assumed to be $0.9$, a very high value without which stress under vibrations could not have been a practically acceptable figure. $\zeta=0.9$ may be justified because considerable axial frictional rub or the fingers during $\delta t=t_1-t_2$ is not modeled. Of course this will be only possible by sophisticated instrumentation like telemetry.
tain limits.

For example in this case the load torque $T_L$ changes say increases, it will increases the finger tip load ($W$) and in turn it will increase induced stress ($S$). But $S$ should not increase beyond a certain limit allowable stress in bending. Only way, to do this in this case will be to change (i) either cross section of fingers (ii) increase $D$ (iii) change the material of the fingers (iv) change $I$, or $I$, (v) change no. of fingers, $N$.

Amongst these alternatives easiest is to change the number of fingers $N$. This amounts to provision of more than one clutch. So one may provide three clutches with $N=3, 4$ and $6$.

Further, there has to be a provision of (i) measuring $T_L$, (ii) comparing measured $T_L$, with designed $T_L$ (iii) if $T_L$ actual is more than designed then, there has to be a provision of measuring how much in excess is $T_L$. Then subsequently there has to be a provision to decide a clutch with number of $N$ to be engaged. Finally, a necessary physical system is to be provided to shift energy flow from flywheel $F$ to process unit through a proper clutch.

Entire system including a controller schematically is shown in Figure 7. This schematic represents (i) main system to be controlled and (ii) the Linear Electronic Circuit Based controller. This controller comprises of $T_L$, the torque meter, A/D converter, Linear Electronic Circuit calculating necessary number of fingers in a clutch corresponding to load torque $T_L$, selection of motors $M_1, M_2, M_3$, corresponding linkages converting rotary motion into rectilinear motion of slider of dog clutches $DC_1, DC_2, DC_3$. It is obvious that A/D converter, LEC based minicomputer estimating necessary number of fingers $N$ and selector of $M_1, M_2, M_3$, could be on one chip denoted here as LEC BASED CONTROLLER.

**VIII . MODEL**

According to equation (VIII-A), i.e.

$$SD^3/T_L = f((I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D))$$ (VIII-A)

Now put $y=SD^3/T_L$ and $x= (I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D)$ in equation (VIII-A), then Equation (VIII-A) changes to

$$y = f(x)$$ (XI)

Plotting $y$ and $x$ on ordinate and abscissa respectively, one gets graphic plot of variation of $y$ as $x$ varies. This graphic plot is converted into polynomial form of model as under

$$Y=A_0 + A_1x + A_2x^2 + A_3x^3 + \ldots \ldots \ldots$$ (XII)

**CASE (i):**

Now only considering second term of the model i.e. Equation (XII), one gets

$$y = A_1x$$ (XII-A)

Substituting in Equation (XII-A) and substituting for original variables for $y$ and $x$, equation (XII-A) takes the following form

$$SD^3/T_L = A_1((I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D))$$

$N=(1/A_1). (SD^3/T_L)/((I_L.T_L.D)/ (I_F.R.w.d.E.g.t^2))$ (XII.B)

Here $'t' \text{ is a specific time instant during the period of clutch engagement. However from the point of view of the physics of the system it is } T_L \text{ which in fact decides } N \text{ for specified material of the finger i.e. the parameters } S \text{ and } E \text{. In fact instead of } t, V_D \text{ (digital voltage) as detailed below should be substituted for } 't'.}$

**CASE (ii):**

Now only considering third term of the model i.Equation (XII), and let us denote this contribution to total $y$ as $y''$, then

$$y'' = A_2x^2$$ (XIII)

Upon substituting for $y''=SD^3/T_L$ and

$$x= (I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D)$$

Equation (XIII) would take the form

$$SD^3/T_L = A_2((I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D))$$

$N=(1/A_2). (SD^3/T_L)/((I_L.T_L.D)/ (I_F.R.w.d.E.g.t^2))$ (XIII.B)

Here also $'t' \text{ is a specific time instant during the period of clutch engagement. However from the point of view of the physics of the system it is } T_L \text{ which in fact decides } N \text{ for specified material of the finger i.e. the parameters } S \text{ and } E \text{. In fact instead of } t, V_D \text{ (digital voltage) as detailed below should be substituted for } 't'.}$

**Fig(8).**

Perhaps it could be as under

**Fig(9):**

In the above block

$$K_1=SD^3/I_L D/(A_1 I_F.R.w.d.g.E)$$ (XII.C)

**CASE (ii):**

Now only considering third term of the model i.Equation (XII), and let us denote this contribution to total $y$ as $y''$, then

$$y'' = A_2x^2$$ (XIII)

Upon substituting for $y''=SD^3/T_L$ and

$$x= (I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D)$$

Equation (XIII) would take the form

$$SD^3/T_L = A_2((I_F.R.w.d.N.E.g.t^2)/ (I_L.T_L.D))$$

$N=(1/A_2). (SD^3/T_L)/((I_L.T_L.D)/ (I_F.R.w.d.E.g.t^2))$ (XIII.B)

Here also $'t' \text{ is a specific time instant during the period of clutch engagement. However from the point of view of the physics of the system it is } T_L \text{ which in fact decides } N \text{ for specified material of the finger i.e. the parameters } S \text{ and } E \text{. In fact instead of } t, V_D \text{ (digital voltage) as detailed below should be substituted for } 't'.}$

**Fig(10):**
Similarly for 3rd, 4th, 5th......9th component of polynomial form one should develop complete block diagram. (Refer Figure (11))

Let $K_s = (SD^1)/(A_f(Rw/d)gE)$

Substituting for $t$, $V_D$ (digital voltage) as detailed below should be inserted for 't'.

Fig(10):

In equation (D1) the frictional torque between motor shaft and its bearings, rack – pinion and their bearings is assumed to be proportional to angular speed. This is of course true in the event of the use of light engine oil as a lubricant rather than Grease and/or dry lubricant (carbon based lubricant) as a lubricant. However the resisting torque during the period of clutch engagement being un – avoidable that needs to be considered and presented by the term $(Kt^{-n2})$. The interpretation of the term $(Kt^{-n2})$ is at time $t = 0^+$, a resisting torque would be very high which is an expected reality.

Hence equation (D1) can be considered as a mathematical model representing somewhat lesser non-linearity than the equation (D1) which comprises of both the non-linear terms viz (1) $b \cdot w^{n1}$ and (2) $k \cdot t^{-n2}$.

An approach to solution of these non-linear differential equations will be two ways

1) Refer the treatment of solution to ordinary non-linear differential equations or
2) Alternatively solution to these non-linear differential
equations by (DC analog computers i.e. What is known as a modern electronics using OP-AMP or LECs) or else
3) by adding LEC which is simulating above detailed non-linear differential equation which in turn is simulating the phenomenon of engagement of a new dog clutch.

VIII. CONCLUSION
This paper is an extension of our previous paper[16] in which we are suggesting an approach to develop a controller which will be capable of providing instantaneous transfer of control from one clutch to another (i.e. in µsec). For this we have proposed to design one more Linear Electronic Circuit depicting/simulating the actual non-linear behavior of the motor used in the schematic of our LEC Based Controller.

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