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Design Considerations for Hybrid Powered Flywheel-Cam Assembly Using Dynamic Cutting Force Impact Analysis

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ABSTRACT

Dynamic Compressive cutting forces in respect of this paper deal with impact generating motions that are incidental to dimensional consequences of machine logics of operation. This computational derivation is considered in line with the physical principles of motion dynamics as applied to rotary-linear force and power transmission. Technically, the computation of process variables and their defined physical constants and constraints are the basis for the combination of factors for the design of the machine. Thus, the hybrid basis for this design helps to deploy other sources of force or power, including, solar, municipal grid, power generating set, and manual turning of the flywheel to generate cyclic motions that are dynamically processed on the basis of direct contact between components in logical sequence of operation. The simulation results for the design show the conversion of rotary motions under uni-directional angular displacement into compressive linear cutting forces with calculated impacts for industrial materials processing. Computationally, process simulation for this design show that angular acceleration, α of 147.06 rad/s^2 produced 8426 degrees of angular inclinations, thus implying that a continuous application of 200N input force can generate 23.4 revolutions of the flywheel, which are expected to impact a rotary force on the shaft as to transmit same to the cam to effect the linear motion required for the cutting activity.

Key words: computational derivation, compressive stresses, generative impact forces, drag torque, rotational kinetic energy

INTRODUCTION

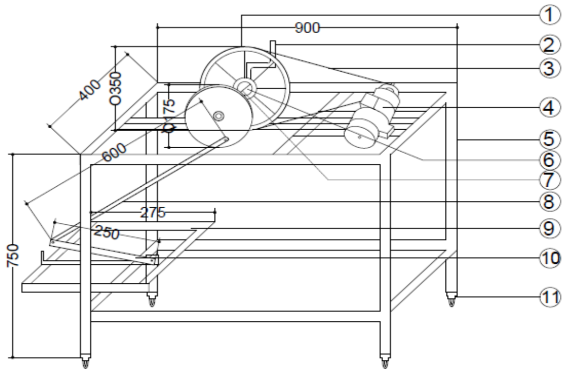
As could be seen, the computational derivations for the design as stated below were used to design the machine's motion logic. Thus, coupling components for the cutting phase of the design are made of cam, follower (or motion lever), the cutter mechanism, base support and stopper. The structural links of these components are aligned to deliver the input force from the flywheel and achieve the required cutting operation. Considerably, the rotary movement of the flywheel impact a rotary force on the cam through the rotating shaft. It should be noted that the location of the motion lever arm at a defined distance away from the center of the cam is strategically intended to create an upward and downward thrust movement on the motion lever [1].

Notably, this front and back linear movement is therefore crucial to the up and down impact cutting force delivered to the cutting mechanism [2]. Consequently, the surface stresses generated by this motion at the contact point between the cam and the follower or lever arm is complex due to the cyclic nature of the dynamic load. This problem can thus be resolved by taking into account the attendant compressive stresses [3] within the contact area of the components and analyzing them in relation to the ultimate tensile strength or load sustaining capacity of the individual materials within the defined time [4].

In line with the design, the cutter is further welded to a support base that is designed to stabilize and make the cutter coupling firm during service time. This support base also incorporates vibration dampers to reduce the effects of process transients that are inimical to dimensional accuracy of cut materials. The base also supports the cut feedstock from interrupting further cutting operations. An adjustable flat shutter endplate is provided to serve as a stopper device for accurate measurement of cut pieces.

Materials and dimensions of structural members for a typical fabrication of proposed design

As could be seen below, Fig 1 is a design specification of the structural arrangements, components link and alignments intended for the proposed hybrid cutting machine. The design dimensions of the structural members and components and their logical sequence of operation is indicative of the direction of force flow and transmission. Thus, the stability of the machine is guaranteed by the elimination of all vibration and chatter initiators [5] that may be incidental to increased performance in terms of elevated speed [6].



List of Components
1. Flywheel device
2. Shaft handle for manual turning
3. Drive belt for motor driven operation
4. Electric motor
5. Structural support frame
6. Flywheel bearing and shaft support
7. Shaft linking flywheel and cam
8. Sliding motion lever arm
9. Base support and stopper for materials loading
10. Bolted cutter blade and frame
11. Flexible mobility roller

Fig. 1 Satructural design and dimensions of hybrid cutting machine

DESIGN CALCULATIONS FOR THE FLYWHEEL COMPONENT

The design of the flywheel for the proposed hybrid metal cutting machine took cognizance of the kinetic generative impact forces required to cause material cleavage. Thus, the design calculation for the manual operation of the hybrid power cutting machine considered a rotary-linear motion where the rotary force impacted on the flywheel by the turning handle or electric motor, transmit energy which results a linear uni-directional force in the form of kinetic energy expressed as [7]:

$$KE = \frac{1}{2} I\omega^2 \quad \dots\dots\dots\dots\dots\dots (1)$$

where;

I = moment of inertia of the flywheel during operational phase

ω = rotational speed of the flywheel in relation to the impacted rotary force.

Characteristically, the moment of inertia of the flywheel for storage of cam useable energy is expressed as:

$$I = \frac{1}{2} mr^2 \quad \dots\dots\dots\dots\dots\dots (2)$$

The design implication of mass *m* in equation (2) is that large mass value of a flywheel increases its inertia I which is its resistance to changes in its rotational velocity. This in effect reduces revolving ability but increases the energy it accumulates, which is needed energy for the required impact. Hence, an increase in mass, increases energy generation and accumulation efficiency. Consequently, upon substitution of equation (2) into equation (1), we have a kinetic relationship that defines the energy transmission and dynamic storage capability, expressed as:

$$KE = \frac{1}{4} mr^2\omega^2 \quad \dots\dots\dots\dots\dots\dots (3)$$

The impact of this dynamic force is further transferred from the bearing supported flywheel through the shaft to the cam. Thus, in computation for design stresses for the shaft, it has been reported that certain critical safety factors are responsible for the selection of materials for such machine parts during design analysis [8]. These include:

- evaluation of modes of possible failure
- determination of relationship between load and load and stress ($\sigma = P/A$)
- determine the maximum usable value of stress, i.e. stress without failure
- select the factor of safety expressed as;

$$\sigma_{all} = \sigma_{max} / \text{n} \quad \dots\dots\dots\dots\dots\dots (4)$$

where,

σ_{all} = allowable stress

σ_{max} = maximum stress

n = factor of safety

Thus, factor of safety for the design on the basis that 200N of input force produced 64J of power or 64N.m of force. This means maximum strength of the machine cutting ability should be valued at 64J of power. If we set the allowable strength to be 25% reduction of this maximum, then factor of safety n is;

$n = \sigma_{max} / \sigma_{all}$ …………………..(4.1)

where σ_{max} = 64, σ_{all} = 48. Thus, n=1.33.

It should be noted from the numerical analysis flowing from equations 4-4.1 above, that since the factor of safety is greater than unity, cumulative components interactions can support material loading without failure up to an additional margin of 33%. This implies that if the loading of materials for cutting operations grows by more than that 33% margin, the cutting device would be expected to yield [9]. Thus, if such failure occurs during the loading of an appropriate material with the required tensile strength, then the cutter couplings should be changed for higher materials of strength or the flywheel and motor size should be increased. Thus, the design recommends that materials to be cut with this device should not exceed the strength supportable by 48J of power output or 48N.m of force.

In order to determine the cross sectional area of the shaft, which also determine the selection of the appropriate bearing, the expression to apply is;

$A = P/\sigma_{all}$ …………………..(4.2)

where;

A= cross sectional area

P= load

σ_{all}= allowable stress

Thus, A=D being shaft diameter as in Fig 2 below and D_o is the bearing internal diameter, housing the shaft. In view of the foregoing, the allowable bearings for applications is coupled to the flywheel in such flywheel powered systems and are less preloaded due to reduction in bearing life, maximum permissible speed and increase in drag torque [10].

Thus, where an axial force F_a causes an axial displacement in an angular contact ball bearing, the axial displacement of such impact is obtained by the expression:

$\Delta x = 2x10^{-6}\sqrt[3]{F_a^2/100Z^2}\,d_b\, sin^5\alpha$ …………………..(5)

where:

F_a = axial force (N)

b_b= diameter of the bearing balls (mm)

Z= no. of balls in the bearing

Sin α= angular orientation of balls in the bearing

Δx= axial displacement (m)

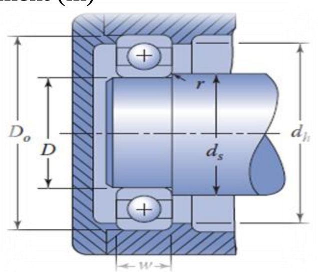


Fig. 2 Dimensions and couplings of ball bearing, shaft and housing (Source: Ugural p. 491)

Fig. 3 20mm Ball Bearing (Source: www.bearingwholesalelots.com/category-s/2362.htm)

Cutting force transmission by flywheel and cam system

In view of the foregoing, the design calculations for this work considered the following parameters:

Energy from force exerted on flywheel= 200N

Change in rotational energy = angle of rotation by exerted force (of 200N) = 57.3°

(Recall that, 1 rad = 180°/π = 180°/3.142 = 57.3°)

Distance of turning handle from flywheel center = 0.320m (radius)

Weight of the flywheel device = 8.5 kg

Anticipated power (force) output required to drive lever arm = 64.0 N.m (64.0 J)

The design parameters above can be used to calculate the force and dimensional requirements for application during the fabrication of the machine. They are computed and derived as follows:

Dimensional Considerations for Machine Flywheel Design

To find the input force (work) on the flywheel, we can use the equation

$W = rF\theta$ …………………..(6)

where;

r = radius or distance of the handle from the center of the flywheel

F = the applied or input force

θ = angle supporting the line of input force

In view of the details above, there is enough information to calculate the machine torque at the flywheel, having known the rotational angle. Further, we can find the final angular velocity using the applicable kinematic relationship after which we calculate the rotational kinetic energy from the expression in equation (1).

Computation of net force

The work output or force at the handle connected to the flywheel is expressed in equation (7) as:

$W = (\tau)\theta$ ………………..(7)

where,

τ = radius x force, and

$\theta = 57.3^o$

It should be noted that τ is the applied force multiplied by the radius (i.e. r x F). Consequently, the design does not consider any occasion of a retarding friction, as force, F is perpendicular to r and the angle θ is given as 57.3^o i.e. 1 rad.

Substituting the given values in equation (7) above yields;

$W = r\ x\ F\ x\ \theta$ = (0.320m) (200N) (1.00 rad) = 64.0 Nm

Note that 1Nm= 1J, this implies that;

W = 64.0J of energy (or work) is the energy produced from the flywheel and transmitted through the shaft into the cam as an impact force on the follower or lever arm. Thus, the flywheel enabled rotary force is further impacted on the cutting blade component as a linear downward force.

Angular velocity of the flywheel and determination of the speed of cut of the machine

To find the angular velocity, ω of the flywheel, it should be noted that at the point of takeoff from rest, $\omega = 0$.

This means that the process kinematic relationship results equation (8) as shown below:

$\omega^2 = \omega_o^2 + 2$ ………………..(8)

Where;

ω_o is angular velocity encountered at the initial point, thus, $\omega_o = 0$

Taking the square root of the resulting equation (8), gives;

$\omega = (2)^{1/2}$ ………………..(9)

Now we need to find angular acceleration α, of the flywheel. Thus,

$\alpha = \frac{\tau_{net}}{I}$ ………………………….…(10)

where the net torque, τ_{net} is,

τ_{net} = r x F = (0.320m) . (200N) = 64.0 Nm

I = inertia

Thus, equation (10) imply that angular acceleration of the flywheel is proportional to net torque of applied force on the shaft and inversely proportional to rotational inertia. In the foregoing circumstance, the moment of inertia for a flywheel in this design is given as:

$I = ½\ mr^2 = 0.5(8.5kg)\ (0.320\ m)^2 = 0.4352\ kg.m^2$

Substituting the values of torque and moment of inertia into the expression for α, we obtain,

$\alpha = \frac{64.0\ N.m}{0.4352\ kg.m^2} = 147.06\frac{rad}{s^2}$ ………………..(11)

Now, substitute the value of equation (10) and the given value for θ into the above expression for ω in equation (9):

$\omega = (2)^{1/2} = [2(147.06 rad/s^2)\ (1.00\ rad)]^{1/2} = 17.14$ rad/s

Thus, from computation 147.06 rad/s^2 amounts to 8426 degrees of angular inclinations, implying that for a continuous input of 200N, 23.4 revolutions of the flywheel are expected to produce revolutions on the shaft as to transmit rotary force on the cam.

Determination of power requirement per revolution

While the final rotational kinetic energy is given as,

$KE_{rot} = \frac{1}{2I\omega^2}$ ………………………….(12)

And it should be noted that both I and ω were found above. Thus, substituting the values, we have:

$KE_{rot} = 1/2I\omega^2 = (0.5)\ (0.4352\ kg.m^2)\ (17.14\ rad/s)^2 = 3.7$ J

Hence, by design simulation, the rotational kinetic energy impacted on the flywheel and further transmitted to the cam and motion lever arm is 3.7 J per revolution and 17 revolutions on the input of 64 J of energy on the flywheel. Further, determination of the size ratios between the flywheel and the cam as to find the number of revolutions of the cam per revolution of the flywheel, taking cognizance of energy losses due to shaft and bearing transmissions. Whatever differences exists, can be resolved upon fabrication and testing of the machine.

The view of this paper is that engineering materials within the ultimate tensile strength (UTS) supported by this size of force can be processed. This further implies that the cutting speed and depth of cut of materials using this machine is significantly dependent on the amount of input energy from the flywheel. Hence, while materials with low UTS can be cut with the manually operated section, materials with medium and high UTS would be better with the motor driven coupling, since the higher the motor capacity the more the output cutting force.

DESIGN PROCESSES FOR FABRICATION

The design process of this industrial hybrid powered cutting machine considered some fundamental steps, including the following:

1. Design and operational assessment for possible improvement
2. Modification and development
3. Design and development of standard frame
4. Complete assembly of components and equipment

It should be noted that the structural support frame of a previous design was reviewed and re-engineered to suit the concept and content of the hybrid powered design, proposed in this paper.

Table -1 Structural support members

Component specified	size (l x w x h)	Material used
Frame	(900x 750 x 400) mm	2inch angle steel

As could be seen in Fig 1 above, the structural support members are made of 2 inch angle steel which should be welded as indicated with the dimensions stated in Table 1 above**.** The dimensions of the assembly and the various components are as indicated in Fig. 1 above.

Table -2 Design force delivery components

Components specified	Size	Material used
Flywheel	ϕ350mm	Steel
Motor	12 volts	Phosphor bronze
Shaft/ link	ϕ 20mm (pipe)	Reinforced steel
Ball Bearing (2pcs)	6004ZZ Size:20mm x 42mm x 12mm Ball Bearing 6004Z	6004ZZ Material: Chrome Steel
Belt drive	0.5m (l)	Reinforce plastic
Revolving handle (detachable)	ϕ 20mm rod in Z shape	Steel

Table -3 components of motion and cutting coupling

Component specified	Size	Materials used
Cam	ϕ175mm	Steel
Motion lever arm	600 mm (l)	18mm steel flat bar
Cutter ram blade	250mm (l)	18mm steel flat bar
Cutter base plate	255mm (l)	90^o angle steel bar

DISCUSSIONS

Appropriate Motor, Flywheel and Cam Selection

In the fabrication of any engineering design, material selection is a very important aspect [11]. This means that in the choice of the appropriate size of the motor, spinning handle, shaft, bearings, flywheel, cam, follower or lever arm, for implementation of this design, there is the need to compute the various linkages of the components in line with the design requirements. This infers that the side thrust resulting from the nature of the linkages has a direct relationship to the pressure angle and the coefficient of friction of the follower [12]. For instance, the amperage of the motor must be determined as to know if it can drive the cutting process on the basis of the assigned linkages and what materials it can cut and the time for such cutting process.

It is also important to know the amount of power consumption of the motor in relation to the output, or performance of the motor. This aspect is very crucial in the machine life cycle since it is the determinant for the economic and technical viability of the machine [13]. The next crucial issue is to determine the strength of the materials to be cut and how long it would take to cut, which will significantly depend on the output efficiency of the motor or the manual spinning handle.

On the application of flywheel and cam coupling, the ratio of flywheel diameter to cam diameter and the angle of placement of the motion lever arm is of crucial importance when determining the force of power transfer to the cutting mechanism. Thus, the appropriate components to be selected must be dependent on the design criteria and parameters; implying that the processes associated with the production or fabrication of one material may likely compete with the processes associated with the production of another material [14], hence the need for proper articulation of the selection process, which should be guided by a knowledge of the displacement law and logical motion of the mechanism is a crucial aspect especially when it is on the basis of the process optimality criteria required for high speed cam-follower system [15]. Consequently, design parameterization as a means of reviews and reinvention is fundamental to a product viability [16] as proposed in this paper.

Components stability and alignment

The design considered the stability of the machine under high speed continuous cutting operation. This necessitated proper stability measures which has to do with standard alignment of the components in the best possible positions. These alignments are also based on theoretical analysis as have been indicated in this paper. Thus, the components are to be arranged within the logic of operation of the machine taking into accounts various damping practices for vibration control under high speed cutting operations.

Further, the measurements and angles of placement where determined in accordance with the theoretical and mathematical analysis earlier detailed in this work. The spud support for the flywheel and cam are both welded to the crossed trusses that brace the structural frames. This is firmly guided to ensure high sense of stability and alignment. Further, the alignments of the shaft as a connecting link between the flywheel bearing and the cam is arranged to ensure the unrestrained flow of force to the cam as shown in Fig 4 below. The listed components in Table 2 above are the design specifications for force delivery components of the machine.

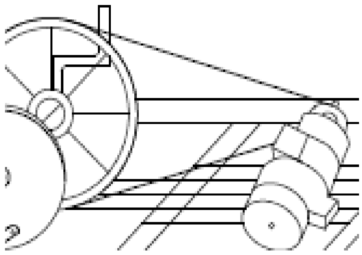


Fig. 4 Flywheel, belt and DC motor coupling

It should further be noted that the revolving handle is a detachable design and can be removed when the machine is motor operated. However, when the machine is manually operated, the belt link is removed in order to isolate the DC motor from the manual operation. The foregoing notwithstanding, the following details on Table 3 above are the components that constitute the motion and cutting coupling of the machine while Fig 4 is indicative of the force delivery coupling of the design.

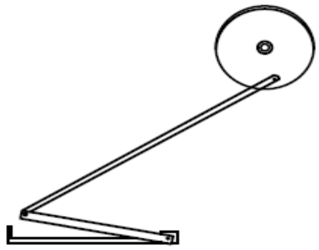


Fig. 5 Cam, motion lever and cutter coupling

DC Motor and Flywheel Coupling of the Design

The delivery of force from the DC motor is controlled by electric energy input into the motor. This force output of the motor as could be seen in Fig 5 above, is determined by the calculation of force or energy requirement for the cutting operation. Thus, the force transmitted from the DC motor impacts on the flywheel through a belt drive connected in alignment as shown in Fig 4 above.

This belt drive acts as the force link and has the capability to sustain the transfer of energy as the force is impacted from the motor. As indicated, the angle of inclination of the belt is important. This angle enhances the transfer of generated force and keeps the flywheel in rotary motion. It should be noted that the power of the DC motor can be sourced from solar power-inverter-battery arrangement, municipal electric power or other forms of electric power supply.

Components and assembly designs

The components of this design are technically configured to render the required force that could result the cutting of materials placed under the cutter blade as shown above, the various components are detailed with their dimensions.

Operational parameters for the Design

The design of this machine is an application utilizing flywheel energy storage and output motion ideology. This implies that the flywheel is relatively crucial to the machine in the sense that the machine significantly rely on the flywheel output power to drive the cutting process. Hence the deployment of all other components of the machine would be dependent on the efficiency of the flywheel design and the alignment of the other components to the flywheel. In this regard, the motion lever arm moves up and down, such that when the motor is powered or the flywheel is manually rotated, the transferred rotary force is transmitted to the cam which transmit same as a linear force arranged as an upward and downward movement of the motion lever-cutter coupling.

CONCLUSION

The design of hybrid cutting machine for industrial deployment have considered the application of process dynamics that deal with impact and cutting forces utilizing components such as flywheel, shaft bearing, cam, motion lever arm, etc. These impact forces are the product of rotary-linear motions that convert angular velocities to linear motions, thereby producing compressive forces. The paper thus finds that when designing structural members for a multi-capability machine as this, the device should be appropriate for the design purpose and manufacturing competences. Further, the material selection process should significantly consider the process displacement law and the design parameterization conditions in determination of suitable materials for optimal applications. These design considerations are crucial to the economic and technical viability of the design. Thus, the input and out mechanical power and the expected performance efficiency of the design should be the driving force when determination is made for the safety factor of the design.

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