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OPTIMIZATION OF FLYWHEEL MATERIALS USING GENETIC ALGORITHM

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ABSTRACT: *An inventive approach to composite flywheel design is put forward for discussion. Flywheel design and development has dominated in many applications where minimizing mass is critical. This is also attractive for various industrial based applications. Hence, the minimum mass required for certain energy storage was used as the objective function. Based on an analytical approach for calculating stresses in flywheels, the nonlinear optimization problem was solved using genetic algorithms that combine an evolutionary algorithm with a nonlinear active set method. The problem was solved for a sample flywheel with varying materials. Minimum mass required is found out for different values of energy storage and corresponding other parameters are found out. Finally, the composite materials found to have the least values of minimum mass required with increased value of angular velocity out of five materials selected for optimization process.*
KEYWORDS: *Flywheel, Angular velocity, Carbon fiber composite, Optimisation*

INTRODUCTION

Many problems which occur in engineering cannot be handled satisfactorily using traditional optimization methods. Engineering involves a wide class of problems and optimization techniques. Some engineering design approaches are simply old fashioned, and have been replaced by computer simulations that exploit various mathematical methods such as the finite element method to avoid costly design iterations and time. The next step followed in the engineering of systems is the automation of optimization through computer simulation. If the required performance factors for the system can be appropriately found, then optimization over them is simply engineering on an ambitious scale.

FLYWHEEL

As stated in [1], a flywheel is a rotating mechanical element which is used to store energy of rotational form. Flywheels have a considerable moment of inertia, and thus it resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed (angular velocity). Energy is transferred to a flywheel by applying torque to it, thereby causing it to rotate, and hence its stored energy, to increase. Similarly, a flywheel releases stored energy by applying torque to a mechanical load, which results in decreased rotational speed.

FUNCTIONS OF FLYWHEEL

Flywheel is used to store the excess energy when the supply is more than the demand and to deliver it when the supply is more than the demand. Flywheel is essentially a rotating mass. It stores energy in the form of kinetic energy. Flywheels are used in many applications such as internal combustion engines, steam engines, power presses, slotting machines, etc.

Size optimization of flywheels for the minimization of mass, is an appealing thought that has received its fair attention. The concept of a flywheel is old, but could very well hold the key to forth coming problems of efficient energy storage. The flywheel has a bright view point because of the recent development of composite materials. A simple example of a flywheel is a solid, flat rotating disk. A flywheel stores kinetic energy by rotating a mass about a constant axis of rotation, which makes it easy to assimilate flywheels into energy conservation systems. Few vehicles currently use flywheels during braking for regenerating energy lost during deceleration. Electrochemical energy storage such as batteries are limited by low cyclic lifetimes, low longtime reliability and low specific energies, these are major concerns in satellite applications. The flywheel is well capable for this application due to high cyclic lifetimes, longtime reliability and high specific energies than batteries. Also, large scale flywheels could be used in energy plants to store large amounts of energy. Finding practical applications for flywheels is not a problem, but optimizing the mass of flywheels, in a given specific set of parameters and constraints, provides a challenge.

In this paper, five different materials namely, Grey Cast iron (GCI 25), Aluminium alloy, Maraging steel, Carbon fiber composite (40% epoxy), E glass fiber(40% epoxy) are taken for analysis[2,3]. Optimization is carried out for all the five materials to find the minimum mass required for certain energy storage values. A comparison is made between energy storage, minimum mass obtained through optimization and corresponding mean radius and angular velocity.

NEED FOR OPTIMIZATION ON FLYWHEELS

The energy storage by a flywheel is given by[1],

$$\Delta E = I.\omega^2.C_\Delta \quad (1)$$

where, I is the mass moment of inertia (kg-m^2), ω is the angular velocity (rad/sec) and C_Δ is the coefficient of fluctuation of speed. The energy stored by a flywheel is the function of its mass, radius and angular velocity. But, the angular velocity is limited to some value because of the hoop stress produced at the rim of the flywheel.

Equation (1) can be written as,

$$\Delta E = mr^2\omega^2 C_\Delta \quad (2)$$

where, $I = mr^2$, m is the mass of flywheel and r is the mean radius of the disc. Assuming coefficient of fluctuation of speed $C_\Delta = 1$.

$$\Delta E = mr^2\omega^2 \quad (3)$$

The vertical upward force, which will produce hoop stress, is,

$$2\rho A r^2\omega^2 \quad (4)$$

where, ρ is the density of the material and A is the cross sectional area.
This is resisted by 2P such that

$$2P = 2[\sigma]A \quad (5)$$

By equating (3) and (4),

$$2\rho A r^2 \omega^2 = 2[\sigma]A$$
$$\omega \le [\sigma]/\rho r^2 \quad (6)$$

Therefore, for safer operation, the flywheel has to be operated at the speed which will not produce the hoop stress greater than the allowable stress of the material. The radius of the flywheel, which is also in direct proportion with the energy storage, is another parameter which decides the hoop stress. The minimum mass required to store a certain value of energy for different types of materials can be found by optimization by keeping the angular velocity and the radius as variables. By optimization, the minimum mass can be found for the different materials for same energy storage and the corresponding angular velocity and radius can be obtained.

OPTIMIZATION

In engineering, the bio-inspired evolutionary computation is a subset of artificial intelligence that involves combinatorial optimization problems [4]. Evolutionary computation uses iterative progress, in a population. This population is then selected in a guided random search using parallel processing to achieve the desired results. As evolution produces effectively optimized processes, it has been found in numerous applications in engineering.
Many such evolutionary algorithms are found in many typical applications of engineering fields. They are genetic algorithms, evolutionary programming, evolution strategy, swarm intelligence, ant colony optimization and particle swarm optimization. A genetic algorithm (GA) is an optimization tool that imitates the process of natural evolution [5]. This heuristic approach is frequently used to generate useful solutions to optimization problems. As the GAs belong to the larger class of evolutionary algorithms (EA), they generate solutions to optimization problems using bio-inspired techniques, such as inheritance, mutation, selection, and crossover [6,7].

OPTIMIZATION OF FLYWHEEL USING GENETIC ALGORITHM

In order to find the minimum mass required and corresponding angular velocity and radius by genetic algorithm for the required energy storage, objective function and constraints and bounds have to be determined. Optimization will be carried out for five different materials with five different combinations of energy storage values. The objective functions, constraints and bounds will be same for all the five materials.

MATERIALS AND THEIR PROPERTIES

The five materials that are used for design of flywheel, and their properties are given in table 1.

Table 1. Material properties[2,3]

Material	Allowable stress, [σ](MPa)	Density, ρ (kg/m³)
Grey Cast iron (GCI 25)	220	7340
Aluminium alloy	400	2700
Maraging steel	900	8000
Carbon fiber omposite (40% epoxy)	750	1550
E glass fiber (40% epoxy)	250	1900

PROBLEM FORMULATION

The objective function and constraints are same for all the five materials with different values of density ρ, and allowable stress [σ]. This can be formulated by using equations (3) and (6).

OBJECTIVE FUNCTION AND CONSTRAINTS

The objective of this problem is to minimize the mass for the given value of energy storage.
From equation (6),

$$\Delta E = mr2\omega^2$$
$$m = \Delta E / r^2.\omega^2$$

where, ΔE= 100,200,300,400,500 J
Therefore, the objective function is
Minimize,

$$m = \Delta E / (r^2.\ \omega^2) \quad (7)$$

The constraints of the problem falls under non-linear constrains because of the orders of ω and r.
From equation (6), the constraints are obtained as follows.

$$\omega^2 \le [\sigma]/\rho r^2$$
$$\omega^2 - [\sigma]/\rho r^2 \le 0$$
$$\rho r^2 \omega^2 - [\sigma] \le 0 \quad (8)$$

RESULTS AND DISCUSSIONS

The problem is solved by using MATLAB 7.10.0. The following procedure is carried out to run the iteration process. First, the objective function and non linear constraints is created as M-files [9]. The ga tool is invoked using command window. Next, fmincon solver is selected as the problem falls with non-linear constraint. Objective function and constraints are entered in the solver in the appropriate areas. The bounds are given as lower (0.1 0.1), upper (2 500) ie, 0.1<r<2 m and 0.1< ω <500 rad/sec. The crossover function is selected as scattered and the mutation function is selected as constraints dependent mutation. In stopping criteria functional tolerance is given as 1e-9, this is used to stop the solver based on two immediate falling results. The maximum iterations are limited to 400. All other functions are left default as they don't affect the iteration process of the problem. The procedure is repeated for all five materials with ΔE=100, 200, 300, 400 and 500 J.
Figure 1 is a plot which obtained after running the solver showing the convergence of soultion. It shows the functional value (minimum mass) and the iteration number for E glass fiber (40% epoxy) for the energy storage of 500 J (refer table 2).

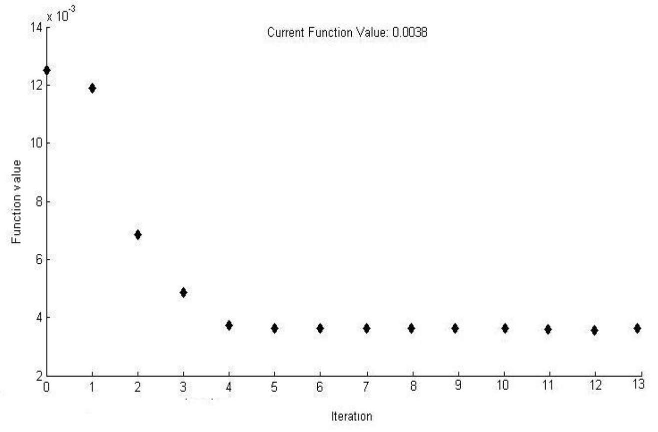

Figure 1. Functional value and iteration

The corresponding radius and angular velocities found from this optimization are, 1.491 m, 243.317 rad/sec respectively. Table 2 shows the materials and the minimum of mass, angular velocity, mean radius obtained for given values of energy storage.

Table 2. Materials and functional values

Material	Energy storage (ΔE) J	Mass (m) kg	Radius (r) m	Angular velocity (ω) rad/sec
Cast iron (GCI 25)	100	0.0033	0.829	208.91
	200	0.0066	1.039	166.67
	300	0.0100	1.089	159.00
	400	0.0130	1.109	156.16
	500	0.0166	1.128	153.42
Aluminium alloy	100	6.7E-4	1.065	361.46
	200	0.0013	1.423	270.48
	300	0.0020	1.488	258.59
	400	0.0027	1.510	254.87
	500	0.0033	1.528	251.95
Maraging steel	100	8.88E-4	1.009	332.26
	200	0.0017	1.344	249.58
	300	0.0026	1.406	238.59
	400	0.0035	1.427	235.04
	500	0.0044	1.444	232.28
Carbon fiber composite (40% epoxy)	100	2.06E-4	1.391	499.99
	200	4.13E-4	1.836	378.91
	300	6.20E-4	1.919	362.41
	400	8.26E-4	1.945	357.66
	500	0.001	1.964	354.15
E glass fiber(40% epoxy)	100	7.6E-4	1.040	348.62
	200	0.0015	1.388	261.31
	300	0.0028	1.452	249.80
	400	0.0030	1.474	246.12
	500	0.0038	1.491	243.31

Mass and the Energy Storage

Figure 2 gives the plot between minimum mass obtained for respective energy storages. It shows that, flywheel made up of cast iron has more mass for same values of energy storage compared with all other materials. It is because of high density and less strength of cast iron. It is followed by, maraging steel and E-glass fiber composite. Carbon fiber composite holds the least values of mass compared with other materials because of less density and good strength properties.

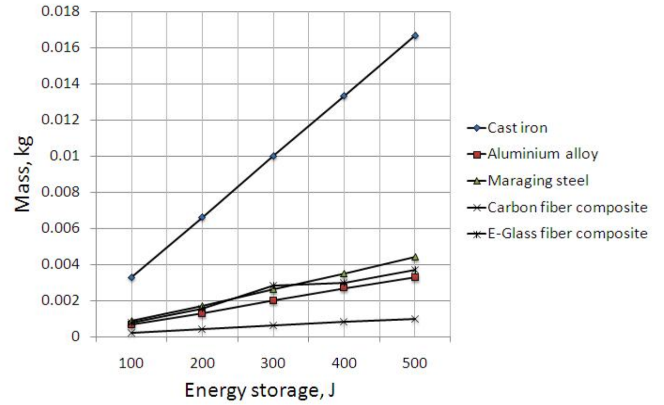

Figure 2. Minimum mass and energy storage of materials

Radius and the Energy Storage

The variation of radius of flywheels for respective energy storages is shown in Figure 3. For the same energy storage, cast iron flywheel holds less values of radius because of its high value of density and less strength properties. Carbon fiber composites have higher values of radius. It is followed by aluminum alloy, maraging steel and E-glass composites in this order.

Angular Velocity and the Energy Storage

As like figure 3, figure 4 also gives the same order of materials in the plot for angular velocity as well. Carbon fiber composites take the maximum values of angular velocities which show the ability of the material to withstand higher speeds. Aluminum alloy, maraging steel and E-glass composites have almost same values of angular velocities and lies in-between carbon fiber composites and cast iron. Cast iron got minimum values of angular velocities which show the inability of the material to spin at higher velocities.

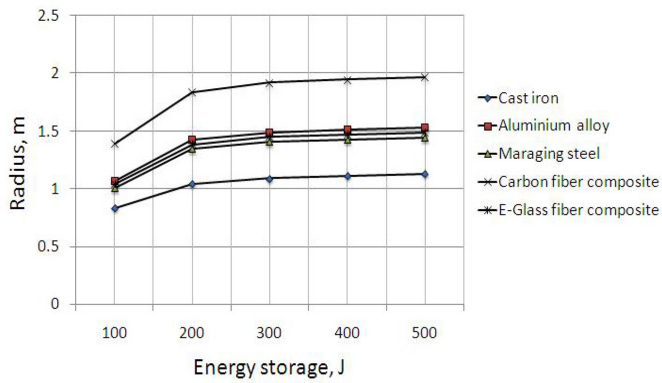

Figure 3. Radius and energy storage of materials

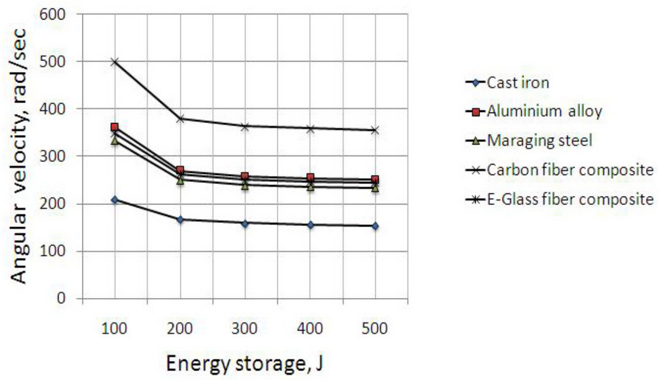

Figure 4. Angular velocity and energy storage of materials

CONCLUSIONS

This optimization is carried out to find the minimum mass and respective values of radius and angular velocity. From the analysis, it is clear that, cast iron flywheels are having higher mass and less angular speeds. Aluminum alloy, maraging steel and E-glass composites lies almost in a same category in between cast iron and carbon fiber composites. Among five materials, carbon fiber composites can be used in flywheels to store energy with less mass. It can be also used in high speed applications, as the values of angular velocities obtained are higher than that of other materials.

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