DEVELOPMENT AND SIMULATION OF A FLYWHEEL-BASED ENERGY STORAGE SYSTEM ON A CLAMSHELL DREDGE

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ABSTRACT

In order to analyze the anticipated performance of a large scale flywheel-based energy storage system in a real-world application, a detailed simulation of a 17 m^3 clamshell dredge equipped with a flywheel device was developed. The simulation includes a mathematical model of the bucket machine and flywheel dynamics, as well as a proprietary power routing algorithm which holds the machine's total power consumption constant.

By including the characteristics of several different Caterpillar diesel generator sets, fuel consumption and emissions data can also be analyzed. The simulation results show a 25% reduction in average electric power demand, a 37% reduction in diesel fuel consumption and dramatic 80-90% reductions in all of the Tier 3 emissions categories when a diesel generator set is used. In this case, monthly fuel costs are greatly reduced, at a lower capital cost. When power is drawn from a pre-existing power grid, capital costs are higher, but can be recovered within two years.

Keywords: Energy recovery, peak shaving, control algorithm, Matlab, Simulink.

INTRODUCTION

Many electro-mechanical cyclical processes could potentially benefit from the use of an energy storage system able to absorb, store, and relinquish large amounts of energy. Commonly used energy storage systems such as batteries (chemical), hydraulic accumulators, or capacitors (electrical) are limited by size, weight, cost, capacity, power output, cycling or efficiency considerations. A spinning flywheel (kinetic energy storage) is an ideal, cost-effective way to store large amounts of readily-available energy.

In the development of a flywheel-based energy storage system, a clamshell-type bucket dredge was chosen as a test application to analyze the performance of such a system via computer simulation. The cycling power draw characteristic of a bucket machine lies namely in the hoisting and lowering of the clamshell bucket. Capturing regenerated power (during lowering) and reusing it in subsequent operations can lead to significant improvements in overall operational efficiency of such a machine.

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CLAMSHELL DREDGE

Dynamics

To ensure relevant results, the specifications of the dredge model used are based on an actual clamshell dredge. All relevant mechanics of the dredge are considered and described mathematically. The model consists mainly of small, mathematically simple parts such as a winch drum or a gear reduction, coupled together mathematically via resultant forces. Main sources of friction and drag are included, such as wire rope elasticity and damping and sheave friction, hydrodynamic drag on the bucket, and forces associated with digging in the soil.

Mechanical systems

The clamshell dynamics model can roughly be divided into six main mechanical systems:

- The close motors, winch and wire rope
  (the close line closes the bucket when operated separately from the hold line)
- The hold motors, winch and wire rope
  (hold and close line used together hoist and lower the bucket)
- The swing (which rotates the tub around its vertical axis)
- The tagline motor and winch (which stabilizes the bucket during swinging)
- The boom motor and winch (to raise and lower the main boom)
- The bucket dynamics/kinematics and soil mechanics
  (models the opening, closing and soil digging actions of the bucket)

Commonly used component parts are motors, gear reductions, winches and wire ropes. Although the boom raising/lowering system is fully modeled, it is not used during dredging operations.

Motors and drives

All motors used are AC induction machines, speed-controlled via PID controllers. They are modeled as devices that convert electrical power into mechanical torque directly applied to a rotating inertia (the rotor) at a constant efficiency of 95%. The motor models outputs are limited by speed-torque characteristics and major drive parameters (slew rate, speed limits, etc.). All electric motors and drives are able to fully regenerate power, also at an efficiency of 95%. The close and hold motors directly drive their associated winch drum. The other motors are coupled to a gear reduction. A gearbox is modeled as a device that multiplies torque and divides speed by its gear ratio. It also has a rotational inertia. Table 1 lists all the motors modeled in the simulation. The motors and drives are the only electric devices considered in this simulation. Minor, low-power systems such as lighting and ventilation systems are ignored.

Table 1. List of motors.

Type	Amount	Nominal power each (KW)	Nominal speed (rad/s)	Gear reduction
Close line	2	439	1.4	1
Hold line	2	439	1.4	1
Swing	2	111	167	1000
Tagline	1	104	105	10
Boom	1	187	105	300

Winches and cables

Winch drums are modeled as rotating devices with rotational inertias that convert torque into linear force. Furthermore, they have a certain radius and length, which together with the cable diameter determines the length of cable per layer on the drum. When a layer fills up, the overall radius of the winch drum increases accordingly. The cables are modeled as damped springs with a variable length (and therefore, variable spring and damping values). The modulus of elasticity for the cables used is 90 GPa, and the damping ratio is approximately chosen so that the overall system is slightly underdamped. Winch and cable details are listed in Table 2.

Table 2. List of winches.

Type	Length (m)	Radius (m)	Cable diameter (cm)
Close	1.8	0.89	5.08
Hold	1.8	0.89	5.08
Tagline	1	0.5	3.81
Boom	1.3	0.44	3.81

Bucket

The dynamics and kinematics of the bucket have been modeled according to the general dimensions shown in Figure 1. The bucket has a capacity of approximately 17 m^3 and weighs 28 metric tons empty. The soil digging dynamics of the bucket have been modeled according to Becker et al. (1992). For the calculation of hydrodynamic drag (through air and water), the bucket is approximated by a cube of similar proportions.

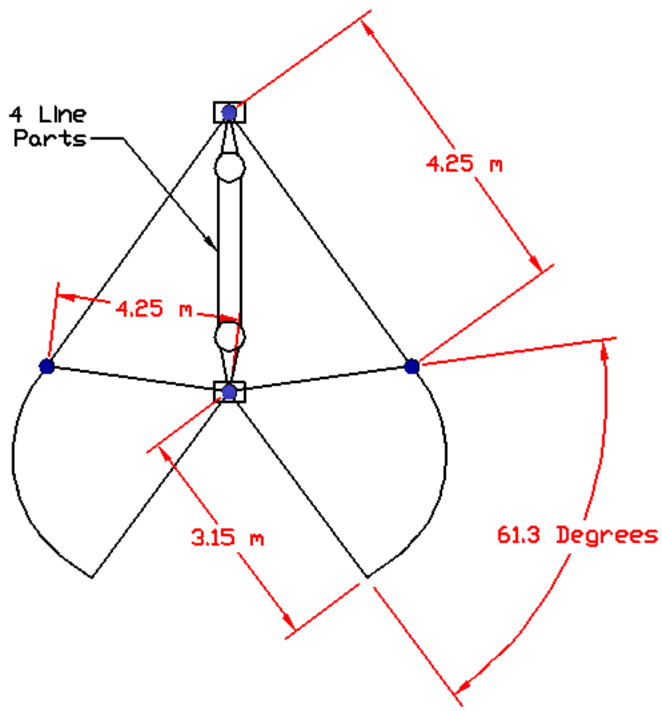

Figure 1. Bucket dimensions.

Dredge control

A simple automatic control system for the clamshell dredge was designed to model the inputs of the dredge operator who pulls the levers. The control system cycles through six steps:

1. Swing to the dig site (start to lower the bucket simultaneously)
2. Lower the bucket to the soil
3. Dig (close the bucket)
4. Hoist the bucket
5. Swing to the scow (and continue hoisting)
6. Open the bucket

This cycle repeats for the duration of the simulation. An alternate version of the simulation can be controlled in real-time by the user through the use of a joystick and a rudimentary graphical 3D output (Figure 2). However, for the simulation to be able to be run in real-time, several compromises must be made to reduce processor load. Therefore, the actual simulation is run using the automatic control system described above, while testing can be done in an interactive manner.

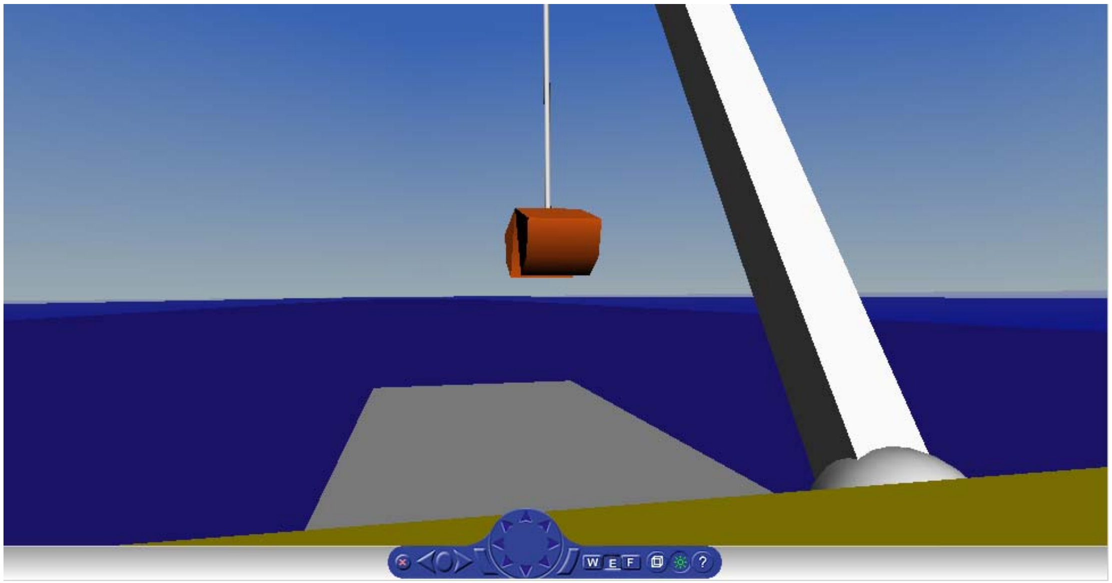

Figure 2. Real-time interactive simulation output view.

FLYWHEEL SYSTEM

Dynamics

Dynamically, the flywheel is a very simple device. It is simply a torque device (an AC induction motor/generator) coupled to a large rotational inertia. The governing equation is simply

$$T = I\dot{\omega} + T_d \tag{1}$$

where T is shaft torque, T_d is aerodynamic drag torque, I is the rotational inertia and $\dot{\omega}$ denotes the time derivative of angular velocity. The total amount of kinetic energy contained in the rotating mass is

$$E = \tfrac{1}{2} I\omega^2 \tag{2}$$

and the power transfer is of course the time derivative of this.

The aerodynamic drag of the spinning flywheel is estimated by considering the shear drag on a flat plate, aligned parallel to a fluid stream:

$$F_{plate} = \tfrac{1}{2} C_{Df} \rho A V^2 \tag{3}$$

where F_{plate} is the drag force, C_{Df} is the shear drag coefficient, ρ is fluid density and V is linear velocity. Assuming the flywheel is cylindrical with thickness D, we can integrate equation (3) over the entire surface of the flywheel, and deduce the total drag torque:

$$T_d = \iint_S F_{plate} r dA = \pi\rho C_{Df} \omega^2 \left(\tfrac{2}{5} r^5 + Dr^4\right) \tag{4}$$

A number of empirical formulas exist to determine the drag coefficient and in this case the following formula for turbulent flow is used (from Munson et al. (1990)):

$$C_{Df} = \frac{0.455}{(\log(\mathrm{Re}))^{2.58}} \tag{5}$$

where the Reynolds number Re is based on the flywheel radius and tip speed. A much more detailed analysis can be found in Dorfman (1963).

Details on the simulated flywheel are listed in Table 3. These specifications were chosen as a compromise between several factors, such as overall weight, energy capacity and (aerodynamic) power dissipation. Note that the induction motor operates in a speed range above its nominal speed, in the constant-power region. This is preferable for a flywheel system that should be able to output nominal power regardless of speed.

Table 3. Flywheel details.

Motor/generator		
Nominal speed	1200	RPM
Nominal power	746	kW
Flywheel		
Diameter	1.9	m
Thickness	0.31	m
Inertia	3100	$kg.m^2$
Speed range	120-200	rad/s
Energy capacity	40.3	MJ
Power dissipation @ max speed	71	kW

Control system

The flywheel system, or any energy buffering system for that matter, has two main goals. First, it should store and reuse regenerated power, realizing a lower overall average power consumption. Second, it should buffer the equipment's power requirements in such a way that the power source sees a relatively constant load profile, free of extreme peaks and valleys. Given unlimited (or very high) energy storage capacity, or perfect predictability of the equipment power demand, it is a trivial task to achieve these two goals. However, in the interest of practicality and cost, it is desirable to dimension the device such that its capacity is only slightly higher (say, a by factor of 2) than the machine's maximum estimated peak-to-peak energy fluctuations. In the case of the clamshell dredge, for example, this estimate is based on the maximum gross bucket weight (56 metric tons), the maximum expected vertical bucket travel (40 m), which amounts to a (gravitational) potential energy of around 22 MJ. A good control system should therefore regulate the flywheel operation so that there is enough capacity to absorb a possible upcoming regeneration peak, and similarly, there should be enough reserve energy available to feed a demand peak.

Topology

There are four main power generating or consuming systems:

A. The main power source: electrical grid, diesel generator, etc.
(power generation)
B. The "equipment" (in this section, "equipment" will refer to the clamshell dredge as whole)
(power consumption and (re)generation)
C. The flywheel energy storage system
(power consumption and (re)generation)
D. An excess power sink
(power consumption)

Note that this categorization pertains purely to the operating principles of the flywheel control algorithm; the topology of the actual power electronics equipment is not being considered here. The four (4) systems labeled A through D in Figure 3) are connected to a (hypothetical) central black box which coordinates energy transfer between the systems.

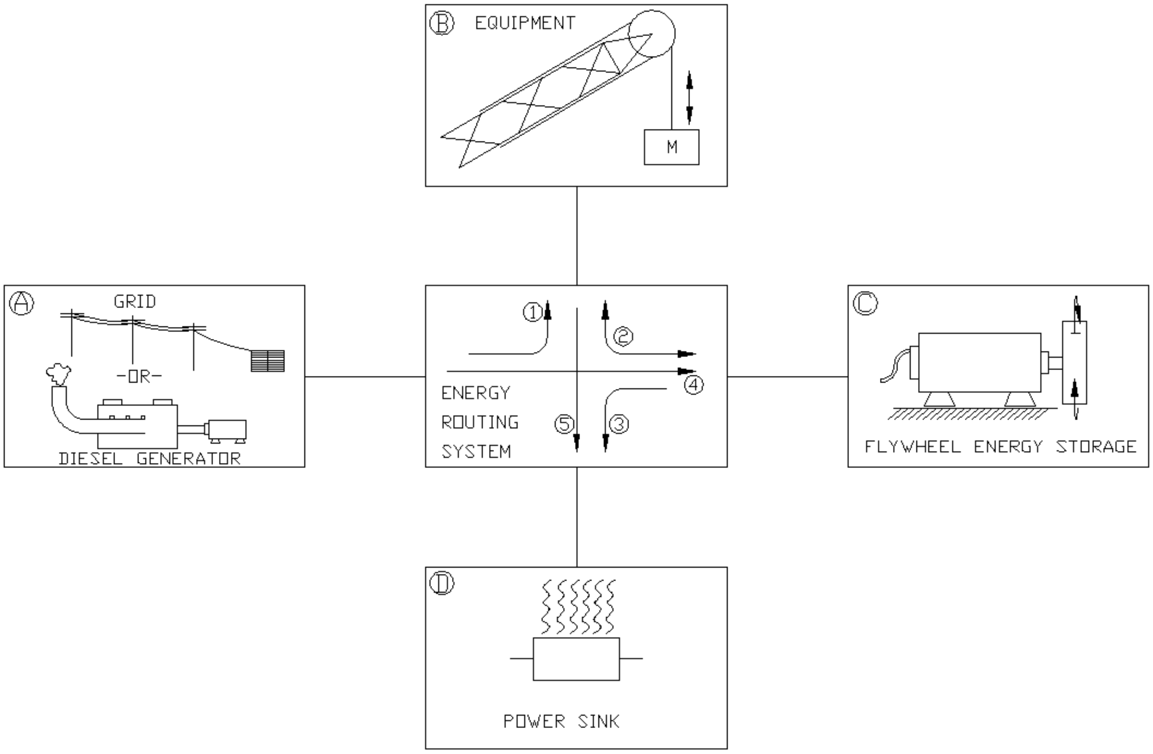

Figure 3. Power routing topology.

Table 4. Energy transfer routes.

Energy transfer between the 4 systems				
	To A	To B	To C	To D
From A		R1	R4	-
From B	-		R2	R5
From C	-	R2		R3
From D	-	-	-	

Algorithm

The controller routes power to and from the four (4) systems according to the following priorities (in order of importance):

1. the power demand of the application (B) is satisfied;
2. the flywheel (C) operates within its preset limits;
3. the power drawn from the main power source (A) is (almost) constant;
4. the flywheel contains sufficient energy to supply the next demand peak
5. the flywheel has sufficient “headroom” to absorb the next regeneration peak
6. a minimal amount of power is routed to the power sink (D).

There are several possible routes along which the black box can transfer energy, denoted as 1 through 5 in Figure 3 and Table 4. The unlabeled routes are either impossible or impractical in real-life situations, and are not considered.

For each route listed above, an energy index (I_E) and a power index (I_P) is defined, both ranging from -1 to +1. The energy index is related to the flywheel charge and the power index is related to the power being demanded by the application. The amount of power to be transferred along each route is a function of these two indices. Graphically, a surface in three dimensional space is defined for each route. The value of I_E and I_P can be seen as coordinates defining a point on this surface. The height of the surface (ranging between -1 and 1) at this point is then a measure of the amount of power to be transferred along that route. These surfaces have been chosen so that the priorities listed above are satisfied.

As an example, consider a typical surface for route R5, which controls the amount of power routed from the equipment to the power sink (Figure 4). In this case, I_E and I_P are directly linearly related to the flywheel charge and the machine's power demand. The associated surface has height 0 almost everywhere, except for where $I_E>0.9$ and $I_P<0$. In other words, when power demand is negative (the dredge is regenerating) and the flywheel is almost fully charged, the system begins to dissipate power through the sink.

The power and energy indices can be directly linearly related to the current power demand or flywheel charge, respectively (such as in the case of R5), or they can be filtered in some way. Similarly, the surface height is somehow related to the amount of power to be transferred along that route. For example, for route R4 the power transfer is scaled by a factor obtained by passing the equipment's power demand signal through a low-pass butterworth filter with a cutoff frequency below the machine's typical operating cycle frequency. The surface (Figure 5) is shaped so that power is continuously routed at a fairly constant trickle through R4 (approximately at the rate of the machine's average power consumption), except for when the power demand is high and flywheel is almost depleted (diverting power generation resources straight to the equipment) and when the flywheel is near maximum charge.

Besides the main control system, some minor logic can be added to further optimize the system's performance. Two (2) such additions are a grid peak limiter, which limits the maximum power draw from the grid (or generator set) to a preset value, and a precharge unit, which precharges the flywheel to compensate for initial filter start-up transients.

The system is easily adapted to other applications. The most important parameters to consider are those for the low-pass filters (filter order and cut-off frequency). The power routing surfaces as developed for this clamshell dredge are generally suitable to most cyclical applications. Usually only minor parameter adjustments (by trial-and-error simulations) are required to optimize performance.

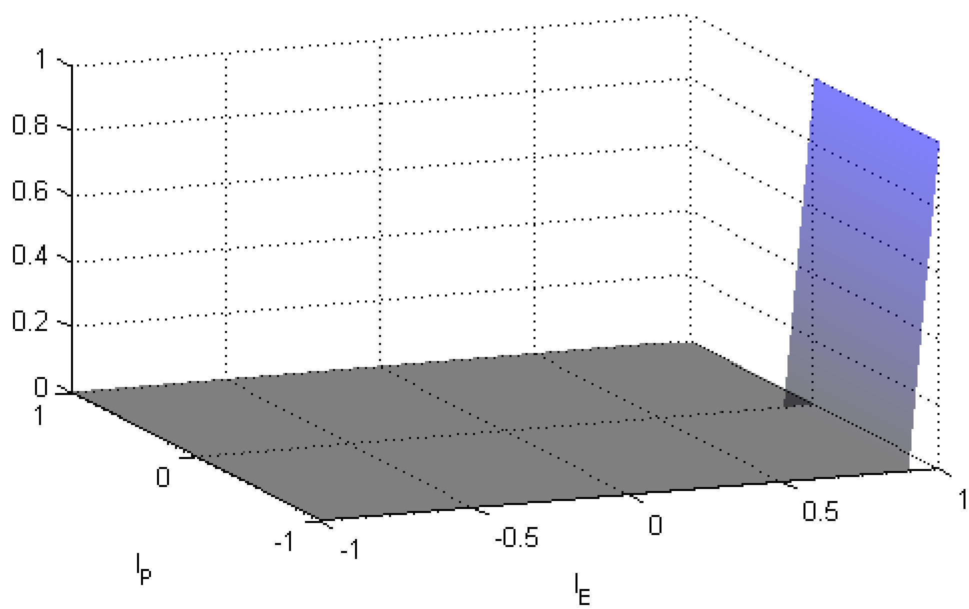

Figure 4. Power transfer surface for route R5.

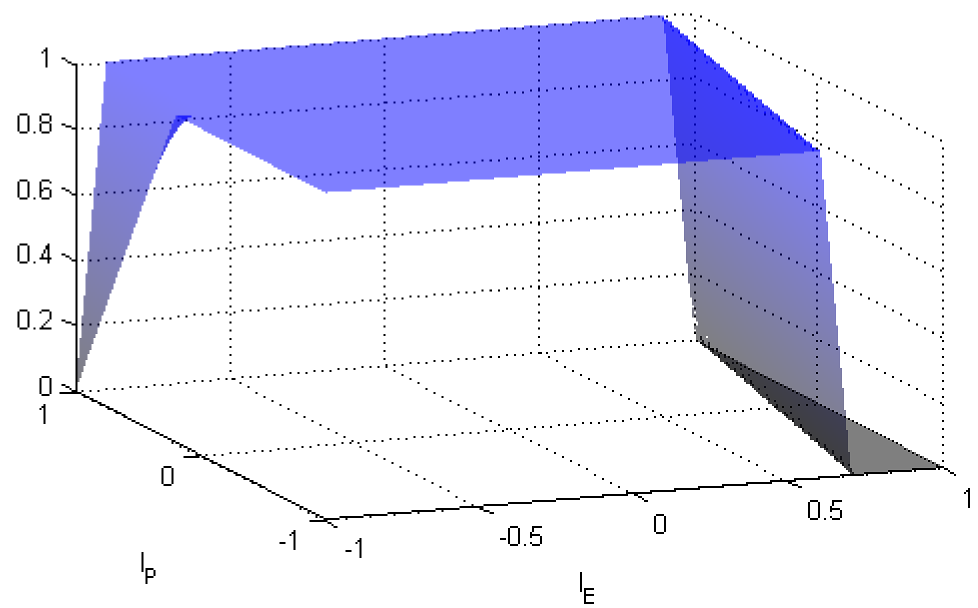

Figure 5. Power transfer surface for route R4.

IMPLEMENTATION

Simulink

All simulations were developed in and run in Simulink, a software package that is used in conjunction with MATLAB (both by the MathWorks). It provides a graphical interface to model highly complex dynamic systems as the familiar block diagrams (Figure 6). In short, it is a very extensive numerical ordinary differential equation (ODE) solver. As long as a complex system (such as a clamshell dredge) and be broken down into mathematically simple components (masses, springs, etc.) it can be modeled in Simulink in a fairly straightforward manner.

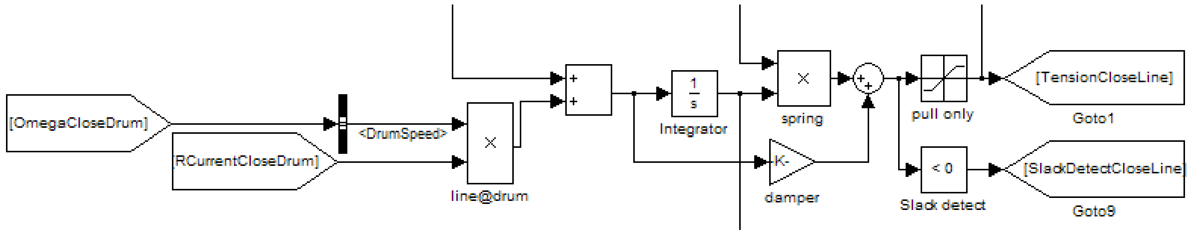

Figure 6. Simulink block diagram.

The simulation is split up in two separate parts. First, the clamshell dynamics simulation is run for a certain amount of time (say, 400 simulated seconds). This simulation outputs, among other things, the dredge's power requirement (load profile). This load profile is subsequently used as an input for the simulation of the flywheel dynamics and the flywheel control system. The simulation is split up for several reasons. The first reason is modularity. The flywheel simulation can accept any time-based load profile as input, be it generated by simulation or actual measured data. The other reason is computational efficiency. Since there is only a one-way dependency between the dredge dynamics and the flywheel system, the simulation can be split into two parts, each utilizing its own optimal solver.

Solver

The mathematical nature of the dredge dynamics simulation is different from that of the flywheel control system. The dredge dynamics model is a "stiff" nonlinear differential equation. This means that the solution can sometimes change very abruptly, on a time scale that is very short compared to the time scale of interest. For example, when the clamshell bucket closes and the two halves hit each other, the relative velocity of the bucket halves drops to zero very abruptly, and therefore needs to be calculated in simulation time steps in the order of microseconds. In this case, this is due to the literal "stiffness" of the steel that the bucket is made of. However, it would take very long to compute the entire simulation (400 seconds) in simulation steps of 1 microsecond. Therefore, a variable-step stiff solver is used, which takes big calculation steps (say, 0.1 seconds), until a "stiff" nonlinearity is encountered, which it then calculates in much shorter steps.

The flywheel control system simulation contains many logic-based components, which can change their output between discrete states instantaneously. This would pose a problem to a variable-step stiff solver, which would reduce its step size indefinitely whenever such a discrete transition occurs (which is often). Therefore, the flywheel control system is simulated using a fixed-step discrete solver, which is not compatible with the dredge dynamics model.

Simulation process

Before the simulation is started, a parameters file that includes simulation settings (solver, step time, simulation duration), dredge parameters (inertias, geometry, soil data, speed-torque characteristics, etc.) and flywheel control system settings (power routing surfaces, filter settings, etc.) is loaded. First the dredge simulation is run, and then its power demand output is loaded into the flywheel simulation as an input. The most important output of the flywheel simulation is the system's total power draw. This output (and others) is used in the post-processing, where resulting electric grid power draw and cost, or diesel generator set fuel consumption and emissions are calculated and plots of this data are generated. Also, a simple animation of the resulting data is generated (Figure 7), which is useful as a quick check for any obvious errors in the simulation output.

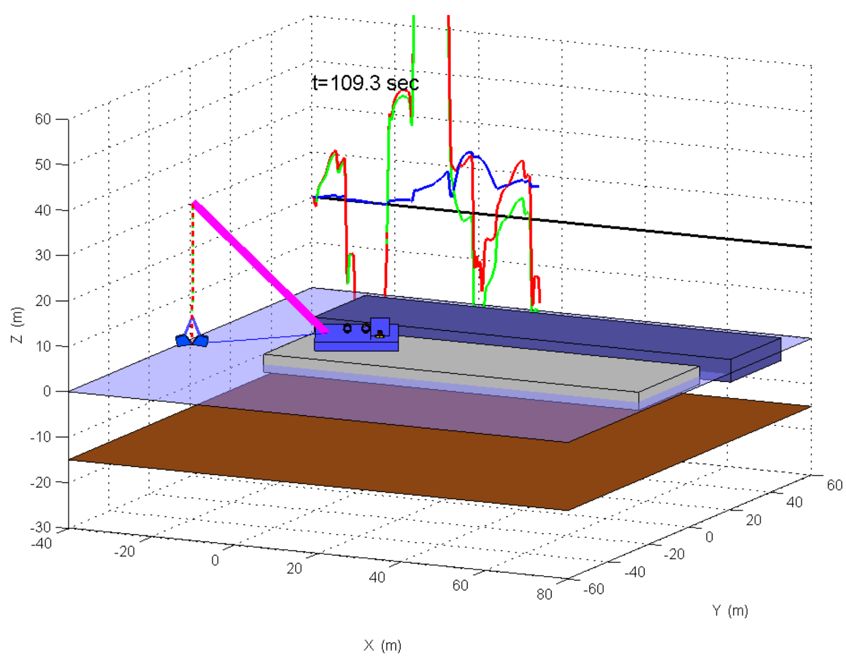

Figure 7. Screenshot of the simulation output animation.

RESULTS

Power usage

The overall power draw profile for the dredge is significantly improved when the flywheel system is implemented (Table 5, Figure 8). The high peaks (which coincide with the hoisting of the bucket) are fully buffered by the stored energy in the flywheel, and the resulting power draw profile shows only minor fluctuations. The effect of the flywheel system's start-up transient can be seen in Figure 8, which plots the total external power draw of the dredge (with (red) and without (green) the flywheel system enabled). Initially, the flywheel's precharge is supplying most of the power to the dredge, while external power draw slowly picks up. Figure 9 shows a plot of how the dredge power demand is divided between the different motors.

Table 5. Average and peak loads.

Power usage						
	Total power demand		Generator load with energy storage		Generator load without energy storage	
Peak	937	KW	233	KW	937	KW
Average	184	KW	209	KW	277	KW

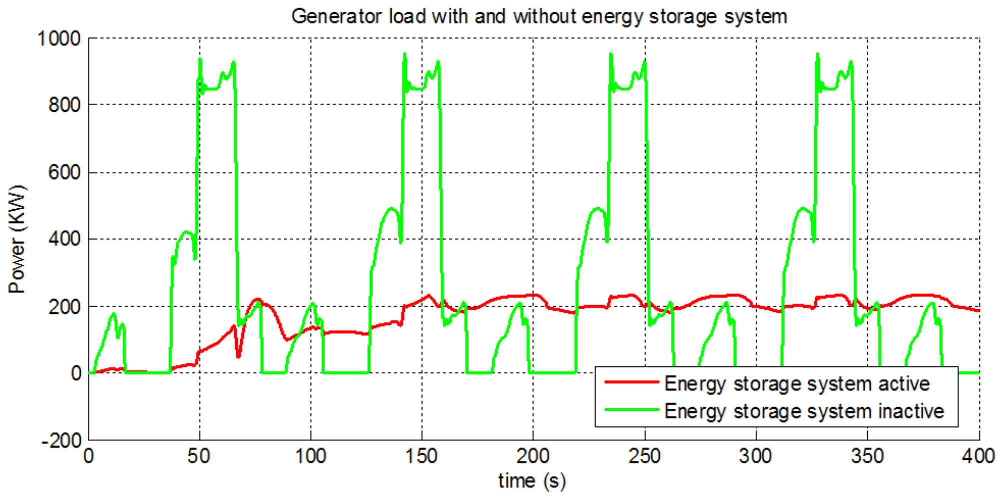

Figure 8. Power profile plot.

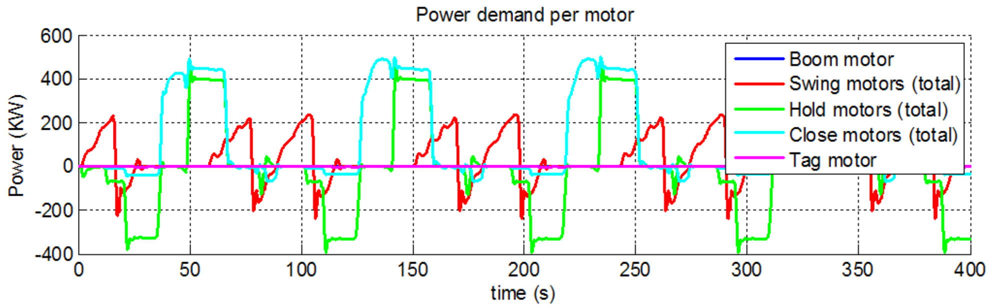

Figure 9. Power profile per motor.

Benefits – grid power

The power draw results as discussed above were used to calculate power cost when utility power is used as the main power source for the clamshell machine. The calculations are based on the Pacific Gas and Electric E20 rate schedule (see http://www.pge.com/tariffs/electric.shtml), 20 hour/day, 30 day/month operation. Based on this simulation, a 25% decrease in power costs can be expected by implementing this energy storage system. This analysis does not take into consideration penalties for low power factor or high demand peaks, both of which would likely increase costs for the conventional setup, but not for the flywheel-equipped machine.

Table 6. Utility power savings.

Estimated monthly cost		
	Summer	Winter
With energy storage system	$14,423	$9,873
Without energy storage system	$19,116	$13,086

Benefits – diesel power

The other possible power source is the use of a diesel-electric generator set. In this case, the greatly reduced peak power draw that the flywheel system realizes allows for the use of a much smaller generator set. Detailed genset data provided by Caterpillar was used to calculate fuel savings and environmental benefits.

Fuel use

For the non-flywheel equipped dredge, a 1150 KW CAT 3512 genset is needed, while a much smaller 275 KW CAT C9 (comparable to the CAT 3406) genset can be used in combination with the flywheel system. Figure 10 shows the fuel efficiency curves of these two generator sets superimposed on histogram plots of the dredge's power draw (with and without the flywheel system). The efficiency curves show that a generator set is most efficient when operating near its maximum power rating. The histograms are a measure of the relative amount of time that the dredge is demanding a certain amount of power. When unaided by the flywheel device, large amounts of power (around 900 KW) are drawn for short periods of time, but most of the time the generator set operates at less than half of its capacity. The flywheel-equipped dredge, however, draws power much more consistently (fairly constant around 200 KW). A suitable generator set would only operate near its most efficient point, resulting in considerable fuel savings (Figure 11). The averaged fuel consumption was reduced by 37% (from 103 liters per hour to 65 l/h). At a fuel cost of around $2.00 per gallon, that equates to a savings of $12,000 per month.

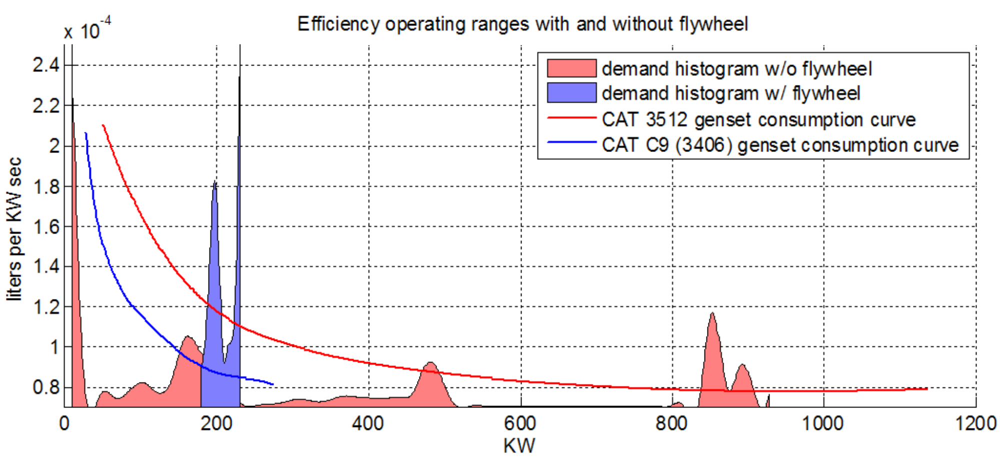

Figure 10. Power demand histograms and efficiency curves.

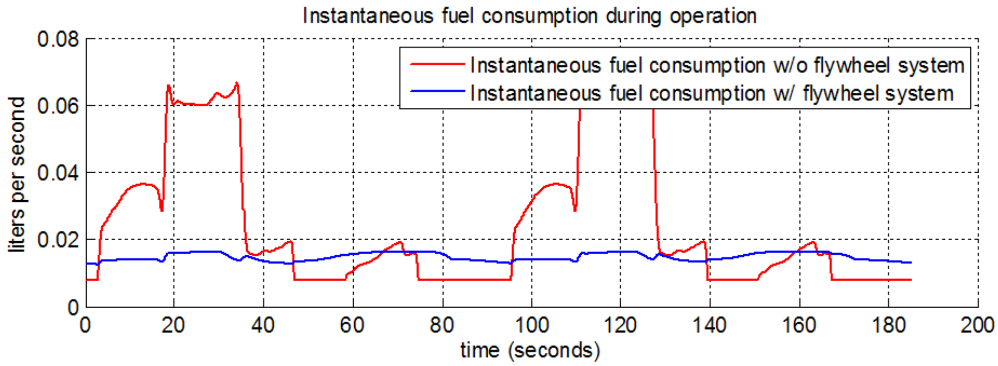

Figure 11. Fuel consumption plot.

Emissions

Emissions benefits could also be calculated using the data provided by Caterpillar. Figure 12 shows the results for the three (3) main Tier 3 emissions categories. The constant power draw of the flywheel-equipped system greatly benefits the generator set emissions. Emissions are reduced by 80-90% for all three emissions categories.

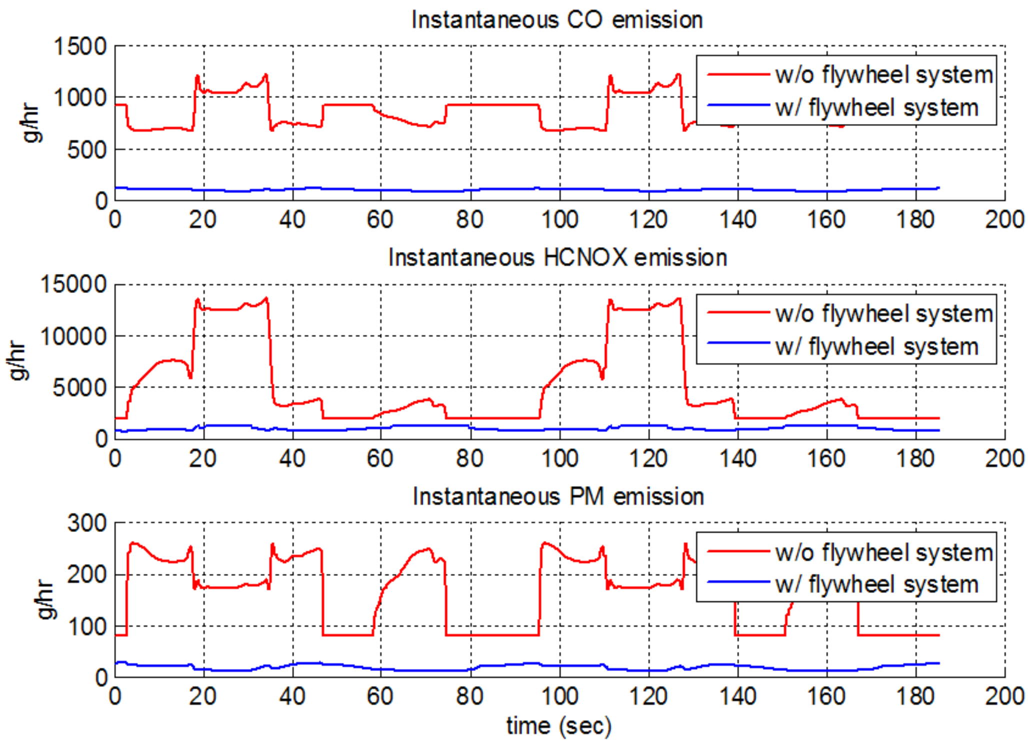

Figure 12. Tier 3 emissions.

Table 7. Capital costs estimate.

	Unique capital costs				Added capital cost	Monthly savings	Cost recovery period
	Conventional		Flywheel equipped				
Grid	DB grid	$75,000	Motor/Flywheel	$150,000	$95,000	$3,953	24 months
			Controls	$20,000			
Genset	CAT 3512	$450,000	CAT C9	$175,000	-$180,000	$12,000	instant
	DB grid	$75,000	Motor/Flywheel	$150,000			
			Controls	$20,000			

Capital cost recovery

A rough estimate of the capital cost differences between traditional power sourcing and a flywheel-equipped machine is shown in Table 7. Monthly cost savings on fuel and grid power are based on the discussions in previous sections of this paper. This estimate assumes that without a flywheel system, a dynamic braking resistor grid and associated power inverter would be needed to dissipate regenerated power. For this specific situation, the added capital cost of implementing a flywheel system can be recovered in about two years. If the machine is not powered through an existing power grid, the use of a much smaller generator set makes the flywheel system much less costly to implement in the first place. In addition, enormous fuel savings further make the implementation of such an energy storage system very profitable.

It must be noted that this is only a very rough cost analysis based on a newly built machine for this particular situation. A retrofit situation would require a much more detailed analysis be made on an individual basis.

CONCLUSION

This simulation was meant as a case study, to analyze the anticipated performance of a flywheel system in a real-world application. The dredge and flywheel simulation were modeled and work well. Average power demand is reduced and stabilized, eliminating any large peaks. The results show economic benefits significant enough to recoup the capital cost of such a system. When diesel generator sets are used and environmental considerations are a concern, this flywheel system provides great benefits over a more conventional genset configuration. It should be noted that a mathematical model, however detailed, can never fully include all of the intricacies of an actual physical system. Therefore, the next step should be to verify these results through a scale model or prototype flywheel system.

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