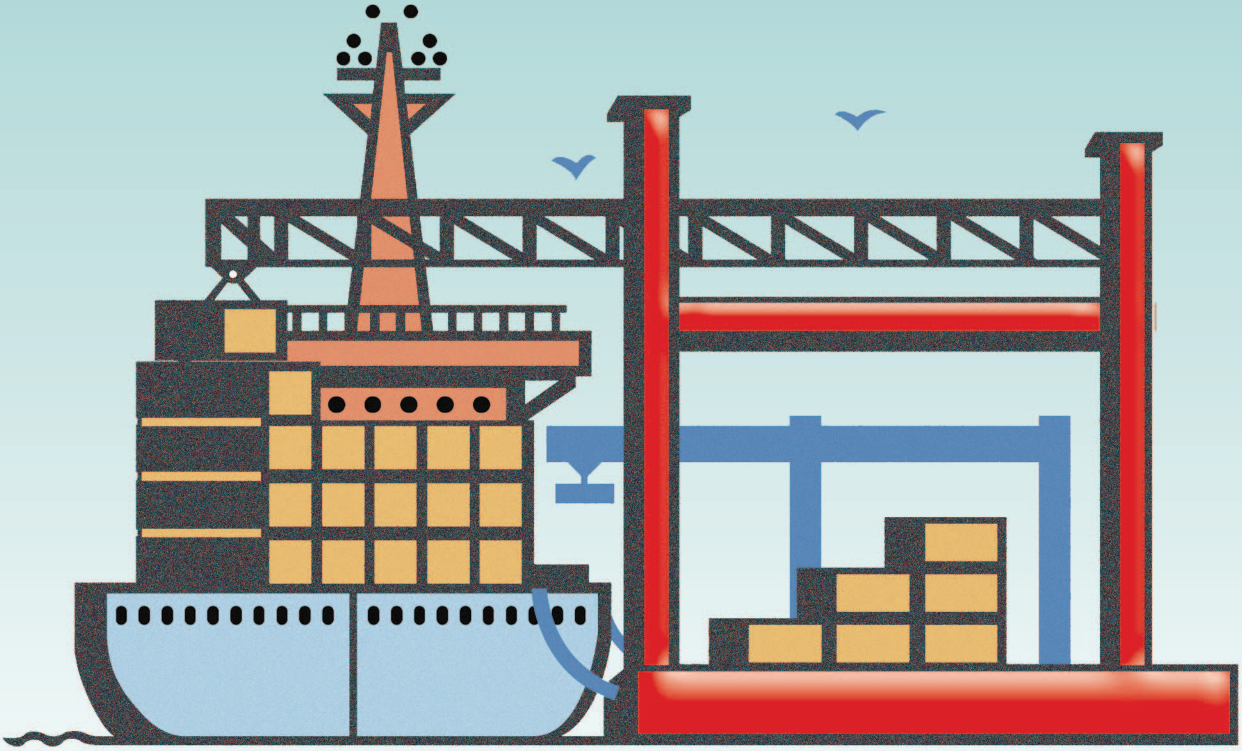

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SAVING ENERGY USING FLYWHEELS

Energy recovery and emission cutting in a mobile gantry crane

BY MARK M. FLYNN, PATRICK MCMULLEN, & OCTAVIO SOLIS

RUBBER-TIRED GANTRY (RTG) CRANES are commonly used in shipping ports around the world to move containers massing up to 40 metric tons. These cranes are mobile and derive their electrical power requirements for the hoist motor from a diesel engine and generator set rather than from the utility system. Because these cranes are independent of the utility system, energy regenerated via the hoist motor as a container is lowered to the ground and is typically wasted as heat in dissipator resistors.

In large coastal shipping ports, thousands of diesel engines are operated within ships, trains, trucks, and cranes. Although these engines are the workhorse of the industry, their exhaust is a known pollutant that can cause cancer and other diseases. Around the vicinity of the ports of Los Angeles and Long Beach, California, in particular, the diesel exhaust is associated with 70% of pollution-related health problems; moreover, diseases caused by the port

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pollution are responsible for hundreds of deaths annually in this area [1]. Because of the problem, these two ports—the busiest in the United States—plan to reduce diesel emissions by 50% over the next five years.

Container cranes, such as the RTG crane shown in Figure 1, are major contributors of port-based diesel emissions. These cranes employ conventional power trains consisting of a diesel engine coupled to an alternator that provides electrical power for a set of hoist, trolley, and gantry motors. The diesel engine prime mover allows an RTG crane to be unencumbered by a utility mains connection as it moves in the shipyard.

When a shipping container is lifted by a conventional RTG crane, the diesel engine provides the energy demanded by the hoist motor. When the container is lowered, the container's potential energy is converted by the hoist motor into electrical form, but the conventional drive system has no means to store this regenerated energy. Consequently, this energy is typically dissipated as heat in resistor banks, resulting in a reduced overall system efficiency and increased fuel consumption and emissions.

HIGH-SPEED FLYWHEELS ARE IDEAL ENERGY STORAGE DEVICES FOR USE WITH RTG CRANES.

This article describes the results of an experimental test during which the conventional power train of an RTG crane was converted to a hybrid version using a pair of high-speed flywheels for energy storage. High-speed flywheels are ideal energy storage devices for use with RTG cranes, as they are able to both source and absorb large amounts of power at the high cycle rates demanded by the hoist motor. They have been used with much success in other demanding high-cycle environments when long life is required [2], [3]. This article will provide 1) an overview of an RTG crane, 2) its electrical system performance when lifting and lowering loads without flywheels, 3) an overview of the flywheel and its associated motor drive, and 4) the improvement in the operation of the crane when flywheels are employed.

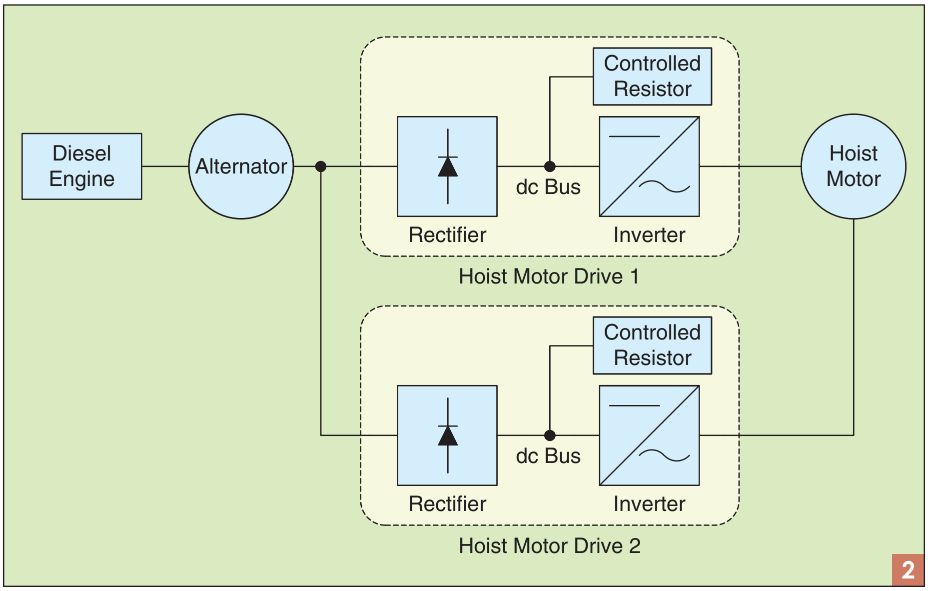
RTG crane.

Conventional RTG Crane Overview

Mechanical

RTG cranes such as the one shown in Figure 1 are known as one-over-four RTG cranes because they are able to raise one shipping container above a stack of four containers high. The crane grabs hold of a container with a device called a spreader, which has a mass of 10 t. The crane can lift a maximum shipping container mass of 40.6 t yielding a total lift load of 50.6 t.

Using hoist, trolley, and gantry motors, RTG cranes can move containers in three degrees of freedom. The hoist motor is used to raise and lower the container, trolley motors move the container from one side of the crane to the other, and gantry motors are used to reposition the entire crane. This article focuses on the testing conducted with the hoist motor only, because the trolley and gantry motors afford lesser regeneration opportunities.



RTG crane hoist motor drive.

Electrical

The simplified power train for the crane tested is shown in Figure 2. The 455-kW rated diesel engine turns a 500-kVA, 460-$V_{LL,rms}$, three-phase alternator. The output of the alternator is connected to two independent hoist motor drives, each of which powers an isolated three-phase winding in the hoist motor. Each motor drive connects to the alternator via a three-phase, full-bridge, passive

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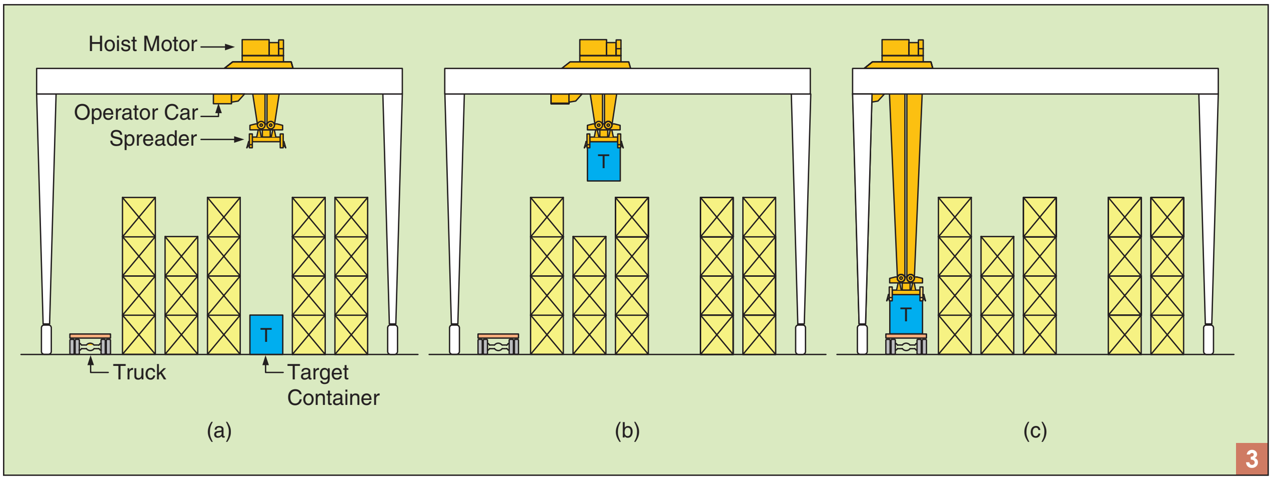

Typical crane operating scenario: (a) Target container to be acquired with spreader. (b) Trolley container to awaiting truck. (c) Lower container onto truck and release spreader.

diode rectifier producing a nominal dc bus voltage of 650 V. The maximum hoist motor power (measured at the dc bus) is limited by the motor drives to approximately 300 kW (150 kW per motor drive).

During a regeneration event (i.e., when a container is lowered), the voltage at each dc bus rises significantly commensurate with the limited dc bus capacitance. When the voltage on a particular bus equals 730 V, the respective chopper-controlled resistor bank is activated to dissipate the regenerated energy.

Crane Testing Method

During the operation at the port, crane operators attempt to maintain a pace of moving one container per minute. A typical operating scenario consists of the crane loading the containers onto the awaiting trucks as shown in Figure 3. In such a case, the empty spreader is lowered to a stack of containers that can be anywhere from one to four containers high. The target container is acquired and lifted out of the stack. The crane trolleys the container to a position above the truck and then lowers the container onto the truck. The cycle is completed when the empty spreader is raised away from the truck and is then trolleyed back to the container stack.

In the above scenario, the empty spreader is raised and lowered once; likewise, the combined spreader and container load is raised and lowered once. There are also two trolley operations, one with an empty spreader and one with a combined spreader and container load. From these observations, a testing method was devised that simulates the typical operating scenario and allows for the evaluation of the crane's fuel consumption and emissions output both with and without the flywheel energy storage. The test method consists of raising and lowering the empty spreader once a minute for 30 min followed by raising and lowering a combined spreader and container load once a minute for 30 min. Thus, at the end of a standard one-hour test, 60 cycles are performed. All auxiliary loads such as the exterior lighting and the operator car's air-conditioning system were in use during the test. The trolley events were neglected because the energy consumed and regenerated during this time is small compared with that of the hoist motor. The test method is summarized in Table 1.

TABLE 1. CRANE OPERATIONS PERFORMED DURING STANDARD ONE-HOUR FUEL CONSUMPTION AND EMISSIONS TEST.

	Raise	Lower
Empty spreader operations	30	30
Combined spreader and container load operations	30	30

In practice, the target container for a given move can be located at a variable height within the four-container-tall stack. The maximum fuel consumption and emissions occur when the target container is located on the ground level between the full-height container stacks as shown in Figure 3. These worst-case conditions were simulated during testing by raising and lowering the hoist to the height of four containers, which is approximately 10.6 m.

According to port authorities, the typical shipping container has a mass of about 15 t. Thus, a container with a similar mass of 15.3 t was selected for use during testing. Throughout the testing, the fuel consumption and emissions were measured. In addition, the electrical system performance was recorded at the dc bus of each hoist motor drive; these locations correspond to the connection points for the flywheel energy storage system described below.

Crane Operation Without Flywheels

Lifting Event

During the first phase of testing, the baseline fuel consumption and emissions output from the diesel engine were determined. The crane was operated according to the one-hour test described earlier without the flywheel energy storage. Figures 4 and 5 show the dc bus power supplied to each hoist motor drive during an empty spreader lift and 15.3-t container lift, respectively. When the hoist power is ramping toward its peak, the hoist is accelerated; once the desired lifting speed has been achieved, the hoist power demand is reduced and the load is lifted at a constant speed with constant power.

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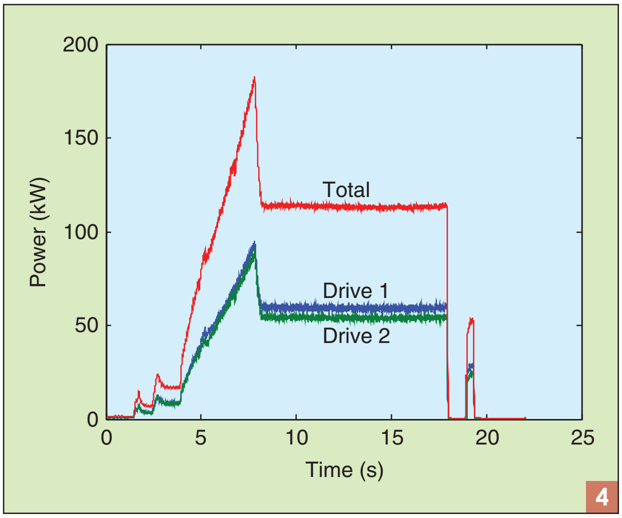
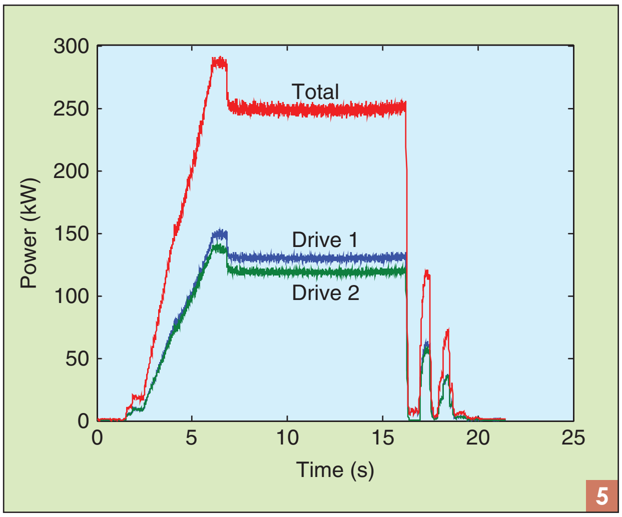
At the beginning and end of the lifts, short-duration power fluctuations can be observed. The fluctuations, although not desirable, are the signature of the human operator at the controls of the crane and reflect one's personal style of manipulating the joystick controls. In addition, it is noted that the two motor drives do not supply exactly the same power. For instance, when the load is lifted under constant power, Drive 1 supplies 59 and 131 kW, respectively, and Drive 2 supplies 54 and 119 kW, respectively (Figures 4 and 5). The mismatch in either case is the same; specifically, Drive 1 supplies 10% more power than Drive 2. The variance can be attributed to motor drive controller settings and tolerances as well as slight mismatches between the two motor windings. However, neither of the above two anomalies is a cause for concern during the fuel consumption and emissions test, because the hoist motor drives perform similarly with or without the flywheels and the same human operator is used for both portions of the test.

THE CONVENTIONAL RTG CRANE CANNOT STORE THE ENERGY REGENERATED WHEN THE HOIST IS LOWERED.



DC bus hoist motor drive power during spreader lift.



DC bus hoist motor drive power during container lift.

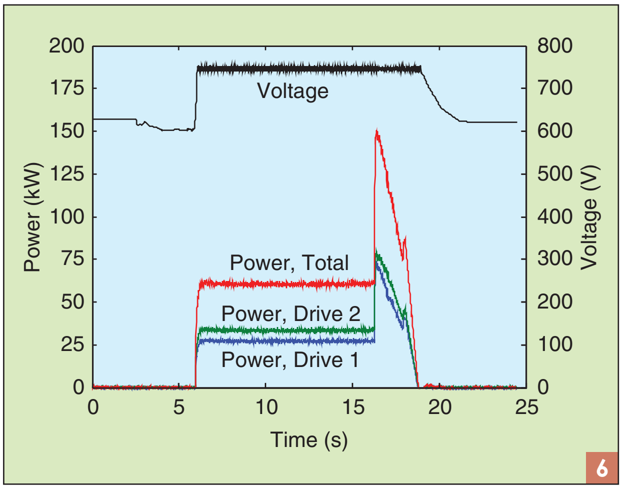
Lowering Event

The conventional RTG crane has no ability to store the energy regenerated when the hoist is lowered. This energy is thus dissipated as heat by the resistors shown in Figure 2. Figure 6 shows the dc bus voltage of Drive 1 and the filtered dc bus power regenerated from both motor drives during the lowering of the empty spreader. The waveforms are similar for the case when the container is lowered. During the constant power portion of the waveforms, the hoist is lowered at a constant speed. To stop the descent of the hoist, the power regeneration from the motor drives is increased, thereby extracting the kinetic energy from the spreader and the mechanical hoisting components as can be observed during the interval from 16 to 18.5 s. Note that while the hoist is being lowered and the resistor is dissipating power, the voltage oscillates between 730 and 750 V as the chopper switches the resistor into and out of the circuit. In addition, the motor drive power mismatch during lowering is reversed when compared with the lifting case.

RTG Crane Efficiency

The aggregate efficiency of the crane's hoist system consisting of the mechanical hoisting components, the hoist motor, and the hoist motor drives directly affects the portion of the load's potential energy, which can be captured by the flywheels and made available for reuse. It is thus a major factor in determining the maximum possible fuel and emissions savings. The hoist system's efficiency is presented below as calculated from the manufacturer's data and as measured during experimental testing.

1) *Calculated efficiency:* The efficiency of the hoist system can be computed using the hoisting speed provided by the manufacturer. For example, the manufacturer



Motor drive power and voltage during lowering of the spreader.

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states that the RTG crane hoists a 40.6-t container (either up or down) at a rate of 0.383 m/s. If the container is being lifted, the power, P_L, supplied to the combined spreader and container load is

$$\begin{aligned} P_L &= mgv \\ &= 50,600 \text{ kg} \times 9.81 \text{ m/s}^2 \times 0.383 \text{ m/s} \\ &= 190 \text{ kW}, \end{aligned} \tag{1}$$

where m is the total load mass, g is the acceleration due to gravity, and v is the hoisting speed.

After the acceleration phase is complete, loads massing more than 22 t are hoisted at a constant speed dictated by the maximum continuous combined dc bus power ($P_{\text{dc-max}}$) of 250 kW. (The 250-kW continuous power limit can be observed in Figure 5 for the case of a 25.3-t load lift.) Therefore, the one-way efficiency (η) of the hoist system when lifting a 50.6-t load can be computed as

$$\begin{aligned} \eta_{\text{one-way, lift}} &= \frac{P_L}{P_{\text{dc-max}}} \times 100\% \\ &= \frac{190 \text{ kW}}{250 \text{ kW}} \times 100\% \\ &= 76.0\%. \end{aligned} \tag{2}$$

The manufacturer's data indicate that the hoisting speed for a spreader-only load is 0.866 m/s. Using (1) with a 10-t spreader load, P_L is found to be 85.0 kW. The total dc bus power required during the constant speed portion of the lift is found from Figure 4 to be 113 kW. Thus, the one-way lifting efficiency is computed as

$$\begin{aligned} \eta_{\text{one-way, lift}} &= \frac{85.0 \text{ kW}}{113 \text{ kW}} \times 100\% \\ &= 75.2\%. \end{aligned} \tag{3}$$

It is possible to compute efficiency values for every load mass in between the points given and also for lowering events if desired. However, here it is simply concluded that the hoist system efficiency is approximately constant over the load range. To confirm the above calculations, the measured efficiency data are presented below.

2) *Measured efficiency:* By comparing Figures 4 and 6, an aggregate two-way efficiency estimate for lifting and lowering operations can be computed for the hoist system. Specifically, from Figure 4, it was observed that an average total power of 113 kW was required to lift the empty spreader at a constant speed of 0.866 m/s. The total power received during regeneration when the spreader was lowered at the same speed was 61 kW. The efficiency is thus calculated as

$$\eta_{\text{two-way}} = \frac{61 \text{ kW}}{113 \text{ kW}} \times 100\% = 53.9\%, \tag{4}$$

$$\eta_{\text{one-way}} = \sqrt{\eta_{\text{two-way}}} = 73.5\%. \tag{5}$$

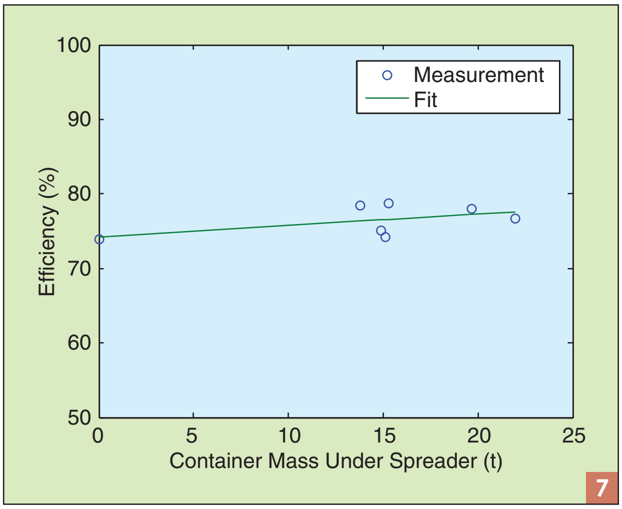
The one-way efficiency obtained in (5) represents an average value of the one-way lifting and lowering efficiencies with a spreader load. It is lower than the value obtained in (3) because of the presence of the less efficient lowering event in the average.

Figure 7 presents the measured one-way efficiencies computed using the above method for a range of hoist loads. Each measurement point in the figure represents the average of several measurements performed for the respective load. The measured efficiencies range from 73.9–78.7%, with a mean value of 76%. While the linear fit suggests a modest efficiency improvement with increasing load, the measured efficiencies for container masses greater than 13 t lie in a narrow band that can be approximated as constant. Of chief importance is that because of the 76% mean hoist system efficiency, nearly one-fourth of a given container's potential energy cannot be recovered as it is lowered. However, despite this disadvantage, it is shown in the following sections that the flywheel storage system remains capable of greatly reducing the fuel consumption and emissions output.

Overview of Flywheel and Motor Drive

The flywheel energy storage unit consists of a three-phase permanent magnet synchronous motor-generator coupled to a steel flywheel on the same rotor. The rotor assembly is levitated on active magnetic bearings and spins in a vacuum to minimize losses. A three-phase inverter functions as the flywheel's motor drive; the drive and flywheel motor are designed to transfer a maximum power of 150 kW to and from the dc bus. Energy storage is 4.57 MJ (1.27 kWh) at a maximum speed of 36,000 rev/min. The mass of the unit is 320 kg yielding a specific energy of 14.2 kJ/kg. The flywheel unit is shown in Figure 8 with a cutaway view of the rotor superimposed.

When flywheels are used with an RTG crane, two units are employed; a single unit provides isolated energy storage to an individual hoist motor drive as shown in Figure 9. The two units are packaged together and installed underneath a crane support beam as shown in Figures 10 and 11. Total energy storage with two flywheels is 9.14 MJ, which is much more than the 5.26 MJ of potential energy released by a



One-way hoist system efficiency versus container mass.

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maximum hoist load of 50.6 t as it traverses 10.6 m. When a minimum operating speed of 10,000 rev/min is taken into account, the total usable energy storage is 8.43 MJ.

The excess energy storage was reduced by decreasing the maximum operating speed to 20,000 rev/min yielding a usable energy storage of 2.12 MJ (0.59 kWh) for the flywheel pair. This decrease is advantageous as it results in decreased losses and simplified motor drive and magnetic bearing control. The final maximum operating speed was selected by considering the typical container mass most often encountered in operation and the efficiencies of the systems involved. For instance, typical containers mass 15 t, and relatively few mass more than 20 t. Thus the ability to capture the energy regenerated from lowering a 20-t container is a desirable goal.

When lowered 10.6 m, a 20-t container (30 t including spreader) releases 3.12 MJ, which is more than the capacity of the flywheel pair. However, when the efficiency of the energy flow path from the container to the flywheel mass is included, the storage capacity is sufficient. For example, the hoist system's mean one-way efficiency was found to be 76%. The average one-way efficiency of the flywheel motor and its drive is 89.5%. Using these two values, the amount of energy that can be captured as a combined 30-t spreader and container load descends 10.6 m is

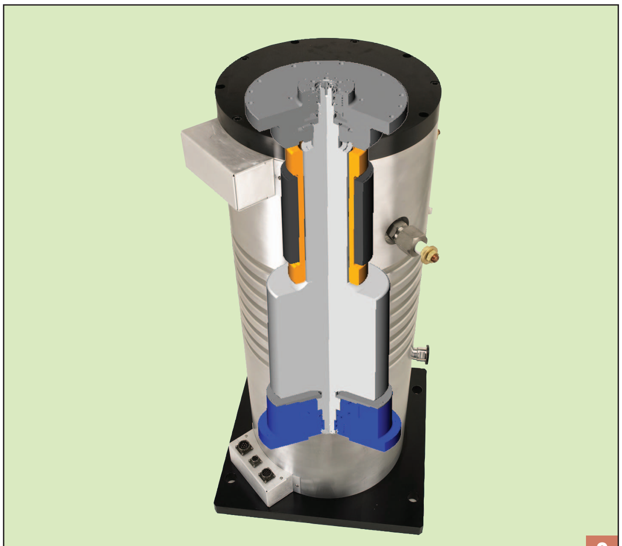
$$3.12\ \text{MJ} \times 0.760 \times 0.895 = 2.12\ \text{MJ}. \quad (6)$$

Other forms of energy storage for RTG cranes such as supercapacitors, have been reported in the literature [4]. However, compared with supercapacitors, high-speed flywheels can offer higher efficiency, higher cycle life without degradation, reduced ambient temperature concerns, and increased reliability owing to the absence of the hundreds of series connections in supercapacitor banks [5].

Crane Operation with Flywheels

Initialization

When an RTG crane is turned on at the beginning of a work shift, the diesel engine is started and allowed to warm up. The alternator is then connected to the hoist



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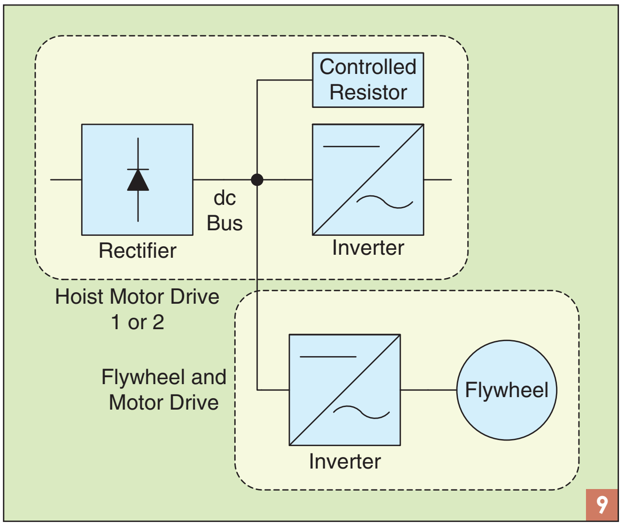
Flywheel unit with rotor superimposed.



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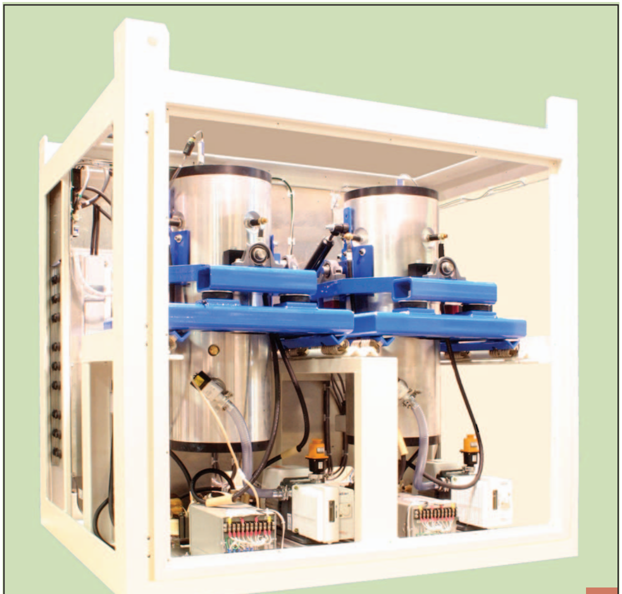
Flywheel interface to an individual dc bus.



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Two flywheel units arranged in a single package.

11

Flywheels installed on RTG crane.

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motor drives and the dc buses are energized. If the speed of an individual flywheel is below 10,000 rev/min, the respective unit is motored to this minimum operating limit where it remains until the first lowering event. If the speed of a flywheel is otherwise above 10,000 rev/min, it is allowed to coast at its present speed until the first lowering event described below.

THE ABILITY TO CAPTURE THE ENERGY REGENERATED FROM LOWERING A 20-T CONTAINER IS A DESIRABLE GOAL.

Lowering Event

When not in service, the spreader is stowed at the maximum lift height. Thus, the first hoist operation performed by a crane operator is a lowering event of the empty spreader. As the hoist is lowered, the resultant voltage rise at each dc bus is used by the respective flywheel controllers to compute an appropriate power command for the flywheel motor drives to capture the regenerated energy.

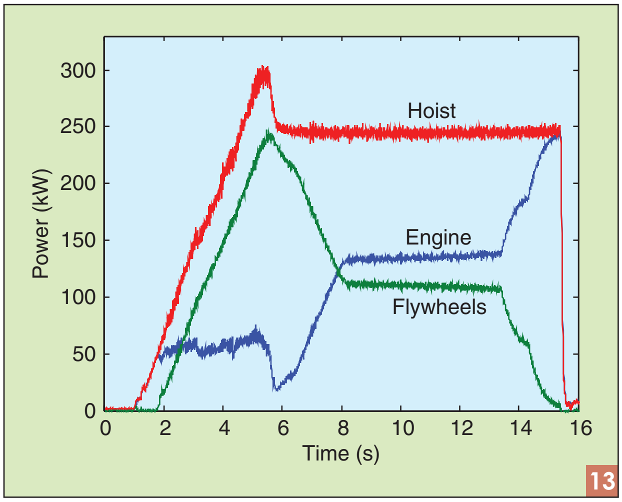
Figure 12 shows the total power regenerated by the hoist motor drives to the dc bus when the 15.3-t container is lowered; the regenerated power during the lowering of the empty spreader was shown in Figure 6. The speed of each flywheel increases during this time, as the potential and kinetic energy of the load are absorbed. The mismatch in flywheel speeds reflects the power mismatch of the hoist motor drives and is of no concern during operation. If the container is more massive than 20 t, the flywheels will be fully charged to 20,000 rev/min before the hoist descent is completed. In this event, the excess energy will be dissipated by the chopper-controlled resistors.

Lifting Event

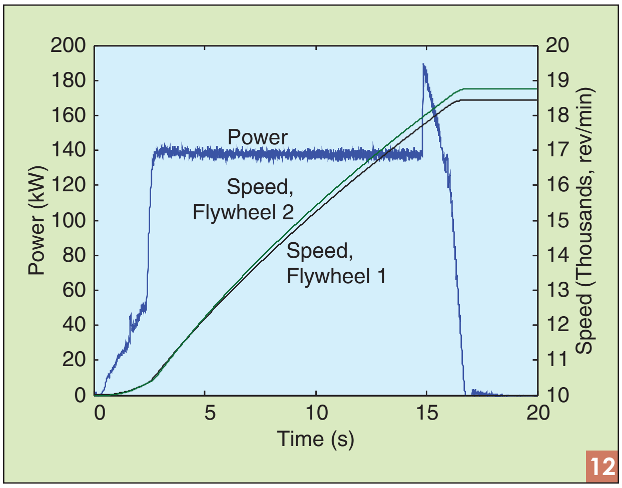
Energy stored in the flywheels during a lowering event is available for reuse during a subsequent lift. Figure 13 shows the hoist power provided by the diesel engine and the flywheel units during the lift of a 15.3-t container. The corresponding flywheel speeds are provided in Figure 14. The waveforms for the spreader lift are similar.

During a lift, the flywheel controller measures the engine power at the dc bus and is programmed to limit the engine power to 50 kW by supplying the power difference required by the hoist while it is accelerating. In this manner, the peak power demand on the diesel engine is reduced, which in turn reduces the engine wear, fuel consumption, and emissions output. After the power peak, the hoist is lifted at a constant speed. The flywheel controller then gently reduces the maximum flywheel output power to 60 kW per flywheel unit (120 kW per flywheel pair), allowing the engine to ramp up in power gradually and thus avoid heavy particulate emissions.

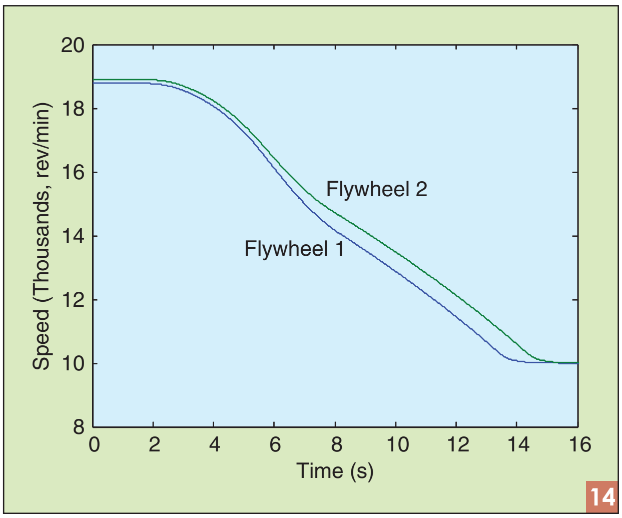
As the flywheels approach a fully discharged state of 10,000 rev/min, the remaining hoist power demand is transitioned to the engine gradually (Figure 13). Because of the power mismatch between the hoist motor drives,



DC bus powers during container lift with flywheels.



Regeneration during lowering of the container with flywheels.



Flywheel speeds during container lift.

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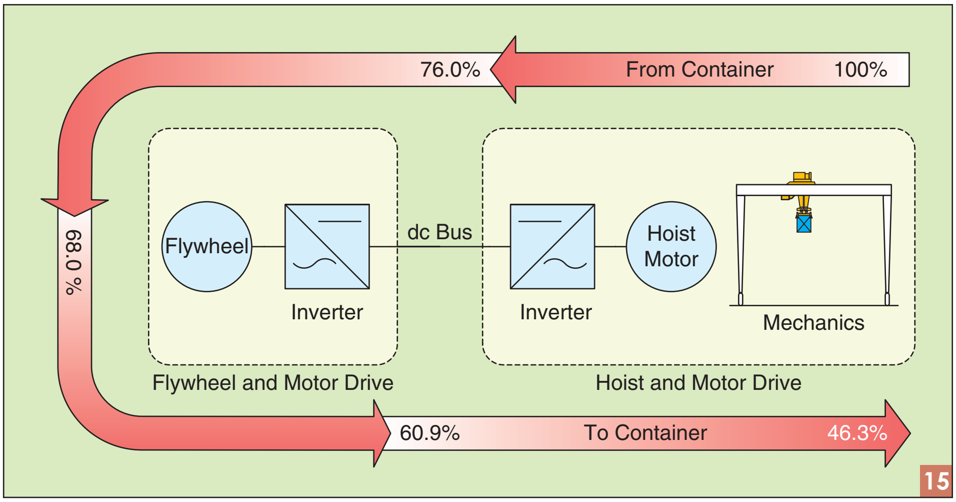

Potential energy captured from and returned to the container.

TABLE 2. FUEL AND EMISSIONS RTG TEST RESULTS WITH AND WITHOUT FLYWHEELS.

	No Flywheels	With Flywheels	% Reduction
Fuel consumption (L/h)	25.4	20.1	20.9
Nitrous oxides (kg/h)	0.386	0.286	25.9
Particulate emissions (kg/h)	0.0408	0.0136	66.7

the flywheels are not likely to reach 10,000 rev/min at the same instant. Therefore, the power transition can occur in two steps as each flywheel is discharged.

Figure 15 illustrates the percentage of a container's potential energy that can be captured by the flywheels during a lowering event and then returned to the container during a subsequent lifting event. As the figure shows, theoretically more than 46% of a container's potential energy can be reused; however, in practice, diesel savings are somewhat lower because of additional system losses. For example, some activities, such as gantry and trolley events and, most importantly, intervals when the engine is idling but the hoist is not in use, consume diesel fuel but do not provide significant opportunities for energy regeneration. Power consumed by auxiliary systems such as air conditioning and lighting also increases fuel usage without the prospect of energy recovery.

Testing Results Summary

Table 2 summarizes the fuel and emissions results during the one-hour testing for the cases with and without the flywheel energy storage. Significant improvements were made in all quantities measured. Although the nearly 21% fuel consumption reduction is excellent, it is lower than the theoretical maximum as expected, which is largely because the engine was idling for 50% of the time during the one-hour test. Future enhancements to the flywheel energy storage system are expected to yield further improvements.

Conclusions

The flywheel system has shown through experimental testing to greatly reduce the fuel consumption and emissions output. In addition, the reduced peak power demand from the diesel engine increases the engine life. Furthermore, because of the energy storage made available by the flywheels, the diesel engine can be reduced in size for greater fuel and emissions savings. Initial field tests with a reduced-size engine have yielded fuel savings of up to 35% and more. As an added measure of reliability, if a single flywheel system were to become inoperable, the crane can continue operating with the remaining flywheel. If desired, this lone flywheel can be configured to perform at elevated power levels for a limited time until the service can be completed.

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